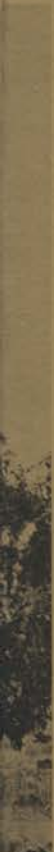
AUSTRALIAN GRASSLANDS

EDITED BY R. MILTON MOORE

This book is a comprehensive account of the Australian grasslands and of their capacities for providing adequate nutrition for grazing animals, the products of which, whether as wool, meat, or dairy products, are important in the national economy. The wool and beef industries were established on indigenous grasslands and in many areas, particularly in the drier parts, are still dependent on native plants. Problems of sustaining the productivity of arid and semi-arid lands and of increasing the output of higher rainfall areas are discussed.

The establishment of productive pastures of exotic species in the higher rainfall areas of both tropical and temperate areas is the outcome of research embracing climate and soils, species adaptation, major nutrient and trace element deficiencies, and effective nodulation of pasture legumes.



The major subdivisions of this book written by scientists eminent in their fields are: the environment including the native herbivores, the grazing lands and pastures, the principal factors affecting productivity, and production from grasslands.

Lavishly illustrated, with 67 plates, 5 colour maps, and 60 figures, and with a consolidated list of references of very considerable use, the book will fill an important gap in the literature for students and teachers of agriculture, and for grassland research workers. It is relevant to world pasture conditions, too, in that countries developing their own grazing industries will find Australian experience and methodology a valuable guide in improving their own grasslands.

AUSTRALIAN GRASSLANDS

AUSTRALIAN GRASSLANDS

Edited by

R. MILTON MOORE

AUSTRALIAN NATIONAL UNIVERSITY PRESS
CANBERRA 1970

Printed in Australia
by Halstead Press, Sydney
Registered in Australia for transmission
by post as a book

National Library of Australia Card No. and SBN 7081 0449 5
Library of Congress Catalog Card No. 72–96408

For the late J. Griffiths Davies, C.B.E., D.Sc., Ph.D.,
first Chief of the Division of Tropical Pastures, CSIRO

PREFACE

Despite recent developments in mining and the increasing contributions of minerals and other forms of production to the economy, Australia is still essentially a pastoral country. More than 50 per cent of the land (about three times the world's average) is used for grazing and about 40 per cent of national export income is derived from the grazing industries. Nearly 75 per cent of the country is arid or semi-arid and occupancy of much of this drier part is effected only through the sheep and cattle industries. The value of the grazing industries therefore cannot be assessed solely by their contributions to national production.

In the last thirty years or so spectacular increases in stock-carrying capacities have been achieved by amendment of soil nutrient deficiencies and the sowing of introduced pasture species in the sub-humid parts of southern Australia. The northern, tropical, and sub-tropical areas are on the threshold of developments of similar magnitude. The story has singular aspects; domesticated grazing animals performed the first step in the improvement of production by changing the composition and modifying the environments of sub-humid grazing lands to suit accidentally introduced annual legumes—subterranean clover in the south, and Townsville lucerne (recently renamed Townsville stylo) in the north. Increases in the productivity of large areas of temperate Australia have depended almost wholly on subterranean clover. Townsville stylo will seemingly play a similar role in sub-humid tropical areas.

This book is about this so-called pasture revolution and the ways in which it came about. It is also about the drier and larger part of Australia where animal production continues to depend almost entirely on the native vegetation. There is less about this part, simply because less is known. The point is made that more needs to be known to ensure continued economic utilisation of arid lands for comparatively low cost production of wool and beef and for conservation of wildlife. To these uses might also have been added a potential for tourist and recreational purposes.

There are sections on the Australian grassland environment, the different grasslands and how the productivity of many of them has been increased, and on the more important factors, other than organism-caused diseases, affecting animal production. A final chapter discusses production from grasslands in economic terms.

Grass systematics and physiological factors affecting individual grassland species have been subjects of recent Australian publications and are not discussed here other than very generally. Similarly specific aspects of animal nutrition and intake and digestibility of species are discussed only in the broadest terms.

Except when treeless grasslands are mentioned specifically, 'grassland' is used in the European sense to denote all communities on which animals are fed—annually sown crops excepted. In Australia it has been customary to use 'pasture' in this sense and to speak of native, natural, and improved pastures: the first denoting communities of native species, the second communities composed mainly of native species but containing a high proportion of volunteer introduced species, and the last, communities entirely or principally of sown species to which fertilisers are often applied. Thus in Australian usage 'native pasture' embraces a wide range of communities from tropical woodland understoreys of *Heteropogon contortus* to shrublands of mulga (*Acacia aneura*) and shrub steppes of saltbushes and blue-bushes. A *Heteropogon contortus* community in which the exotic *Stylosanthes humilis* has established or a Stipa-Danthonia community with volunteer species of Medicago might be called 'natural pastures'. If the legumes were sown or became dominant following applications of fertilisers the communities might be described as 'improved pastures'. The ultimate in 'improvement' in the more humid areas is complete destruction of the native community and its replacement by introduced grasses and legumes.

The description of such a variety of communities as pastures is confusing to grassland scientists outside Australia and indeed has seemed inappropriate to many Australians. The difficulty is to find suitable and acceptable alternatives. Rangeland, a term of American origin, has recently been applied to arid communities in Australia. For the most part it fits these vast, open, and sparingly fenced areas, but it does not seem apposite, for example, to fenced areas of tall native grasses in unfelled humid-tropical woodlands. For want of a better term, I have used 'grazing lands' to denote communities of native plants that are grazed or browsed, and have reserved 'pastures' (against opposition from some authors) for communities predominantly of introduced species, whether sown or volunteer. 'Grassland' embraces both pastures and grazing lands.

A classification of grasslands has been attempted and grazing lands and pastures have been mapped. The classification systems adopted are described with some general comments on the grasslands of Australia in a short chapter which introduces the section on grazing lands and pastures.

Irrigated pastures excepted, grasslands are discussed on the bases of their original vegetation and their climates. A reason for relating the pastures and grazing lands to vegetation is that only about 65 million acres (26 million hectares) of an estimated 430 million acres (172 million hectares) suitable have been improved. There are more grazing lands than pastures and the grazing lands are simply the original plant communities modified to varying degrees. An additional reason is that landholders are accustomed to classify their lands by the original vegetation. It is hoped that the system adopted will be meaningful to them as well as to grassland scientists.

Vegetation formations are not grouped in chapters according to a standard formula. Contiguous formations or sub-formations growing in similar climates, for example tropical rainforests, wet sclerophyll forests, and tropical heaths are discussed in one chapter. This is a convenient grouping because although the soils of these communities differ markedly in initial fertility the pastures that can be grown are the same. Eastern temperate woodlands have a chapter to themselves but the woodlands of the south-west are grouped with the forests and heaths even though each has affinities with temperate formations in eastern Australia. The reasons for this broad grouping are that there are now virtually no grazing lands in the south-west, and the pastures that can be grown in the different formations are for the most part annual and similar. The eastern wet heath lands of both temperate and tropical areas grow pastures similar to those of their adjacent rainforests and wet sclerophyll forests, and are grouped with them. Dry heaths frequently resemble the sclerophyllous shrub layers of dry sclerophyll forests and since they may be sown to similar pastures the two formations are discussed in the same chapter. Because they have Mallee eucalypts in common, Mallee and Mallee heaths are placed together even though their pastures differ. Semi-arid woodlands have been separated rather arbitrarily from other arid communities because of the dominance of eucalypts in the upper layer, the common occurrence of a shrub layer, and the high constancy of species of Aristida in the ground layer.

Descriptions of grasslands based on vegetation required the compilation of a vegetation map. The classification system adopted, a relatively simple one, is described in Chapter 4. This was kept brief to avoid repetition of the descriptions of plant communities in chapters on grasslands.

Except for very recent changes, the scientific names used are those generally accepted by Australian ecologists and grassland scientists. Authorities are not quoted. Common names are not standardised and, since some change from place to place, the same species may have different popular names in different chapters.

To conform with the trend in Australian scientific circles towards complete adoption of the metric system and at the same time provide easy interpretation for those familiar only with the British system, most measurements are given in both systems.

The idea of producing this book came from the Organising Committee of the International Grassland Congress which held its first meeting in Australia in 1970, the year of publication.

The book has been made possible by the co-operative efforts of grassland and other scientists in Australian universities, State Departments of

Agriculture, the Western Lands Commission, New South Wales, and the Commonwealth Scientific and Industrial Research Organization. All contributors agreed to forgo royalties to enable the book to be published as inexpensively as possible.

I have tried to treat the subject as an integrated whole rather than a series of parts and I appreciate the efforts of authors to conform to my philosophical framework. Help was received from many sources. Technical information was furnished by the Department of Primary Industries, Queensland, and by Departments of Agriculture in the other States; particular thanks are due to the many officers who completed or arranged the circulation of questionnaires on grassland and the grazing industries. Thanks are due too to the Soil Conservation Service of New South Wales, the Soil Conservation Authority, Victoria, the Queensland Forest Service, the CSIRO, and the University of Tasmania for photographs of vegetation. Permission to reproduce figures was given by authors, journals, and publishers both in Australia and overseas.

As well as from authors of chapters on pastures and grazing lands, information about vegetation and pasture boundaries was received from a number of botanists and agronomists but in particular from Dr J. S. Beard, Director, Kings Park and Botanic Gardens, Perth; Dr J. S. Carpenter and Mr E. D. Carter, Waite Agricultural Research Institute, Adelaide; Dr J. Ebersohn, Department of Primary Industries, Brisbane; Dr S. T. Blake and Mr L. Pedley, Queensland Herbarium, Brisbane; Mr R. F. Isbell, CSIRO, Townsville; Dr L. J. Webb and Mr G. Tracey, Rainforest Ecology Unit, CSIRO, Brisbane; Dr L. R. Humphreys, University of Queensland, and Professor N. C. W. Beadle, University of New England.

Mr W. F. Goodwin of the Cunningham Laboratory, CSIRO, performed the herculean task of drawing the maps and preparing most of the figures for publication and I am particularly grateful to him for his skilful and painstaking work.

The Department of National Development, Canberra, supplied lithographic copies of the base maps on which the vegetation, grazing lands, and pasture maps were drawn. The Commonwealth Bureau of Census and Statistics provided copies of their livestock distribution maps.

I tender thanks to all these people and institutions. Finally, I owe thanks to my wife who acted as my secretary and helped read the proofs, and to Miss Janne Spring of the Cunningham Laboratory who retyped some of the manuscripts.

R. M. M.

THE AUTHORS

C. S. ANDREW Division of Tropical Pastures, CSIRO, Brisbane, Qld.
P. M. BARROW Department of Agriculture, Adelaide, S.A.
A. W. H. BRADEN Division of Animal Physiology, CSIRO, Prospect, N.S.W.
W. W. BRYAN Division of Tropical Pastures, CSIRO, Brisbane, Qld.
J. E. COALDRAKE Division of Tropical Pastures, CSIRO, Brisbane, Qld.
R. W. CONDON Western Lands Commission, N.S.W., Sydney, N.S.W.
A. B. COSTIN Division of Plant Industry, CSIRO, Canberra, A.C.T.
J. GRIFFITHS DAVIES (deceased) Formerly Division of Tropical Pastures, CSIRO, Brisbane, Qld.
C. M. DONALD Waite Agricultural Research Institute, University of Adelaide, Adelaide, S.A.
E. A. FITZPATRICK Department of Agronomy, University of Western Australia, Perth, W.A.
H. J. FRITH Division of Wildlife Research, CSIRO, Canberra, A.C.T.
FRED H. G. GRUEN Faculty of Economics and Politics, Monash University, Clayton, Vic.
W. J. HOSKING Department of Agriculture, Melbourne, Vic.
G. D. HUBBLE Division of Soils, CSIRO, Brisbane, Qld.
E. M. HUTTON Division of Tropical Pastures, CSIRO, Brisbane, Qld.
J. H. LEIGH Division of Plant Industry, CSIRO, Deniliquin, N.S.W.
J. A. MABBUTT School of Geography, University of New South Wales, Sydney, N.S.W.
IAN W. MCDONALD Division of Animal Physiology, CSIRO, Prospect, N.S.W.
P. W. MICHAEL Division of Plant Industry, CSIRO, Canberra, A.C.T.
R. MILTON MOORE Division of Tropical Pastures, CSIRO, Brisbane, Qld.
L. F. MYERS Division of Plant Industry, CSIRO, Canberra, A.C.T.
R. J. NEWMAN Department of Agriculture, Melbourne, Vic.
H. A. NIX Division of Land Research, CSIRO, Canberra, A.C.T.
M. J. T. NORMAN Division of Land Research, CSIRO, Canberra, A.C.T.
D. O. NORRIS Division of Tropical Pastures, CSIRO, Brisbane, Qld.
P. G. OZANNE Division of Plant Industry, CSIRO, Perth, W.A.
D. F. PATON Department of Agriculture, Hobart, Tas.
F. B. PEARSON Department of Agriculture, Adelaide, S.A.
R. A. PERRY Rangelands Research Unit, CSIRO, Canberra, A.C.T.
R. C. ROSSITER Division of Plant Industry, CSIRO, Perth, W.A.
N. H. SHAW Division of Tropical Pastures, CSIRO, Brisbane, Qld.
M. E. SULLIVAN School of Geography, University of New South Wales, Sydney, N.S.W.
M. M. H. WALLACE Division of Entomology, CSIRO, Perth, W.A.
C. H. WILLIAMS Division of Plant Industry, CSIRO, Canberra, A.C.T.
W. M. WILLOUGHBY Division of Animal Physiology, CSIRO, Armidale, N.S.W.

CONTENTS

A THE ENVIRONMENT

B THE GRAZING LANDS AND PASTURES

C FACTORS IN PRODUCTIVITY

D GRASSLAND PRODUCTION

MAPS

FIGURES

PLATES

TABLES

A

THE ENVIRONMENT

THE CLIMATIC FACTOR IN AUSTRALIAN GRASSLAND ECOLOGY

LANDFORMS AND STRUCTURE (MAP 1)

SOILS (MAP 2)

VEGETATION (MAP 3)

THE HERBIVOROUS WILD ANIMALS

1

THE CLIMATIC FACTOR IN AUSTRALIAN GRASSLAND ECOLOGY

E. A. FITZPATRICK AND H. A. NIX

The biological yield of a pasture community may be regarded as the integrated result of energy, water, nutrient, gas, and associated biotic regimes acting through the course of growth and development. In this study, we are limited to an analysis of the energy and water components of such a biological system. Our basic objective here is to evaluate the macroclimatic environment of Australian pasture communities with particular reference to the light, temperature, and moisture regimes.

We must emphasise that with the limited climatic and biological data available to us, only the macroclimatic environment could be considered. Clearly, deviations from these conditions may be of great ecological significance and can occur through (a) site differences in soils and terrain locally altering the separate components of the energy and water balances, or (b) the effects of meso-scale and micro-scale meteorological systems peculiar to areas too small to be identified within the open network of climatic stations.

BASIC CLIMATIC FEATURES

Australia's latitudinal position dictates much of its climatic character. Prevailing wind patterns and the generally light and erratic rainfall strongly reflect the dominating control of eastward-moving anticyclonic cells along the southern margins of the continent. Seasonal change in Australia is basically linked with the annual cycle of latitudinal shift in the paths followed by these anticyclonic cells. Thus, the intertropical convergence zone, which adjoins the southeasterlies to the north and the westerlies to the south, impinges upon the extremities of the continent in summer and winter respectively, producing marked concentrations of rainfall in these areas at opposite seasons (Fitzpatrick 1964).

Modest relief and the insular character of the land mass tend to produce broadly transitional climatic features and without the extremes and marked discontinuities found in other continents. Even so, a considerable range of seasonal regimes of solar radiation, temperature, and precipitation does occur. Readers interested in a detailed climatography are referred to basic texts (e.g. Kendrew 1961) and to publications of the Commonwealth Bureau of Meteorology (e.g. *Bulletin* No. 1, 1965). No attempt is made here to provide a full description of the whole range of climatic elements over the Australian region. However, the major climatic elements of solar radiation, temperature, and precipitation are discussed below.

Solar Radiation

The existing network of stations at which continuous solar radiation measurements are made is restricted. However, the geographic distribution of this element has been clarified greatly through the application of empirical relationships based upon observed duration of sunshine (Hounam, 1963). Maps showing mean daily radiation for each month have been published (Bureau of Meteorology 1964) and Figs. 1:1a and b have been reproduced from this series.

In January, average daily radiation receipts exceed 600 cal cm^{-2} over a major part of the continent. The greater cloudiness associated with summer rainfall conditions reduces radiation receipts along the eastern and far northern coastlines by 50–150 cal cm^{-2} day. In July, the pattern of solar radiation shows a strong latitudinal orientation. Spatial gradients in daylength and cloud cover associated with winter rainfall influences, reinforce one another. Mean daily receipts range from less than 150 cal cm^{-2} over Tasmania to over 450 cal cm^{-2} over the far

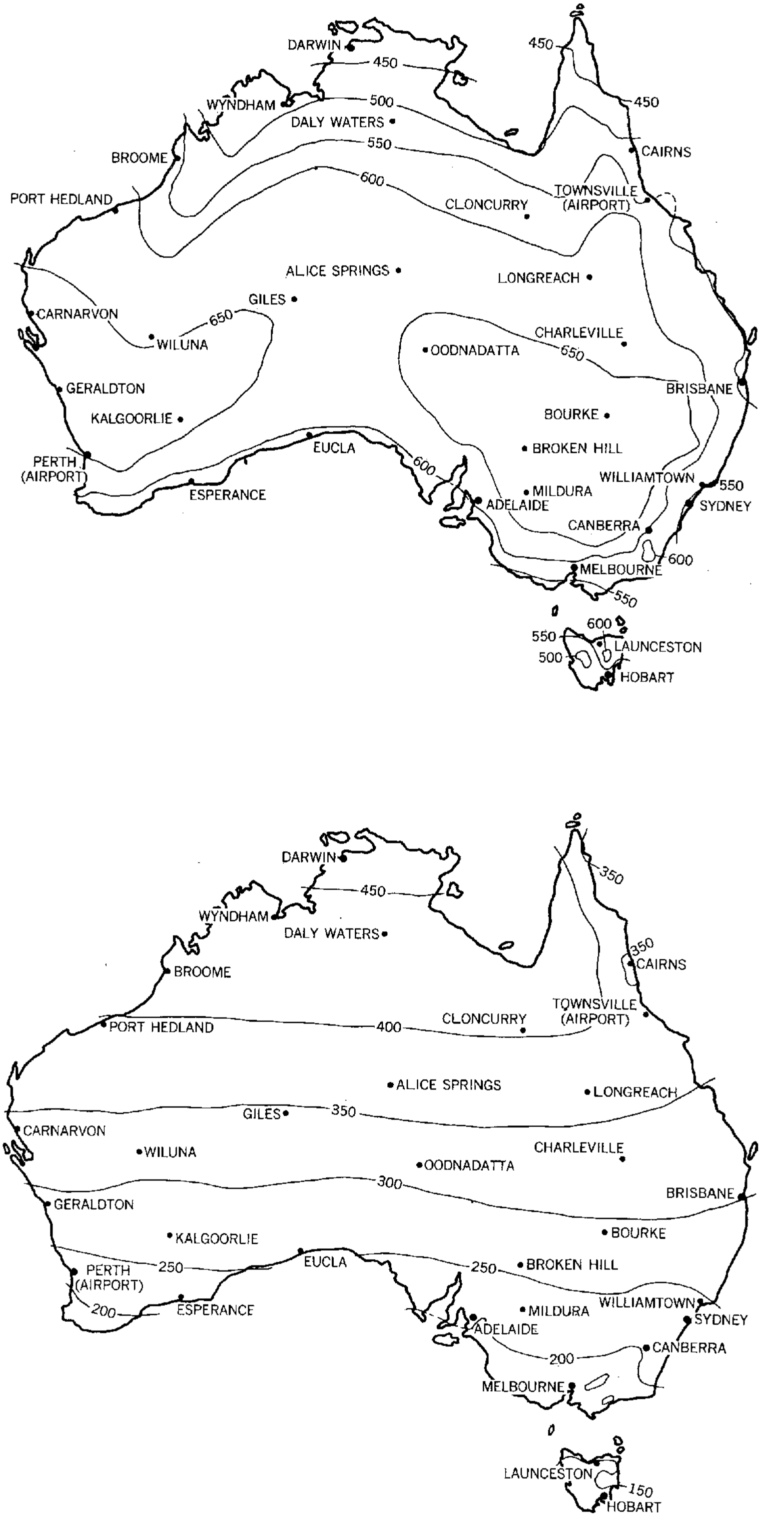
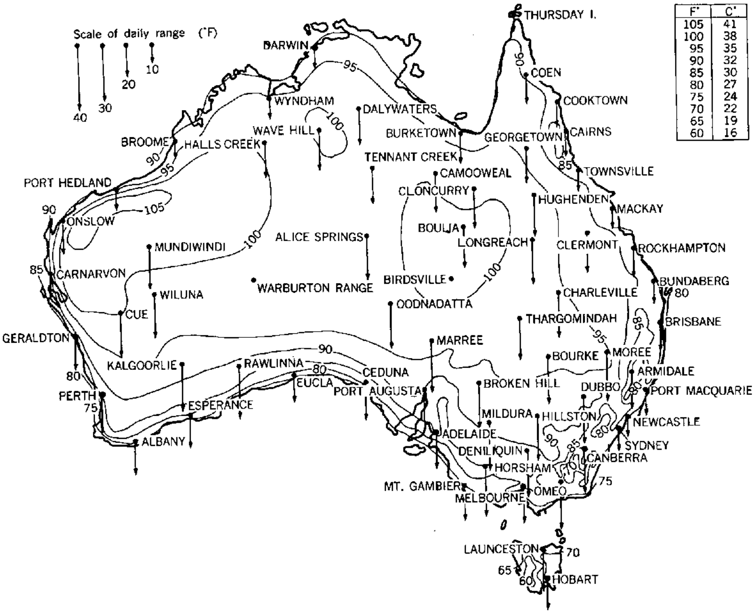
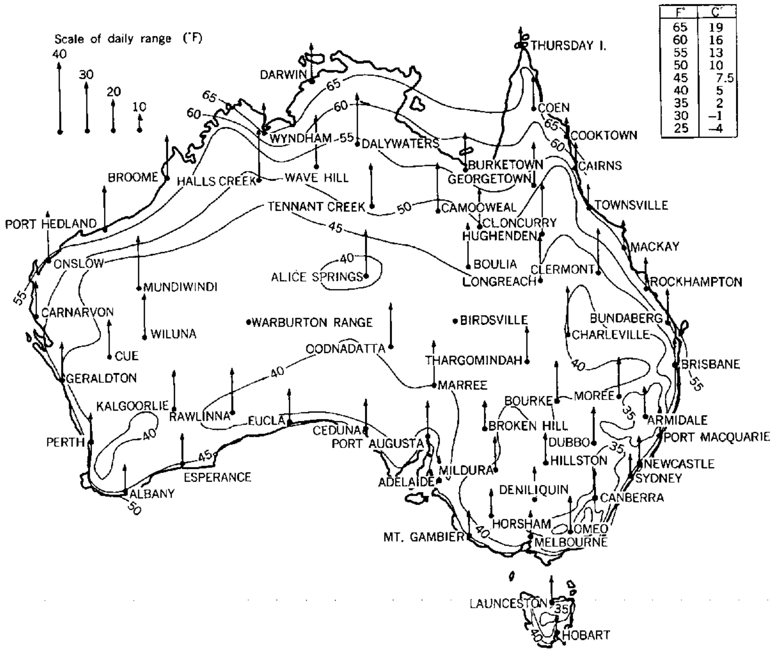


Fig. 1 : 1 Average distribution of total radiation in cal cm^{-2} day^{-1} (a) in January (b) in July (from Bureau of Meteorology, *Bulletin* No. 1, 1965)



F°	C°
105	41
100	38
95	35
90	32
85	30
80	27
75	24
70	22
65	19
60	16

Fig. 1 : 2 (a) January maximum temperature (deg. F) (b) July minimum temperature (prepared from data in Bureau of Meteorology publications, *Bulletin* No. 1 (1965) and *Climatic Averages, Australia* (1956))



F°	C°
65	19
60	16
55	13
50	10
45	7.5
40	5
35	2
30	−1
25	−4

north of the Northern Territory.

Temperature

The normally occurring extremes of temperature at the time of the crest and the trough of the annual curve are of interest from the viewpoint of plant adaptation. The isotherms of mean maximum temperature in January and mean minimum temperature in July are shown in Figs. 1 : 2a and 1 : 2b. Also shown are the mean daily temperature ranges at selected stations calculated from published climatic normals (Bureau of Meteorology 1956).

Mid-summer maximum temperatures exceed 95°F (35°C) over the greater part of inland Australia. As might be expected, temperature gradients are steepest along the southern and eastern coastal margins where maximum temperatures of the order 68–84°F(20–30°C) prevail. The diurnal temperature range over inland areas approximates 27 Fahrenheit degrees (15 Centigrade degrees) and increases generally from north to south. Along the coastal margins the diurnal range is from 20 Fahrenheit degrees (11 Centigrade degrees) in the south and southeast to only 13 Fahrenheit degrees (7 Centigrade degrees) in the far north.

Mid-winter minimum temperatures fall below 45°F (7°C) over the greater part of the continent south of the Tropic of Capricorn. Upland areas

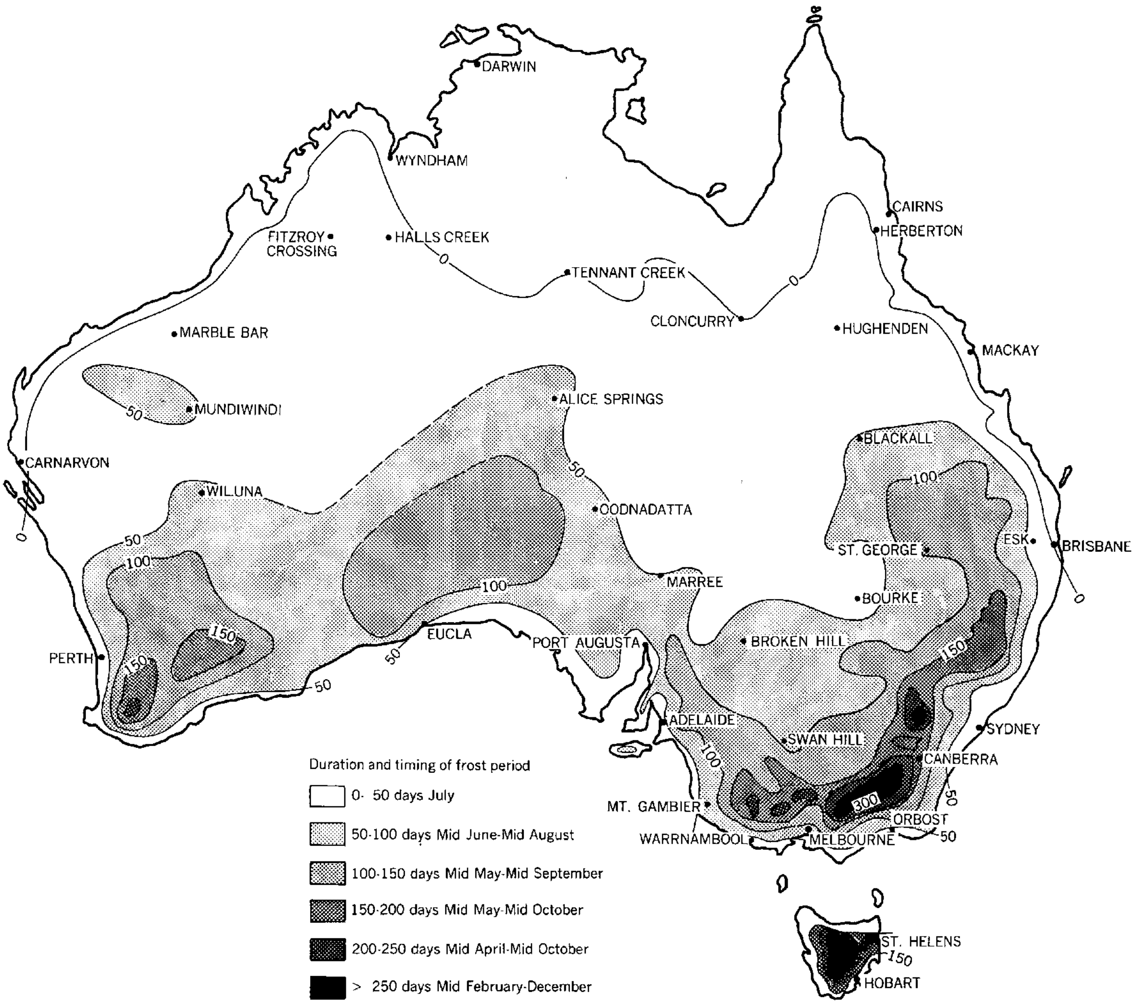


Fig. 1 : 3 Duration and timing of frost periods (prepared from data of Foley (1945))

of New South Wales, Victoria, and Tasmania have July mean minimum temperatures falling below 35°F(2°C) with restricted mountain areas having temperatures less than 32°F(0°C). North of the Tropic of Capricorn minimum temperatures show a marked latitudinal alignment, increasing gradually northward to levels of 65°F(18°C) along the coastal margins of Cape York and the Northern Territory.

The diurnal temperature range in mid-winter is high north of the Tropic of Capricorn, being about 27 Fahrenheit degrees (15 Centigrade degrees) except at locations subject to strong maritime influences. The diurnal range decreases southward from the Tropic, reaching about 20 Fahrenheit degrees (11 Centigrade degrees) and 15 Fahrenheit degrees (8 Centigrade degrees) for inland and coastal areas respectively.

Temperature extremes are of great ecological significance and both heatwaves and frosts can markedly influence the seasonal growth pattern and composition of pasture communities. As temperature data become more freely available in computer compatible form it will be possible to examine these hazards in greater detail.

The average dates of the first and last occur-

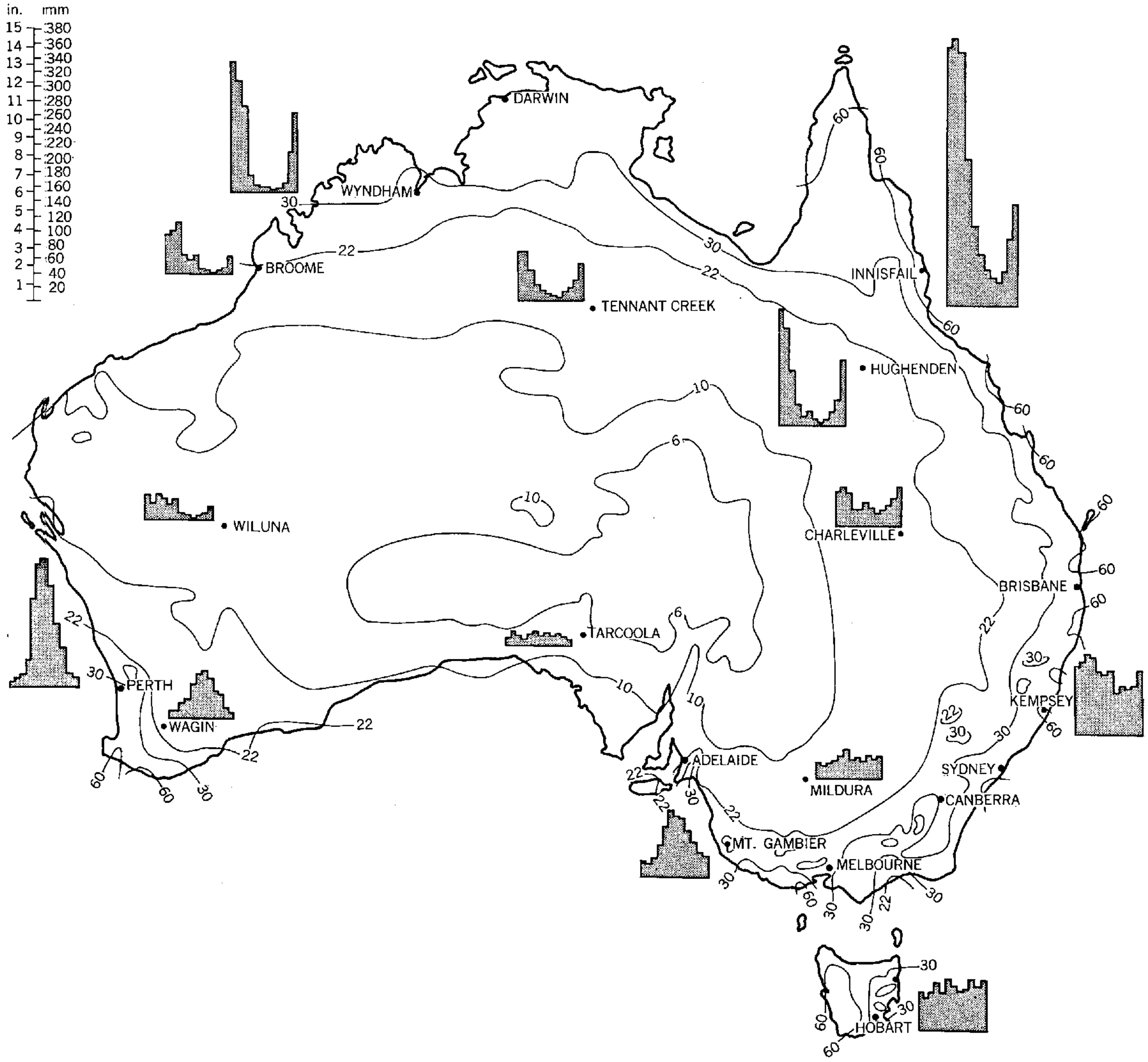


Fig. 1 : 4 Average annual rainfall (in.) and monthly averages for selected centres (Bureau of Meteorology, *Bulletin* No. 1, 1965)

rences of screen temperatures below freezing (32°F, 0°C) are generally used as a measure of the reduction in the length of the growing period due to frost. However, frost incidence is highly variable from year to year and the probability of early frosts in autumn and late frosts in spring may be of considerable importance ecologically. In Fig. 1 : 3 we show areas delimited by dates which represent one standard deviation prior to the mean date of the first occurrence of a screen temperature below 32°F (0°C) in autumn, and one standard deviation after the mean date of the last occurrence in spring. The data presented in Fig. 1 : 3 were calculated from that of Foley (1945).

Precipitation

Rainfall is the dominant component of precipitation over the major part of the continent. Snowfall is confined to very restricted highland areas in south-eastern Australia and Tasmania. Accordingly, precipitation is generally equated with rainfall. Rainfall parameters such as annual or seasonal averages can provide only broad generalisations about grassland ecology. However, a brief description is given here as a background for our later evaluations and as a reference for other contributions to this volume.

Australia has the unenviable distinction of being the world's most extensively arid continent. Fully one-third of the total land surface has an average annual rainfall of less than 10 in. (254 mm). The dry core of this arid area, located over northern South Australia, has averages as low as 5 in. (127 mm). The broad concentric pattern of mean annual rainfall increasing towards the coastline is shown in Fig. 1 : 4. The 30 in. (762 mm) isohyet seldom extends more than 155 miles (250 km) inland. Mean annual rainfall in excess of 60 in. (1524 mm) is confined to the extreme north of Cape York, and localised areas along the eastern coastline, the south-eastern highlands, and the west coast of Tasmania.

MODELLING PLANT RESPONSE TO LIGHT, TEMPERATURE, AND WATER REGIMES

The previous section provides a broad, yet static, view of the environmental setting within which Australian pasture plant communities occur. The various systems of climatic classification (e.g. Köppen 1931) may provide a better resolution, but the climatic 'types' so devised are still only broadly associated with patterns of vegetative growth. As an alternative to climatic evaluation through detailed analysis of individual elements or through the use of arbitrary classification systems, we attempt here to develop a set of scalar models which relate plant response to seasonal regimes of light, temperature, and water.

Derivation of Climatic Input Data

Monthly climatic normals for a standard 30-year period (1911–40) provided the basic data inputs (Bureau of Meteorology 1956). Monthly normals for rainfall, maximum and minimum temperature, and relative humidity were available for 277 stations giving a reasonably close network of stations throughout Australia. Monthly evaporation totals were computed using an empirical method based on maximum temperature and relative humidity data and were shown to give close agreement with Australian standard tank evaporation at widely spaced locations in Australia (Fitzpatrick 1963).

Since monthly data provided a rather crude resolution of seasonal trends, these data were transformed into long-term mean weekly values. A digital computer was used to determine the amplitude and phase angle of six harmonic sine curves fitted to the 12-monthly values of rainfall, maximum and minimum temperature, relative humidity, and estimated tank evaporation.

A composite function, using the six harmonics and passing through all of the twelve data points, was then evaluated at weekly intervals. Since the composite curve precisely fits the monthly values, all the information contained in the original set of data points is retained and an objective interpolation of weekly values achieved.

The interpolated weekly values will be close to true weekly normals for the continuous elements, temperature, humidity, and evaporation. With rainfall, deviations from true weekly normals may occur if the distribution is peaked so that it bridges the latter part of one month and the early part of the next. However, such situations are not common and, in any case, would not be discernible from the original set of monthly normals.

Derivation of Environmental Scalars

The level of climatic data available and the continental scope of the study prevented any consideration of the unique growth and development responses of individual species. The approach used here was to develop more generalised models of plant response to the three major environmental factors—light, temperature, and water.

In deriving these models we have considered dry-matter production at a given factor level relative to the production obtained at optimal or non-limiting levels of that factor. This is referred to hereafter as fractional dry-matter production. Thus, each of the environmental scalars for plant response to light, temperature, and moisture has numeric values ranging from zero, representing a completely limiting situation, to unity, representing non-limiting conditions.

Light Index. The photosynthetic rate of a leaf canopy is the result of a complex interaction between plant structure and physiological properties and the physical properties of the incident light. The only data available as input, and that for a very limited number of locations, were daily total solar radiation. Although this parameter provides a relatively crude index of the light environment, it has been shown to provide a useful measure in the absence of other data (Tanaka, Kwano, and Yamaguchi 1966).

From theoretical considerations presented by Davidson and Philip (1958) and De Wit (1959, 1965), together with experimental data relating to a range of tropical and temperate species (Hesketh 1963; Cooper 1966; Tanaka, Kwano, and Yamaguchi 1966) a general relationship between fractional dry-matter production and daily total solar radiation was formulated. This relationship assumes a pasture canopy with a Leaf Area Index of 5, and was defined by an exponential function (Fig. 1 : 5). This function was used in a computer program to calculate values of a Light Index (L.I.).

As noted previously, estimates of daily total solar radiation (Q_{tot}) have been made from sunshine data where available (Hounam 1963). The limited number of locations with this data spurred attempts to calculate daily total solar radiation from the published normals for all stations used in the analysis. Since the extraterrestrial radiation (Q_{ext}) can be calculated for any latitude and time of year, the possibility of a relationship linking Q_{tot}/Q_{ext} empirically with climatic normals, either singly or in combination, was explored.

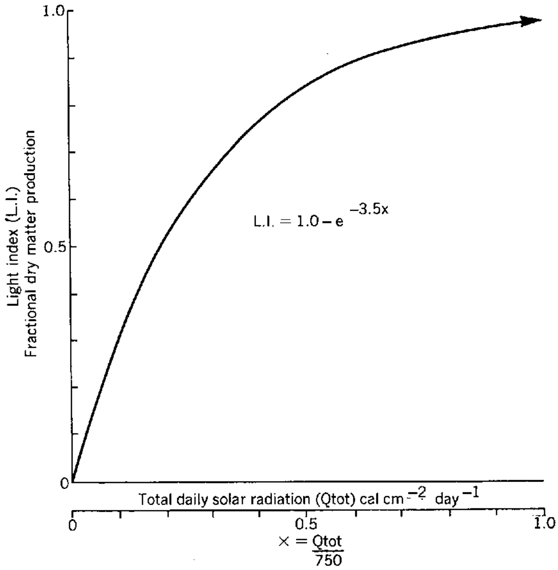


Fig. 1 : 5 Light Index (L.I.). Assumed relationship between mean daily solar radiation and fractional dry-matter production of a pasture canopy with an L.A.I. = 5.

Using mean monthly radiation values from eleven widely separated Bureau of Meteorology (1963, 1966) and CSIRO stations, a highly significant correlation ($r = -0{\cdot}81$) between Q_{tot}/Q_{ext} and mean monthly relative humidity, where this exceeded 45 per cent, was found. At lower levels of humidity there was no evidence of a significant relationship. The correlation between final estimates of mean daily Q_{tot} over monthly intervals calculated from the fitted equation and mean observed Q_{tot} for all stations was highly significant ($r = 0{\cdot}97$). Thus, 94 per cent of the total variance of observed mean Q_{tot} was accounted for by variations in the mean index of relative humidity combined with the effects of latitude and time of year as expressed through Q_{ext}.

Using this empirical relationship monthly estimates of mean daily solar radiation were obtained for each of the selected 277 stations. Monthly maps of mean daily solar radiation produced from these data were in close agreement with monthly maps published by the Bureau of Meteorology. Weekly values were calculated from these data, using the methods of harmonic analysis described earlier. These provided the basic data inputs for calculation of L.I. values, over weekly intervals, at all locations.

Thermal Index. The influence of the thermal regime on plant growth and development has long been recognised and numerous methods have been devised for evaluating effective temperatures. Most methods present static summations of the thermal environment and few take account of the characteristic response curves of plants or the detailed form of daily temperature regimes.

In developing an environmental scalar for temperature response it was recognised that different groups of plants have fundamentally different thermal response curves. Unfortunately, growth data presented in the literature often proved difficult to interpret or compare, owing to differing temperature and light regimes, stage of plant development, and methods of growth measurement.

To avoid extreme departures from naturally occurring daily temperature regimes our attention was confined to those data from controlled environment experiments with two levels of temperature approximating day and night conditions. As described previously, all levels of dry-matter production were transformed into fractional dry-matter production.

Analysis of dry-matter production data for a wide range of species, reported in the literature (Mitchell 1956; Kawanabe 1968; Whiteman 1968) and by personal communication (C.A. Neal-Smith), revealed distinctive thermal response curves for the three broad groups:

(a) tropical grasses
(b) tropical legumes
(c) temperate grasses and legumes.

Though long established that tropical and temperate grass species differ in terms of temperature response, only recently studies have shown that these two groups are fundamentally different in anatomical, physiological, and biochemical features (Hatch and Slack 1966; Hatch, Slack, and Johnson 1967).

The derived curves relating fractional dry-matter production to mean daily temperature are shown in Fig. 1 : 6. They are specified mathematically by a combination of power functions based upon the relative temperature deviations above or below a specified optimum temperature for each group. The maximum absolute deviations were taken as the differences between the optimum temperature and the thresholds (above and below that optimum) at which the fractional dry-matter production is considered equal to zero.

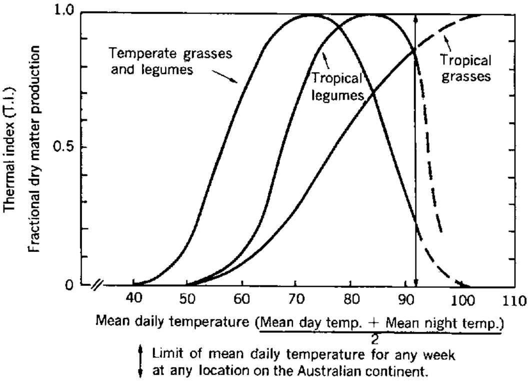


Fig. 1 : 6 Thermal Index (T.I.). Relationship between mean daily temperature and fractional dry matter production in three groups of pastures

Unfortunately no data were available that would enable formulation of a set of curves relative to a single level of peak dry-matter production, thus permitting direct comparisons between the three groups. As a consequence, each group must be considered separately. The curves in Fig. 1 : 5 therefore do not imply comparable dry-matter production at any given level on the three curves. In fact, the limited data available suggested that the absolute dry-matter production of the tropical grasses would exceed that of the temperate grasses at temperatures near optimal for the latter, though far below optimal for the former.

Moisture Index. Climatic classifications based on vegetation-climate associations usually employ some empirical parameter to account for diminished effectiveness of rainfall with increased evaporation (e.g. Köppen 1931). In early climatic investigations in Australia, indices based on the ratio of precipitation to evaporation, or to some closely related parameter, were used to satisfy this need (e.g. Prescott 1934, 1949). One serious deficiency of these approaches was the failure to account for the use of stored water within the root zone following cessation of rains.

Thornthwaite (1948) recognised this shortcoming and attempted to overcome it through the application of a generalised form of monthly water balance accounting. This basic approach is used here, but the type of data input and the method of formulating a moisture index are substantially different.

Within the CSIRO Division of Land Research a generalised form of water-balance accounting formulated by Slatyer (1960) has been used for regional climatic studies. Using long-term weekly rainfall and observed or estimated evaporation data this model has been used to assess regional climate as it affects growth characteristics of native plant communities in northern Australia (Fitzpatrick and Arnold 1964; Fitzpatrick 1965a and b).

Where dry-matter production data have been available, temporal variations in growth rate were in generally good accord with trends in the estimated available soil water. More recently, McAlpine (1970) has compared the outputs from this simple model with extensive measurements of soil water and has found a close correlation between estimated and measured values.

The model used in the present study closely resembles that described above, differing only in that a continuous rather than a stepped function was used to assess the decline of the ratio of actual to potential evapotranspiration with drying of the root zone. The exponential function chosen was taken to represent a drying curve for a medium-textured soil with an assumed available water storage of 4 in. (102 mm). A perennial vegetative cover with a potential evapotranspiration rate equal to $0{\cdot}8E_p$ (tank or pan evaporation) was assumed.

The mean weekly rainfall and mean evaporation estimates derived from monthly normals provided the basic data inputs to the model. A 2–year sequence of mean weekly data was generated for a number of widespread locations. Weekly values of mean available water taken from the water balance output for the second year were found to be in close agreement with weekly averages computed from actual weekly data for long sequences of years (35 years).

In deriving an environmental scalar for fractional dry-matter response to water regime, we use here the ratio of estimated actual to potential evapotranspiration (E_a/E_t). The Moisture Index (M.I.) thus ranges from unity, with water non-limiting, to zero when the available water storage has been exhausted. A linear 1 : 1 relationship between fractional dry-matter production and the ratio E_a/E_t is assumed.

Multifactor Growth Index. Clearly, no simple relation can be formulated that will fully describe complex genotype-environment interactions involving light, thermal, and moisture factors. Intuitively, however, we can specify the requirements of a general Growth Index (G.I.) to the extent that if any one of the three indices (L.I., T.I., M.I.) is equal to zero the multifactor index itself should be zero. On the other hand, if all indices are equal to unity (and only then) a multifactor index should be equal to unity (i.e. optimal conditions). On this basis, the simplest multifactor growth index that can be defined is a multiplicative function of the three indices, that is

$$\text{G.I.} = \text{L.I.} \times \text{T.I.} \times \text{M.I.}$$

Thus, in any given week, the G.I. can never exceed the value of the single most limiting factor as expressed by the Light, Thermal, and Moisture Indices. Also, as with the other indices, the value of the G.I. will range from zero to unity.

Separate values of L.I., T.I., and M.I. were calculated for each week for all 277 stations, using separately the values of T.I. for each of the three groupings of pasture species (Fig. 1 : 6). From these, growth index values for each week, for each group of pasture species, were calculated. To provide an integrated measure for comparative purposes, the mean values of G.I. and also of L.I., T.I., and M.I. over a 16-week interval commencing on each of the 52 weeks were computed. The 16-week period, though arbitrary, was chosen in recognition of seasonal patterns of pasture growth in both temperate and tropical Australian environments.

GEOGRAPHIC DISTRIBUTION OF LIGHT, TEMPERATURE, AND MOISTURE REGIMES

Analysis of Growth Index data in terms of the component Light, Thermal, and Moisture Indices indicates that the light regime is rarely the major limiting factor at any season at any location in Australia. The thermal regime clearly sets the broad framework for seasonal growth patterns and is a major limiting factor over very large areas of southern and inland Australia during the winter months. The dominating influence of the water regime at almost all locations reflects generally meagre rainfall over much of the continent and the rather extreme seasonality of rainfall over much of the wetter portion.

Light Regimes

Midsummer values of the L.I. are high throughout the continent and mean weekly values do not fall below 0·90 even in Tasmania. Much of northern and southern inland Australia has values exceeding 0·95. A slight depression in values occurs at high rainfall locations along the tropical coast.

Midwinter values fall below 0·50 only at locations in the high rainfall zone of western Tasmania and range between 0·50 and 0·60 over the remainder of Tasmania and southern Victoria. Throughout the rest of southern Australia, below the Tropic, values range from 0·60 to 0·75. Mid-winter values above the Tropic of Capricorn everywhere exceed 0·75 with a gradient northward to peak values of 0·88 in the 'Top End' of the Northern Territory and western Cape York.

Temperature Regimes

The wide range of temperature conditions over the continent coupled with the unique responses of the major pasture groups results in complex overlapping patterns of thermal environments. To facilitate analysis of these patterns, the weekly T.I. values were integrated over the summer (November-April, i.e. weeks 45-18) and winter (May-October, i.e. 19–44) seasons for each pasture group.

Tropical grasses. Because of the high temperature optimum for this group of plants, the weekly values of T.I. never exceed 0·90 at any location. The most favourable thermal environments are north-western Australia, north of latitude 22°S, across the Barkly Tableland, around the Gulf of Carpentaria, and along the western side of Cape York. Integrated mean seasonal values of the T.I. range from 0·70 to 0·80 in summer and from 0·35 to 0·50 in winter in these areas.

The eastern coastal lowlands have summer season values ranging from 0·20 on the far south coast at Bega, through 0·40 at Brisbane, to 0·60 at Cairns. Winter values show a steep gradient from north to south, ranging from 0·36 at Cairns, through 0·20 at Rockhampton, to values less than 0·10 south of Lismore. Southern inland areas of Australia have summer values ranging from 0·20 to 0·50 and winter values less than 0·10. Killing frosts set absolute limits to growth periods throughout these areas.

Tropical legumes. Although broadly similar in pattern to the tropical grasses, T.I. values differ because of the lower temperature optimum. Apart from a few small, elevated areas such as the Atherton Tableland, summer seasonal values exceed 0·95 over the whole of northern Australia north of latitude 22°S. Winter seasonal values range from 0·60 inland to 0·80 along the coast, reaching values exceeding 0·90 in the far northern tropical coast.

The eastern lowlands have summer season values ranging from 0·40 at Bega (lat. 36°40′S), through 0·75 at Lismore (lat. 28°48′S), to values exceeding 0·90 northwards from Bundaberg (lat. 24°52′S). As with the tropical grasses, there is a steep gradient from north to south in the winter season values. From 0·80 at Cairns (lat. 16°55′S), values fall through 0·40 at Gladstone (lat. 23°51′S), 0·20 at Lismore, and less than 0·10 southwards from Port Macquarie (lat. 31°26′S). Southern inland areas have summer values ranging from 0·40 to 0·90 and winter values less than 0·10. Frosts limit growing periods in these areas.

Temperate grasses and legumes. Because of limitations to growth at temperatures exceeding 75°F(24°C) and falling below 40°F(4·4°C), rather complex patterns of thermal environments emerge. Thus, summer values of the T.I. over northern Australia and much of southern inland Australia range from 0·60 to 0·90 because of supra-optimal temperatures. At almost all locations on the continent T.I. values of 1·00 will be reached at some time in the year, at least over short time intervals. Over southern inland Australia, including the whole wheat belt, optimum values are attained in autumn and in spring, with depressions in winter and summer due to sub-optimal and supra-optimal temperatures respectively. North of latitude 22°S, peak values are attained in midwinter, and mean values for the winter period range from 0·80 to 0·90.

The coastal lowlands and tablelands of south-eastern Australia and also Tasmania attain peak values ranging from 0·90 to 1·00 in summer. Mean winter values along the eastern lowlands range from 0·20 in Gippsland, through 0·60 at Port Macquarie, to values exceeding 0·90 north of Rockhampton (lat. 23°23'S). The most favourable year-round thermal environments for temperate grasses and legumes are found along the central and northern coastline of New South Wales and at elevations above 1000 ft (300m) in south Queensland (e.g. Mt Tamborine, Blackall Range) and 2000 ft (600 m) in north Queensland (e.g. Eungella Range, Atherton Tableland).

Moisture Regime

Although thermal regimes set a broad framework within which the performance and distribution of pasture species can be viewed, it is the moisture regime which sets absolute limits over a very large part of Australia. Seasonal aspects of the interaction between thermal and moisture regimes are of considerable ecological interest and will be considered in some detail in the next section. The seasonal moisture regimes in themselves are of interest, but cannot be presented here in detail. Instead, in Figs. 1 : 7 and 1 : 8 we present an integrated M.I. averaged over the summer (week 45–18) and winter (week 19–44) seasons.

Summer seasonal moisture regimes (November–April). The most favourable moisture regimes (M.I. > 0·8) extend from the north Kimberley region across the 'Top End' of the Northern Territory, Cape York, and as a thin band, never much more than 100 miles (160 km) wide along the eastern coastline to Victoria and also the west coast of Tasmania. Fig. 1 : 8 shows

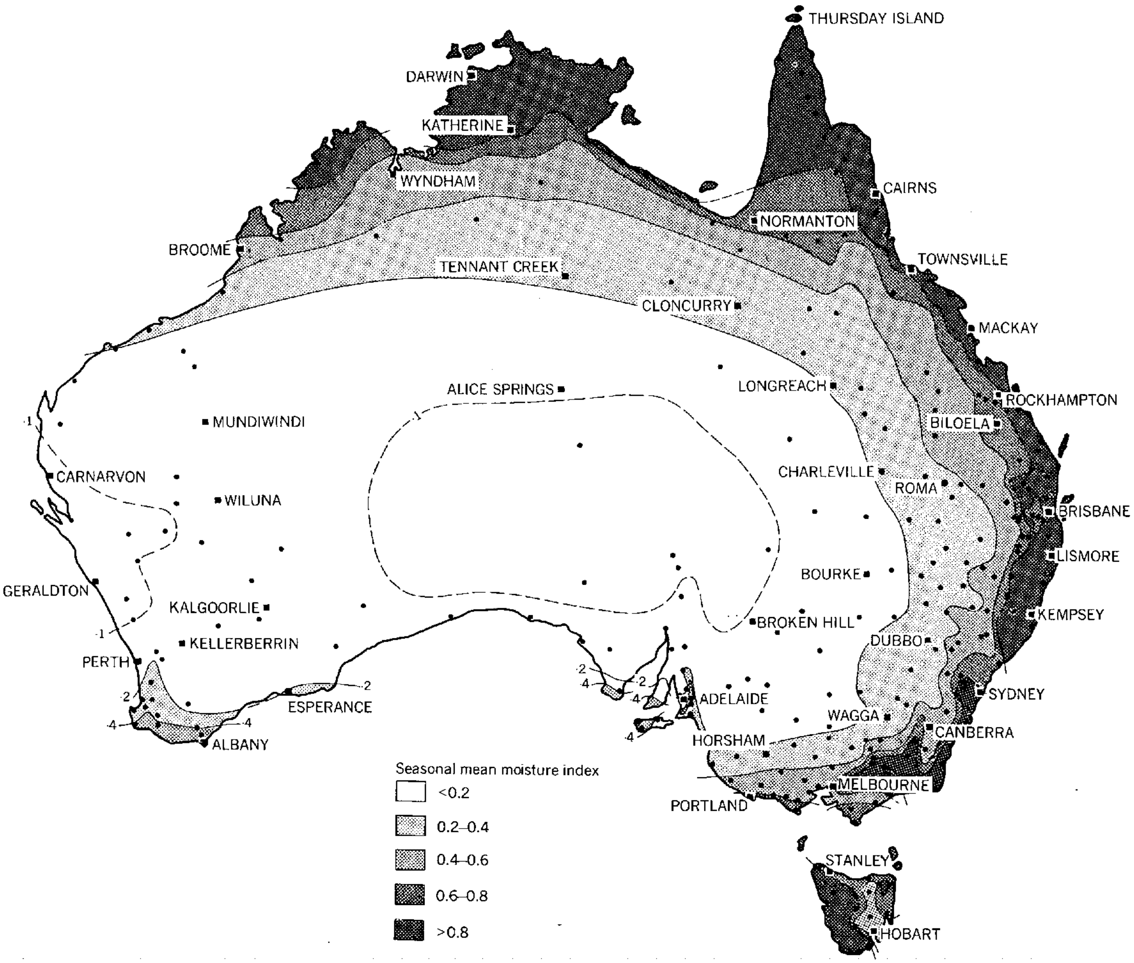


Fig. 1 : 7 Average Moisture Index values for the summer season (November–April)

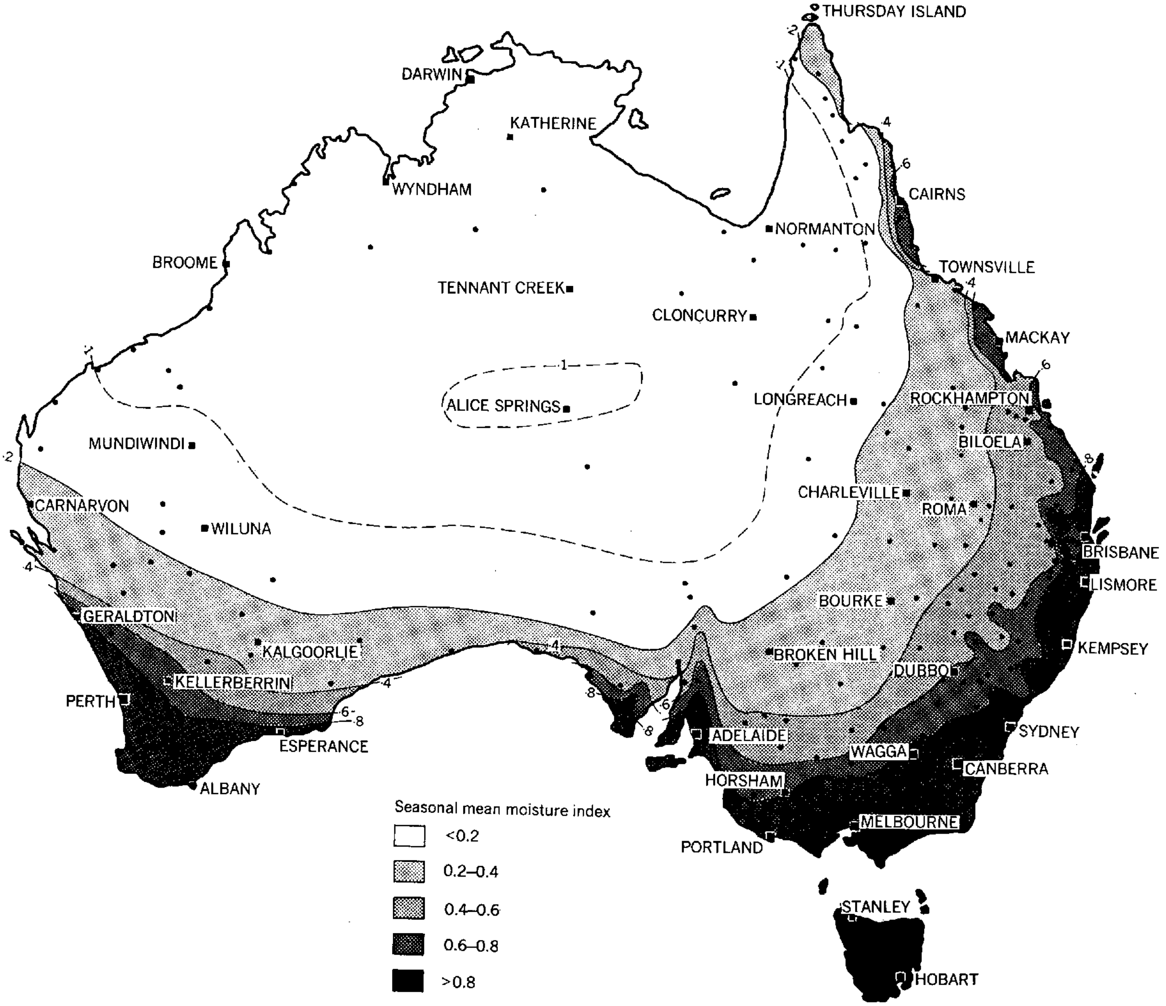


Fig. 1 : 8 Average Moisture Index values for the winter season (May–October)

a rapid transition toward increased summer aridity inland and the sub-humid to semi-arid zone (0·8 > M.I. > 0·4) does not extend much beyond 250 miles (400 km) from the coast. Thereafter, the transition toward the arid core is more gradual. In Western Australia the summer Moisture Index does not exceed 0·4 anywhere south of the Tropic of Capricorn.

Winter seasonal moisture regimes (May-October). The area influenced by typical winter weather systems extends in a broad arc across southern Australia with a narrowing northward extension into Queensland. In general the rainfall variability is low, with a coefficient of variation about the mean seasonal rainfall ranging from 15 to 20 per cent. However, variability increases inland and northward and ranges from 30 per cent upwards to 50 per cent in central and northern Queensland.

The most favourable moisture regimes (M.I. > 0·8) extend in a broad crescent from Geraldton (lat. 28°46′S) to Esperance (lat. 33°51′S) in Western Australia and in another crescent taking in the coastal plains and highland areas of south-eastern Australia from Eyre Peninsula (approx. lat. 34°S) in South Australia to Fraser Island (approx. lat. 25°S) in Queensland. Practically the entire wheat belt of Australia lies within the intermediate zone (0·8 > M.I. > 0·4). Narrow sections of the coastal plain in north Queensland also fall within these limits. Apart from a rapid transition of the M.I. inland from coastal north Queensland, the values less than 0·4 decrease very gradually toward the interior, becoming less than 0·1 over the remainder of northern Australia. An outlier of values slightly greater than 0·1 was identified at Alice Springs (lat. 23°42′S). Presumably this results from orographic influences associated with the Musgrave and Macdonnell Ranges.

Dry season moisture regimes. The extent to which extreme seasonality and consequent seasonal drought influences pasture communities is of great concern ecologically and in pasture and livestock management. To provide an assessment of this aspect we show in Fig. 1:9 the lowest values of the M.I. obtained when averaged over successive 16–week intervals. This map thus portrays the driest consecutive 16–week period at all locations irrespective of time of occurrence. A significant feature of the Australian climatic environment not at once apparent from normal rainfall maps is the fact that all of the continent except the extreme south-west of Western Australia, the Mt Lofty Ranges in South Australia, southern Victoria, Tasmania, and eastern New South Wales and Queensland, has severe moisture deficits (M.I. < 0·2) over at least four months.

The patterns shown in Fig. 1:9 help to explain

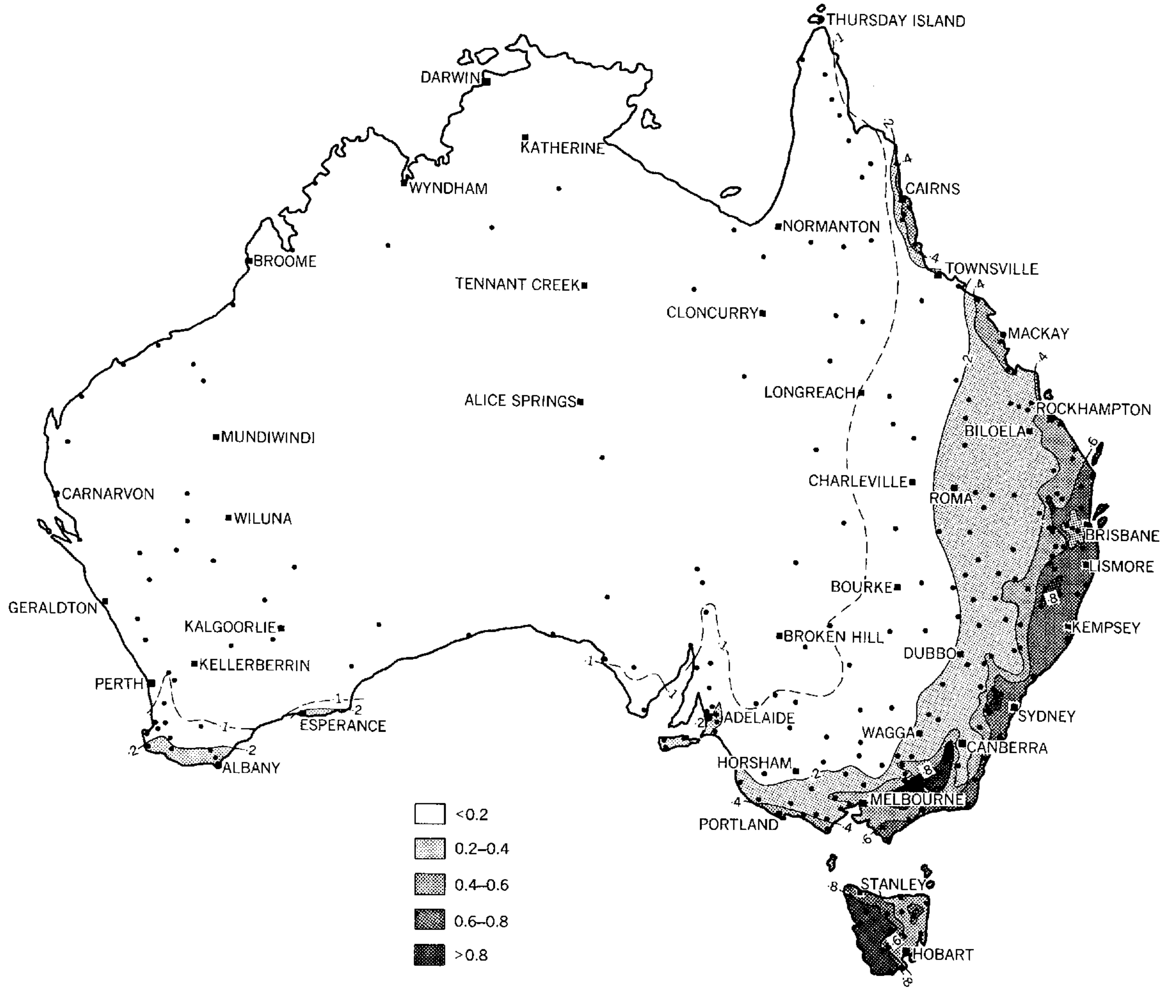


Fig. 1 : 9 Average Moisture Index values for the driest 16-week period of the year

the Australian preoccupation with annual legumes and grasses for sown pastures. Thus, subterranean clover (*Trifolium subterraneum*) and annual medics (*Medicago* spp.) are sown over very extensive areas in southern Australia, and similarly Townsville lucerne* (*Stylosanthes humilis*) promises to be sown over extensive areas in northern Australia (see Map 4). Sown perennial pastures do not occur much beyond the zone delimited by a mean 16–week M.I. value exceeding 0·2 during the driest season and are mainly concentrated in zones where this value exceeds 0·4. A close parallel occurs with the distribution of prime forest stands.

One conspicuous feature of the inland pattern is the 'bulge' inland from Brisbane which reflects overlapping summer and winter seasonal moisture regimes. However, because this zone is at the limits of both tropical and middle latitude rainfall influences, year to year variability is high.

GEOGRAPHIC AND SEASONAL VARIATION IN GROWTH INDEX VALUES

The multifactor G.I. reflects the compounded effects of light, thermal, and moisture regimes upon plant performance and is expressed as relative or fractional dry-matter production with values ranging from zero to unity. It must be emphasised that the environmental scalars for light, thermal, and moisture regimes and the multifactor G.I. were developed for analysis of pasture environments at a macroclimatic level. Also, these simple models relate to the generalised responses of three broad groups of pasture plants and not to the unique responses of individual species.

Limitations in the available climatic data prevented any detailed consideration of year-to-year variation in the component light, thermal, and moisture regimes and resultant G.I. values. Clearly, such variability is of considerable ecological significance and detailed studies are warranted when the data become available. For the present, we simply illustrate the problems of year-to-year and within season variation with the example shown in Fig. 1 : 10. This shows weekly variation in T.I., M.I., and G.I. values for the tropical legume group at Biloela, Queensland (lat. 24°24′S), over three consecutive, but contrasting, seasons. L.I. values were computed, but are not shown because of the relatively small deviations from long-term mean weekly trends.

Clearly, variations in the M.I. account for a large part of both short- and long-term variation in G.I. values at Biloela and this would be true for most locations in Australia. However, the prominent role of the thermal regime in regulating the seasonal growth rhythm is also clearly evident. Thus, for example, the exceptionally favourable moisture regime during the 1950 winter season at Biloela had little effect on the growth response of tropical legumes because of the masking reduction imposed by the thermal regime. The occurrence of relatively severe short-term water deficits during the major growing season is clearly demonstrated and this is quite characteristic of most pasture environments in Australia.

A combined mode of presentation is used here to depict both geographic and seasonal variation in G.I. values for each pasture group. As a measure of the environment over the most favourable period of the year, we use the mean maximum G.I. value attained over any consecutive 16–week period. Of course, the distribution, performance, and survival of pasture communities is a complex function of the total seasonal environment and not merely the environment over the most favourable period of the year. Accordingly, we have prepared annual G.I. curves for selected representative locations and these are shown as inset diagrams in Figs. 1 : 11, 1 : 13, and 1 : 15 based upon the average 16–week G.I. values for each pasture group.

Tropical Grasses

The high thermal requirements of this group coupled with the summer rainfall patterns of northern and eastern Australia result in unimodal G.I. curves with pronounced summer or autumn peaks. The highest mean 16–week G.I. values as described above can therefore provide a useful comparative measure of the growth environment at the most favourable time of the year at each location. The spatial pattern of these values is shown in Fig. 1 : 11.

The gradients of integrated G.I. values clearly reflect gradients in summer season moisture regimes (see Fig. 1 : 7) with modifications imposed by the thermal regime in the east and south-east. A feature of the pattern shown in

---

*Registered common name recently changed to Townsville Stylo.

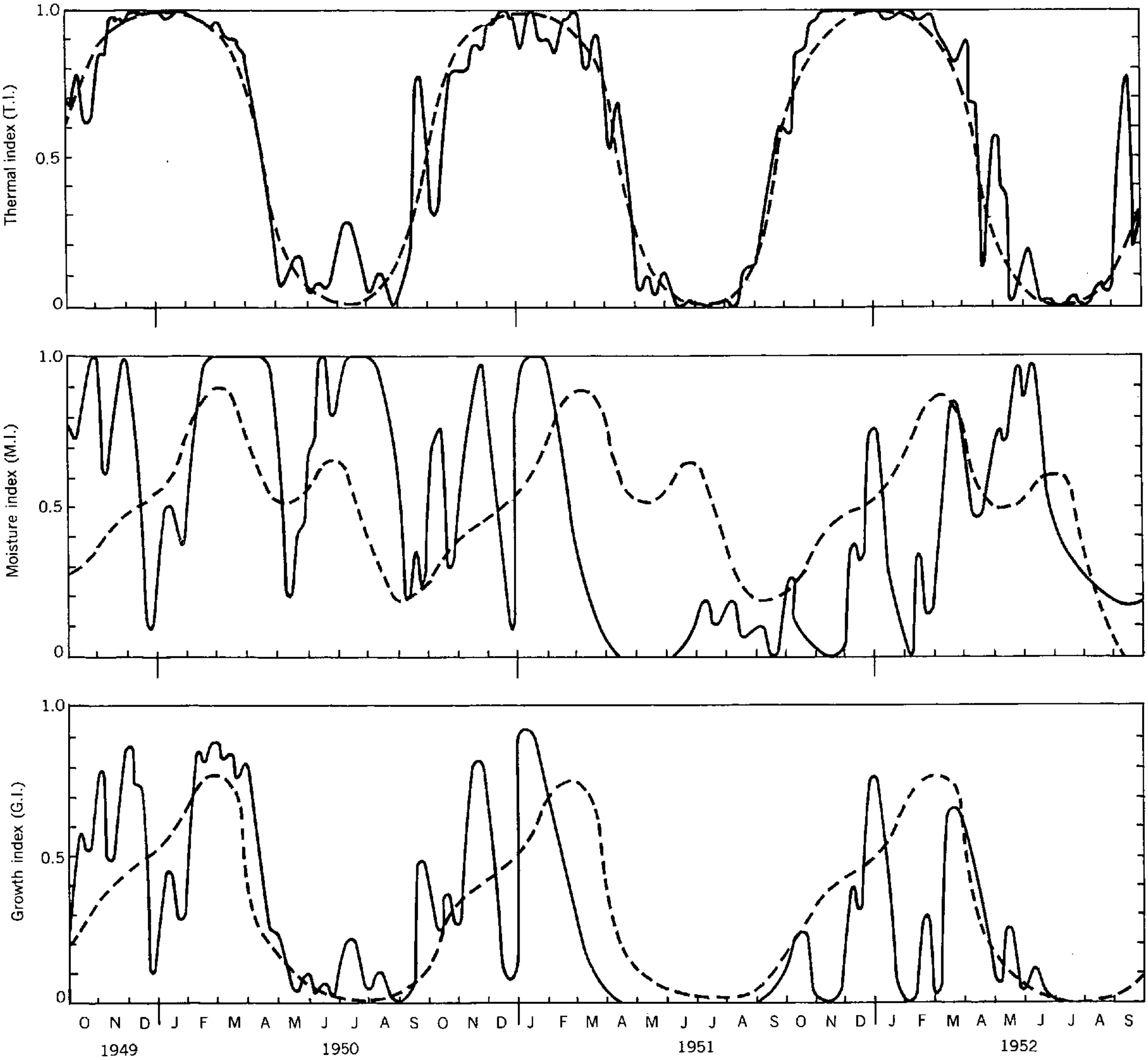


Fig. 1 : 10 Comparison of estimated actual weekly values with long-term mean weekly values of Thermal, Moisture, and Growth Indices for tropical legumes at Biloela, central Queensland

- - - - - - - - - - Values calculated from long-term mean weekly data

———————— Values calculated from actual weekly data

Fig. 1 : 11 is the relatively gradual decrease in the highest mean 16-week G.I. values inland from the northern and north-eastern coastlines. This reflects the capacity of the tropical grasses to respond to the high light and temperature values when water is available, even over relatively short durations.

Peak 16-week G.I. values (> 0·6) are found in the North Kimberleys, the 'Top End' of the Northern Territory, and the western rim of Cape York. The decrease in values south and east of this broad zone reflects a decline in M.I. values inland and a decline in T.I. values southward along the eastern coast. Apart from a narrowing wedge of higher G.I. values extending to the south along the eastern coastline, practically the whole of the area south of the Tropic of Capricorn has very low (< 0·1) mean 16-week G.I. values. This reflects the rather extreme seasonality of the moisture regime with dry

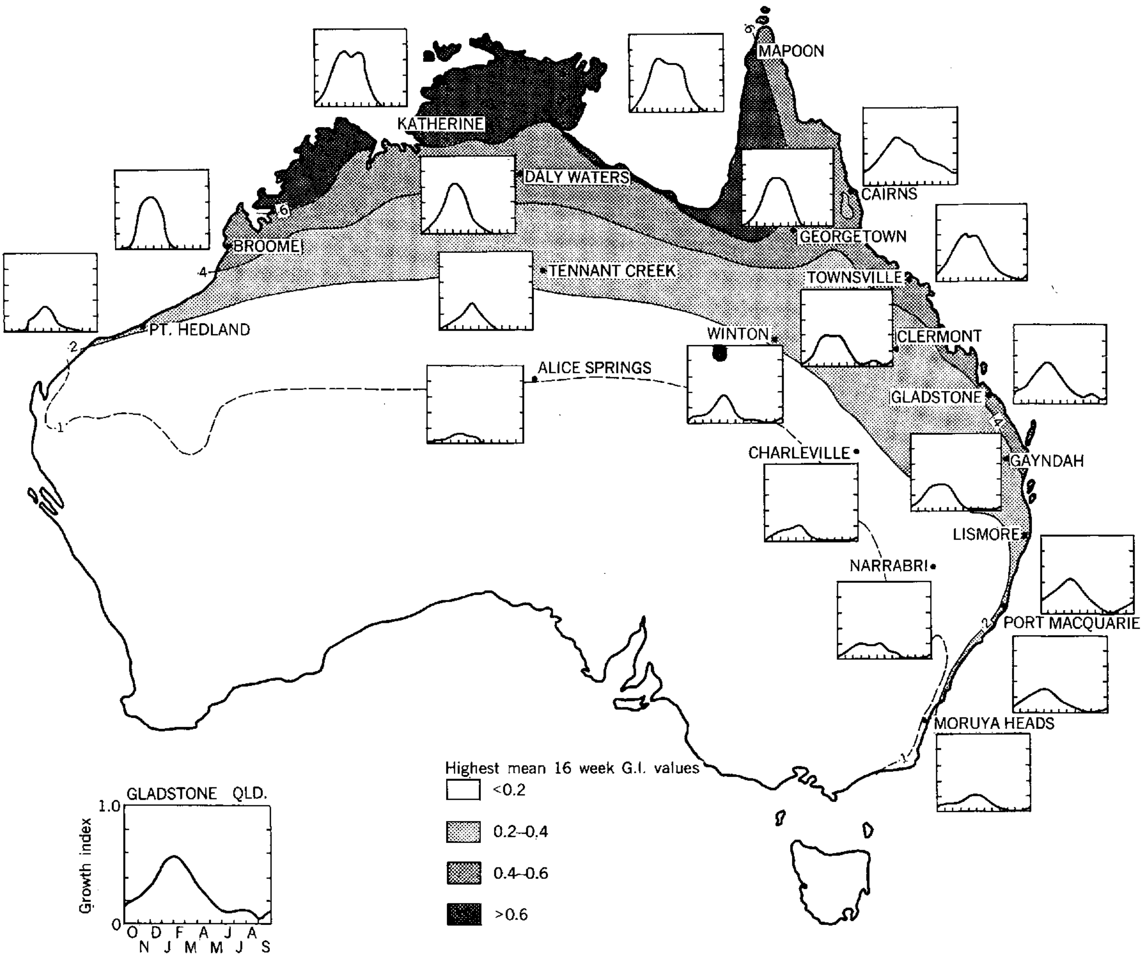


Fig. 1 : 11 Geographic and seasonal distribution of Growth Index values for the tropical grasses

summers and wet winters. However, inland from the southern coastline, summer light and thermal regimes are favourable and, if irrigated, tropical grasses can be productive.

A number of distinctive annual G.I. curves can be identified from the data given in Fig. 1 : 11. However, somewhat similar curves may be the expression of different limiting regimes. Thus the very low winter and spring G.I. values for tropical grasses throughout their range are primarily a function of moisture regime in the far north and thermal regimes in the east and south. To facilitate further discussion, the seasonal course of L.I., T.I., and M.I. values together with the resultant G.I. values at four representative locations are shown in Fig. 1 : 12.

Katherine, N.T. (lat. 14°28′S; *long.* 132°16′E; *elevation* 108 *m; annual rainfall* 926 *mm).* Seasonal trends in light, thermal, and moisture regimes and resultant G.I. curves at Katherine are typical of a broad arc of better watered country across northern Australia. The dominant feature of this environment is the extreme seasonality of moisture regime. To the south, with increasing aridity, both peak values of the M.I. and duration of the wet period decline (Fig. 1 : 11) and variability increases.

Peak values of the G.I. for tropical grasses, over weekly intervals, are attained at inland locations such as Katherine and Croydon in

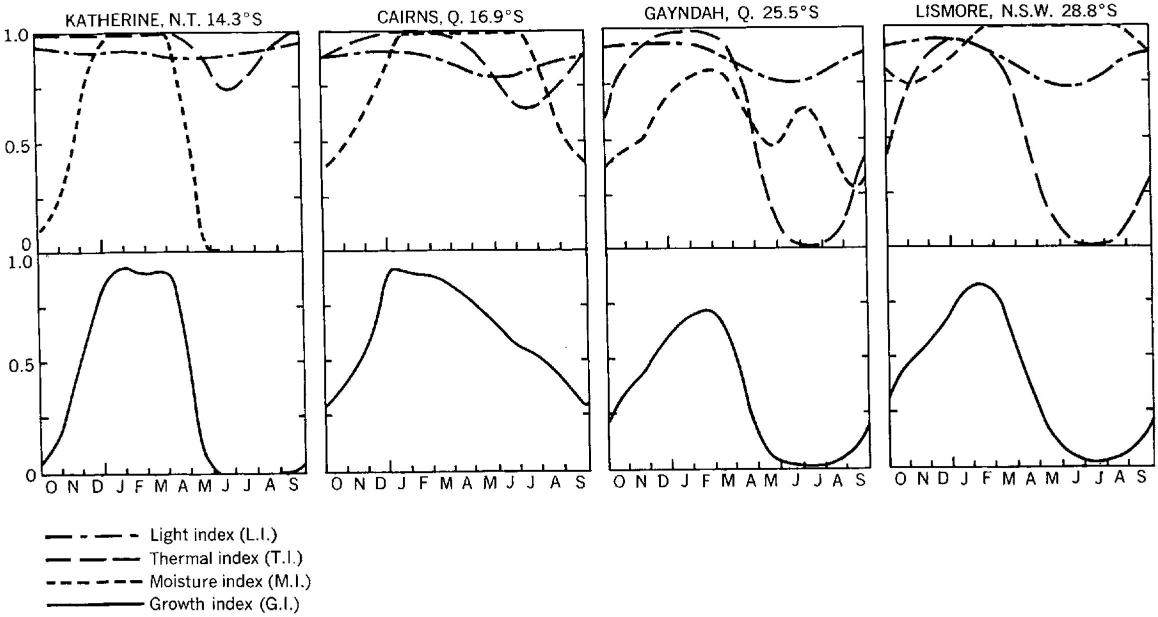


Fig. 1 : 12 Annual trends in Light, Thermal, Moisture, and Growth Index values for the tropical grass group at four representative locations

Queensland because of the highly favourable combination of light, thermal, and moisture regimes over short periods. Thus, Begg (1965) has reported very high photosynthetic rates and photosynthetic efficiency for the tropical grass, bulrush millet *(Pennisetum typhoides)* under natural dryland conditions at Katherine. Areas with higher rainfall than Katherine show a characteristic decline in L.I. and T.I. values because of increased cloud cover. This is counterbalanced to some extent by the longer duration of the wet season.

The grazing lands in this zone are composed principally of drought-evading perennial tussock grasses and tall annual grasses. Areas sown to improved tropical grass species are negligible, the major research effort here being directed towards development of annual legume pastures with good stand-over qualities (Norman 1966).

Cairns, Qld (lat. 16°55′*S; long.* 145°46′*E; elevation* 5 *m; annual rainfall* 2193 *mm).* This location is representative of a relatively restricted area of coastal north Queensland where annual rainfall totals range from 2000 to 4000 mm. Although smaller localised areas may have almost twice the annual rainfall of Cairns, the seasonal pattern of the moisture regime is very similar. This is the only part of Australia where G.I. values for tropical grasses remain at a reasonable level throughout the whole year. L.I. and T.I. values fall below those at Katherine because of increased cloud cover and maritime influences. The greater part of these coastal lowlands is devoted to the cultivation of sugar cane, but significant areas have been sown to mixed pastures of perennial grasses and legumes. Tropical grass species such as guinea *(Panicum maximum)*, para *(Brachiaria mutica)*, and molasses grass *(Melinis minutiflora)* have become widely established.

Gayndah, Qld (lat. 25°37′*S; long.* 151°36′*E; elevation* 104 *m; annual rainfall* 757 *mm).* Light, thermal, and moisture regimes at this location broadly typify a rather large area of sub-humid, sub-coastal Queensland. The moisture regime shows a typically bimodal pattern reflecting the overlap of summer and winter rainfall influences. However, low winter temperatures and killing frosts greatly limit growth of tropical grass species during the winter. Advantage may be taken of winter peaks in the moisture regime by sowing temperate annual grasses such as oats.

Although highly variable, the more continuous moisture regimes favour survival of improved perennial grass species. Thus, Rhodes *(Chloris gayana)*, green panic *(Panicum maximum var. trichoglume)*, and buffel grasses *(Cenchrus ciliaris)* have been extensively sown on better class soils throughout the broad region.

Lismore, N.S.W. (lat. 28°48′*S; long.* 153°17′*E, elevation* 11 *m; annual rainfall* 1323 *mm).* Seasonal patterns at this location are typical of the humid coastal lowlands in northern New South Wales and Queensland. Apart from a drier spring and early summer, the moisture regime is generally favourable. T.I. values are very low during the winter months, but frosts are less frequent and not as severe as those experienced at more inland environments such as Gayndah.

Rather similar patterns of G.I. curves are found in a narrow strip southward along the east coast of New South Wales and into the far eastern corner of Victoria. However, peak values of the G.I. in summer are much reduced and the duration of the winter depression in values is longer because of lower temperatures. Even so, the tropical grasses, paspalum *(Paspalum dilatatum)* and kikuyu *(Pennisetum clandestinum)*, have become widely established along this narrow strip and provide useful grazing during the summer months.

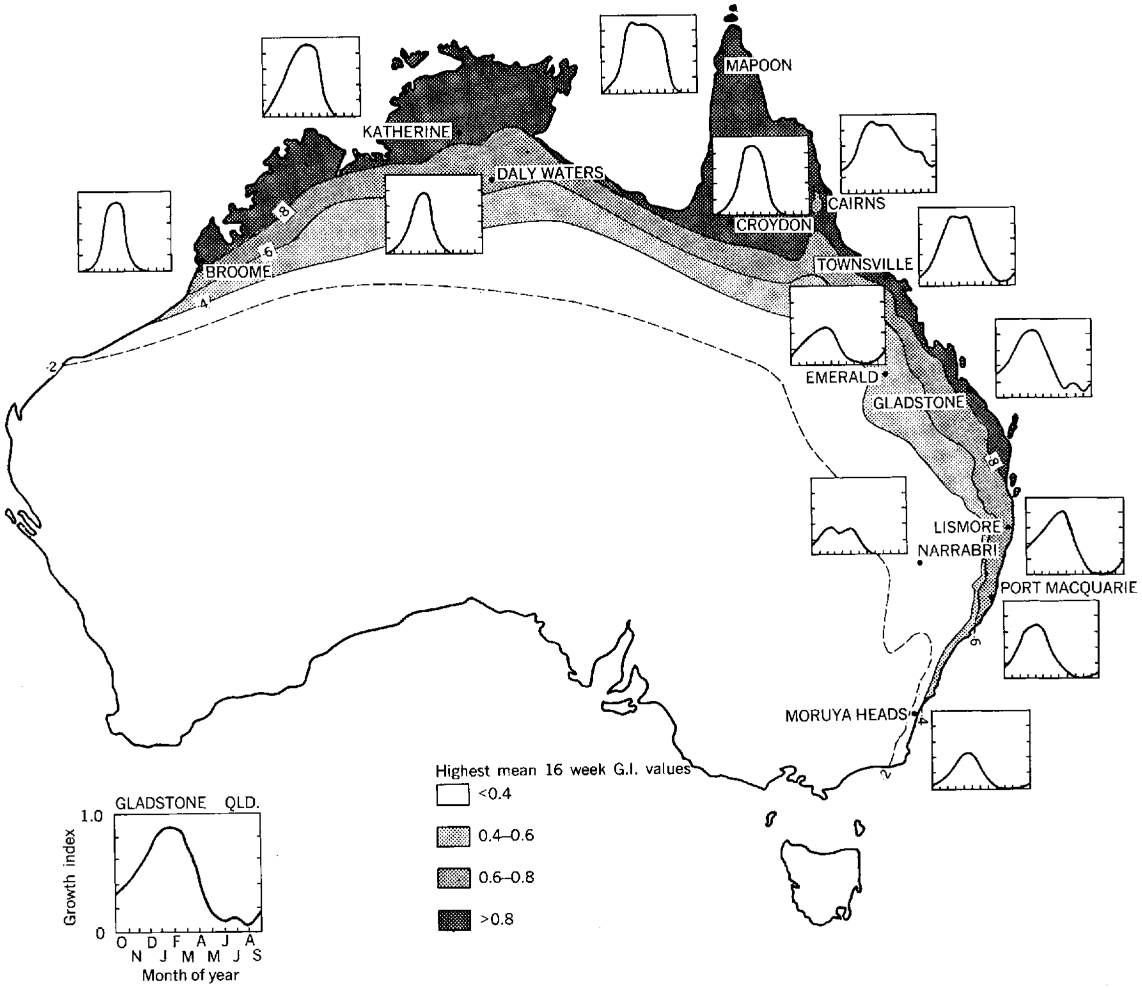


Fig. 1 : 13 Geographic and seasonal distribution of Growth Index values for the tropical legumes

Tropical Legumes

Herbacious legumes are not very common in the native grazing lands of Australia and so a feature of pasture research has been the intense effort devoted to the development of legume-based pastures. Suitable pasture legumes are now available for much of the better watered areas of southern Australia and very extensive areas have been sown. This contrasts with the position in northern Australia where suitable legume species are just becoming available and where relatively small areas have been sown.

The broad gradients of the highest mean 16–week G.I. values (Fig. 1 : 13) are similar to those for the tropical grass group, but the somewhat lower optimum temperature range for the tropical legumes does produce differences in detail. Thus, peak mean 16–week G.I. values (> 0·8) are found in a broad band across northern Australia similar to that for the tropical grasses. However, for the tropical legumes, these highly favourable seasonal conditions extend over the whole of Cape York and as a narrow strip extending southwards along the east coast of Queensland to just north of Brisbane. Moderately high values (0·6–0·8) extend further south along the coastal strip to the vicinity of Taree in New South Wales.

Gradients in the highest mean 16–week G.I. values inland from the coast are much steeper than those for the tropical grasses. This reflects the combined effects of increasing aridity and supra-optimal temperatures. Up to the present, productive tropical legume pastures, whether annual or perennial, do not extend beyond the area delineated by mean 16–week G.I. values exceeding 0·6. Productive pastures of the annual legume Townsville lucerne do not extend far beyond the zone where G.I. values exceed 0·8.

The strongly peaked unimodal G.I. curves which are characteristic of almost all locations are a function of seasonal moisture regime in the far north and thermal regime in the south and east. Killing frosts set absolute limits to growth durations at inland locations south from latitude 22°S. The same four locations chosen as representative of tropical grass environments have been selected for discussion of distinctive tropical legume environments. Seasonal trends in light, thermal, and moisture regimes and G.I. values for tropical legumes at these locations are shown in Fig. 1 : 14.

Katherine, N.T. (lat. 14°28′*S; long.* 132°16′*E; elevation* 108 *m; annual rainfall* 926 *mm).* This location has a highly favourable combination of light, thermal, and moisture regimes over part of

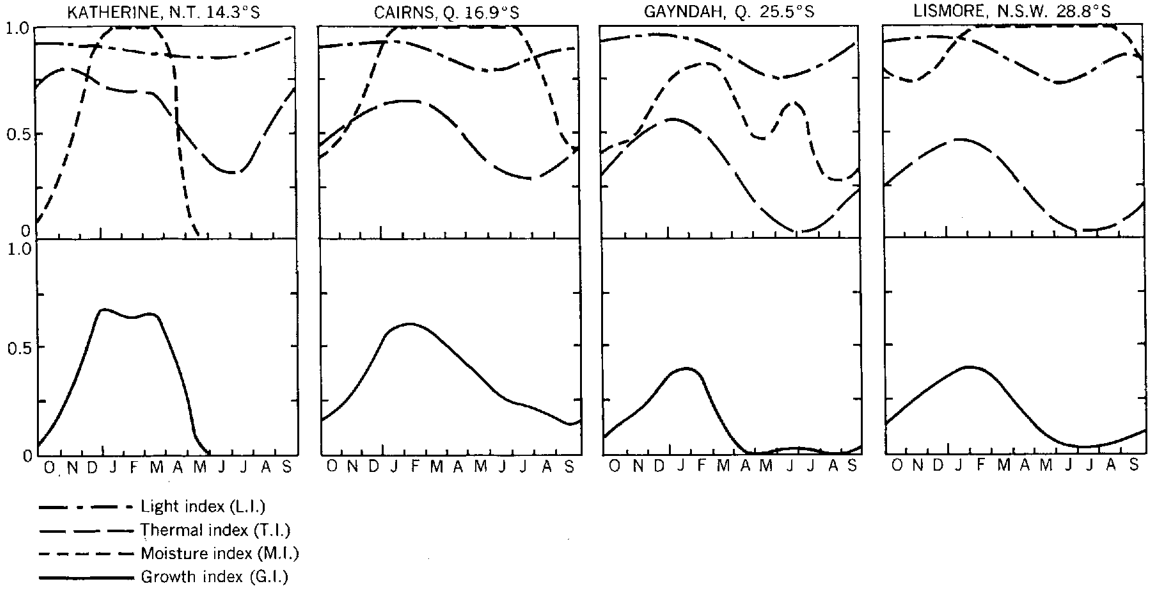


Fig. 1 : 14 Annual trends in Light, Thermal, Moisture, and Growth Index values for the tropical legume group at four representative locations

the wet season and very high weekly values of the G.I. are attained at these times. The extreme seasonality of the moisture regime places limits on the use of perennial tropical legumes. The annual, Townsville lucerne, is well adapted to this environment and shows great promise over much of the area with mean 16-week G.I. values greater than 0·8. Research into pasture systems using this legume has been concentrated at Katherine and at Townsville and near Gladstone in Queensland. It is interesting to compare the rather similar peaks in G.I. curves attained at these three locations (Fig. 1 : 13). Variability in the moisture regime will be greater at Gladstone and Townsville and the winter rainfall component may lower the nutritive value of standing forage.

Cairns, Qld (lat. 16°55′*S; long.* 145°46′*E; elevation* 5 *m; annual rainfall* 2193 *mm).* Clearly this is the most favourable environment for tropical legumes on a year round basis. L.I. and T.I. values are relatively high throughout the year, the winter-spring decline in G.I. values being attributed to a decline in M.I. values at that time. By comparison with other areas, the wet tropical coast has a relatively long history of introduction and use of tropical legumes in sown pastures. Thus, twining perennial legumes such as centro *(Centrosema pubescens)* have been used successfully in mixed pastures with tropical grasses.

Gayndah, Qld (lat. 25°37′*S; long.* 151°36′*E; elevation* 104 *m; annual rainfall* 757 *mm).* The sub-humid, sub-coastal environments of central and southern Queensland have proved to be difficult for tropical legumes, although G.I. trends computed from the long-term mean weekly data appear quite favourable. The seasonal variations shown in Fig.1 : 10, for a typical location, may help to explain this difficulty. In between wet periods, temperatures may rise considerably above optimal levels for the tropical legumes so that these plants must cope with supra-optimal temperatures in addition to the increasing moisture stress. At present, the stoloniferous cultivar siratro, of the legume *Phaseolus atropurpureus*, bred by the CSIRO Division of Tropical Pastures, appears most promising in these areas. The temperate legume, lucerne *(Medicago sativa)*, as a deep-rooted perennial able to withstand periodic water stresses, is used as a legume component of mixed pastures and as pure stands. However, competition from tropical grasses in the summer may be severe.

Lismore, N.S.W. (lat. 28°48′*S; long.* 153°17′*E; elevation* 11 *m; annual rainfall* 1323 *mm).* This location occupies a central position in the humid coastal lowlands extending from near Maryborough in Queensland south to Taree in New South Wales. Throughout this better-watered strip, the summer seasonal environment is highly favourable in terms of light, temperature, and moisture with mean 16–week G.I. values ranging from 0·6 to 0·8. The dominating influence on tropical legume growth is that of the seasonal thermal regime, although there is a depression due to lower M.I. values in spring and early summer. G.I. values are low over the 5–month period May to September, primarily because of sub-optimal temperatures. Frosts occur, but not as frequently as at locations further inland. Active research in recent years has been of particular benefit to this coastal region and increasing areas are being sown to perennial tropical legumes such as siratro, glycine *(Glycine wightii* syn. *G. javanica)*, *Desmodium* spp., and *Lotononis bainesii.*

Temperate Grasses and Legumes

With the early concentration of settlement in southern Australia, temperate pasture species have had a relatively long history of introduction, development, and use. However, the major development of sown pastures coincided with recognition of the value of annual species, e.g. subterranean clover, for the extensive areas with seasonally arid climates. Productive perennial pastures are limited to relatively restricted areas with a less pronounced dry season (see Fig. 1 : 9).

Limitations to growth, together with increasing competition from tropical species at temperatures exceeding 75°F(24°C), set definite geographic and seasonal limits to the distribution of temperate pasture species. Although winter temperatures over much of northern Australia favour temperate species, the moisture regime at that time is completely limiting, apart from a narrowing tongue of winter seasonal moisture extending through Queensland to north of Cooktown (Fig. 1 : 8). In this north-eastern zone, where the water regime will permit, winter annuals such as oats *(Avena sativa)* are grown for fodder and self-seeding annuals such as prairie grass *(Bromus unioloides)* and burr medics *(Medicago* spp.) have become established.

Unfortunately, throughout much of the range of the temperate pasture species in southern Australia, peak light and thermal regimes are almost completely out of phase with peak moisture regimes. Thus, favourable growth conditions are attained over relatively restricted periods in autumn and spring, giving rise to characteristic bimodal G.I. curves. In general, spring is more favourable than autumn. A further complication in north-eastern and eastern coastal Australia is that of an overlap in distribution with the tropical grasses and legumes. North from latitude 28°S, temperate species face increasing competition over a steadily increasing proportion of the year. However, as mentioned above, temperate annuals can thrive during the colder winter months, providing the moisture regime is favourable.

Because of the more complex seasonal trends in G.I. values, the 16–week mean G.I. values are not as useful for comparative purposes as are those for the tropical grasses and legumes. For instance, with the bimodal curves, the 16–week mean G.I. value can span one, but not both, of the G.I. peaks. Nevertheless it does provide a comparative measure of growth during the most favourable period of the year. In north-eastern Australia, where competition from tropical species in the summer season limits the usefulness of temperate species, periods with mean daily temperatures exceeding 25°C (75°F) were excluded. The map shown in Fig. 1 : 15 has

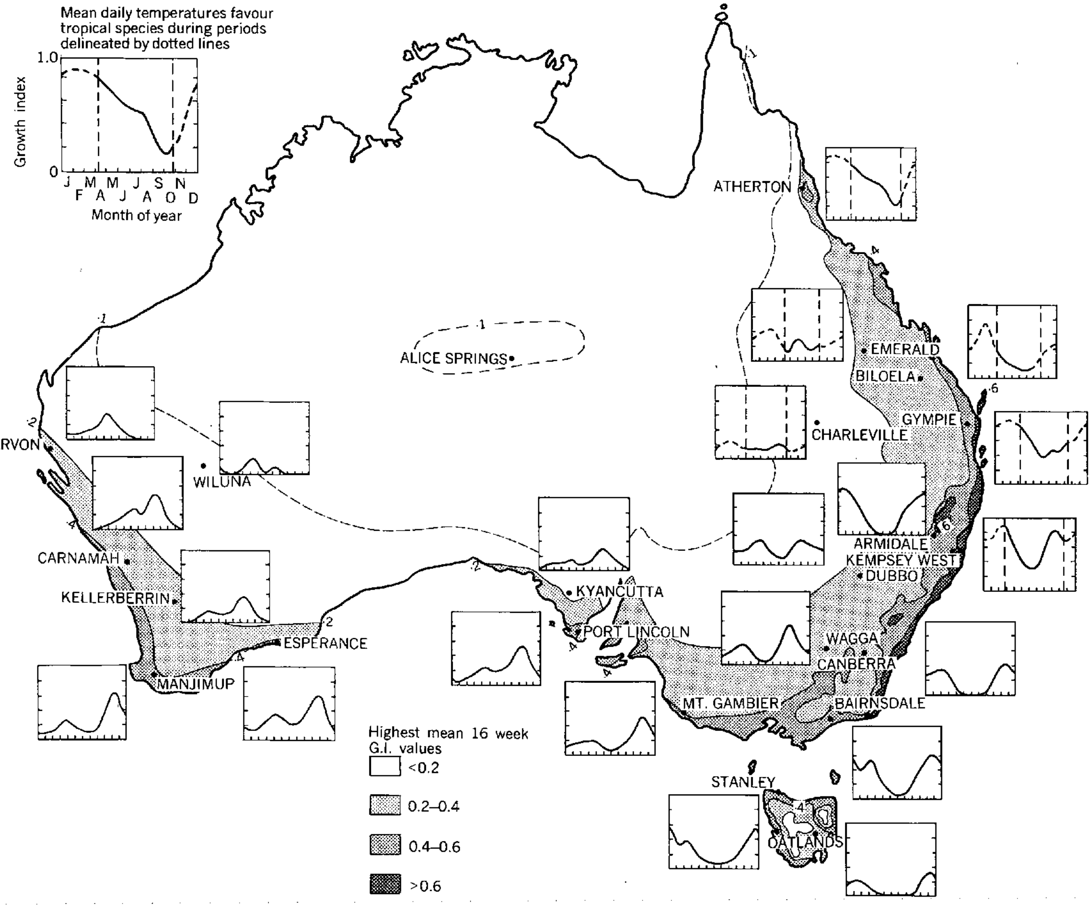


Fig. 1 : 15 Isopleths of highest mean 16-week Growth Index values

been prepared on this basis. Selected annual G.I. curves are also shown.

The gradients of 16-week mean G.I. values reflect those of the winter season moisture regimes (see Fig. 1 : 8) with some modifications along the south-eastern coastal strip imposed by summer moisture regimes. Peak mean G.I. values (> 0·6) are found along the humid coastal lowlands of south-eastern Australia, with outliers in restricted upland areas, e.g. Central and Northern Tablelands of New South Wales. These peak values are attained in late summer and autumn and are a reflection of summer moisture regimes. At all these locations there is some competition from tropical species, e.g. *Paspalum dilatatum*, during this period, although thermal regimes are sub-optimal for this group.

The major part of the area sown to annual temperate pastures and fodder crops has mean G.I. values ranging between 0·2 and 0·4. Throughout this broad arcuate zone, the southern portions are distinctly more favourable because of more reliable moisture regimes and much longer growth durations with the typical bimodal pattern. In these southern areas, growth commences in autumn and, by spring, plants are fully established and capable of maximum use of the favourable environment at that time. At inland locations where peak mean G.I. values fall below 0·2 and the growth period is of short duration, annual forbs and herbs and perennial browse shrubs and trees become a significant feature of the grazing environment.

A number of distinctive annual G.I. curves can be identified from the data shown in Fig. 1 : 15. In north-eastern Australia, the period of significant competition from tropical species is indicated in the inset blocks by dotted lines. In general, productive temperate pastures are restricted to areas south of the Tropic of Capricorn and, over extensive areas, to south of latitude 28°S. To facilitate further discussion of the more important temperate pasture environments, the seasonal course of L.I., T.I., and M.I. values together with resultant G.I. values at four representative locations are shown in Fig. 1 : 16.

Kempsey West, N.S.W. (lat. 31°S; long. 152°50′E; elevation 9·5 m; annual rainfall 1145 mm). The humid coastal lowlands of south-eastern Australia have the most favourable year-round environment for temperate pasture species. Similar conditions are found further north, but at greater elevations, e.g. Blackall

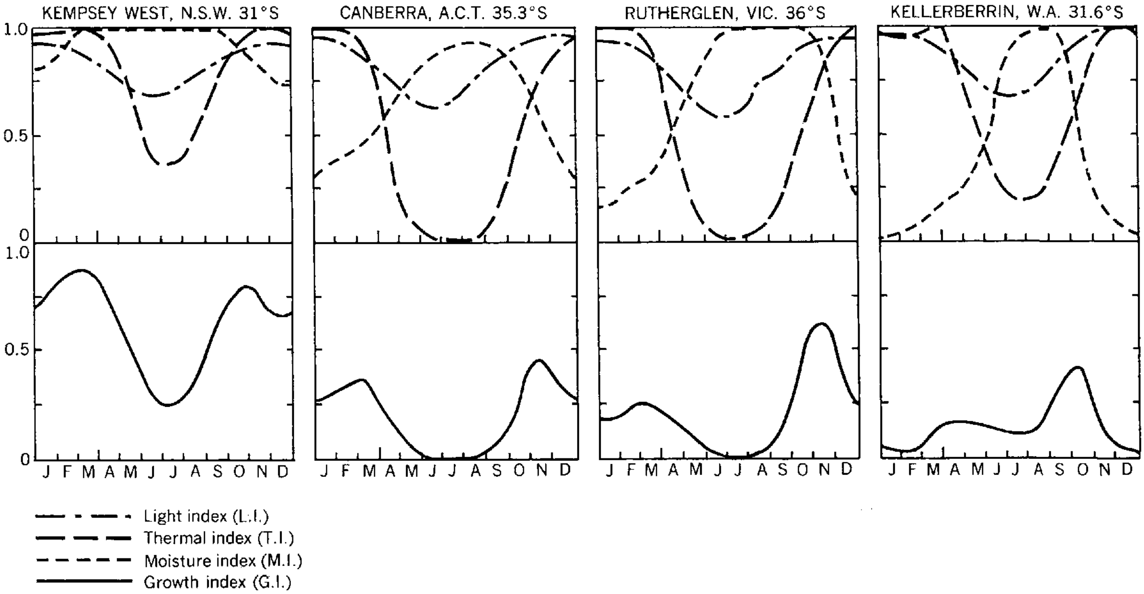


Fig. 1 : 16 Annual trends in Light, Thermal, Moisture, and Growth Index values for the temperate grass and legume group at four representative locations

Range in south Queensland and Atherton Tableland in north Queensland. L.I. and M.I. values are generally high throughout the year, but T.I. values show a characteristic winter depression. Southwards along the coastal strip winter temperatures become more limiting. Proceeding northwards, the higher summer temperatures lead to greater competition from tropical species, e.g. *Paspalum dilatatum*. The central coast of New South Wales, of which Kempsey West is typical, represents a median position between these two limitations to the growth of temperate species. Perennial rye *(Lolium perenne)* and white clover *(Trifolium repens)* are the major temperate pasture species along this humid coastal strip.

Canberra, A.C.T. (lat. 35°17'*S; long.* 149°8'*E; elevation* 560 *m; annual rainfall* 592 *mm).* This location typifies the seasonal patterns that occur on the Southern Tablelands of New South Wales and in southern Victoria and the lowlands of Tasmania. Seasonal trends in the moisture regime and the light and thermal regimes are almost completely in opposition. The winter depression in G.I. values extends over four to six months depending on location and elevation. The moisture regime during the summer months is more favourable than at other southern Australian locations and useful, though highly variable, growth is made during this period. Autumn and spring peaks in G.I. values tend to be of similar size and, in Tasmania, may merge into a single summer peak of G.I. values. Throughout this zone, the more continuous moisture regime favours survival of perennial pasture species such as perennial rye, cocksfoot *(Dactylis glomerata)*, phalaris *(Phalaris tuberosa)*, lucerne, and white clover. However, the annual legume, subterranean clover, is also sown.

Rutherglen, Vic. (lat. 36°*S; long.* 146°28'*E; elevation* 169·5 *m; annual rainfall* 608 *mm).* Seasonal trends in light, thermal, and moisture regimes at this location are broadly typical of the better-watered portions of the winter rainfall zone. Similar annual G.I. curves can be recognised over a very wide area, from south-western Australia across to south-eastern Australia (Fig. 1 : 15). Here again, the seasonal trends in light and thermal regimes are almost completely in opposition to trends in the moisture regime. However, the resultant G.I. peaks in autumn and spring are not comparable, the spring peak being dominant. Although summer G.I. values fall to low levels, because of the depression in moisture regime, deep-rooted perennial pasture species such as phalaris and lucerne can make useful growth. In general, however, the dominant pasture species are annuals, which commence growth in autumn and complete their life cycle in early summer. The value of legume ley rotations based on subterranean clover was first demonstrated at Rutherglen by the Victorian Department of Agriculture.

Kellerberrin, W.A. (lat. 31°38'*S; long.* 117°43'*E; elevation* 250 *m; annual rainfall* 353 *mm).* Although broadly similar in pattern to the previous location, seasonal G.I. values are lower both in autumn and spring and reflect the drier and more seasonally arid environment. Thus, summer conditions are extremely dry and the winter moisture regime curves more sharply peaked. This location is typical of the intermediate to drier fringes of the wheat belt in southern Australia. Development of suitable sown pastures for this broad zone hinged upon the introduction, selection, and breeding of more rapidly maturing annual species. Suitable strains of subterranean clover for lighter-textured acid soils and annual medics for heavier-textured alkaline soils are now available for all but the driest fringes of the wheat belt.

CONCLUSIONS

This study represents an initial attempt to characterise pasture environments in terms of basic biological responses to gross seasonal trends in climatic parameters. Clearly, the methods used can be further refined and developed as the necessary biological and climatic data become available. Thus, further development should lead to formulation of growth and development models for individual pasture species. Simulation of pasture response using long-term historical records of weather sequences will permit assessment of growth in probabilistic terms at stated times and at stated locations.

The extension of this type of analysis to a global scale should permit much more precise identification of pasture environment analogues. This would enhance the efforts of plant introduction teams and also the exchange of information between analogous areas in different parts of the world.

ACKNOWLEDGMENTS

The authors gratefully acknowledge the assistance of Mr C. A. Neal-Smith of the CSIRO, Division of Plant Industry, Canberra, in providing growth data from his phytotron studies. Mrs A. Komarowski of the CSIRO Division of Land Research provided valuable assistance with preparation of data.

2

LANDFORMS AND STRUCTURE

J. A. MABBUTT AND M. E. SULLIVAN

OUTLINES OF RELIEF AND DRAINAGE

Characteristic features of the relief of Australia as shown in Map 1 are, first, the great extent of plains and tablelands and conversely the absence of high mountain ranges; second, the peripheral distribution of the highest ground and hence the closeness of the main drainage divide to the continental margin; and third, the large area of desert landscapes. These major traits have their origin in the geologic build and tectonic history of the continent and in the climatic framework within which geomorphic processes have operated during a long subaerial history.

Structural Units

The three major structural compartments as shown in Fig. 2 : 1 are the stable Western Platform, the Central Basin of gently warped, relatively young sedimentary rocks, and the ancient orogen of the Eastern Uplands, rejuvenated with differential uplift in Tertiary and later time. Since the Palaeozoic, this structural base has been subject to episodes of mainly vertical earth movement or epeirogenesis with intervening stable periods of planation, whence the generally subdued relief and the dominance in the landscape of horizontal surfaces, whether of plateau or plain. Australia lacks the young fold belts which elsewhere, as in New Guinea, give the world its highest mountain chains and most spectacular relief. Limited areas exceed 3300 ft (1000 m) and the continental summit attains only 6600 ft (2030 m) in Mt Kosciusko, where, as in most ranges of the Eastern Uplands, the subdued crestal contours mark an uplifted surface of prior planation.

Outlines of the Continent

The outlines of the continent have largely been controlled by components and their lineaments within these major structural divisions. In the area of the Western Platform, rocky coastal salients mark the faulted margins of uplifted blocks, and broad embayments and estuaries occur where sedimentary basins meet the coast. In the north-west, for instance, the three blocks which form the Hamersley and Kimberley Ranges and the Arnhem Land Plateau separate Eighty Mile Beach and King Sound on the Canning and Fitzroy Basins, Joseph Bonaparte Gulf on the Bonaparte Gulf Basin, and the western part of the Gulf of Carpentaria on the Macarthur River Basin. North-easterly lineaments within the blocks have determined the main trend of the coast here. On the south, the Eucla Basin forms the head of the Great Australian Bight, between rocky fault-margin coasts which extend westwards to Cape Leeuwin and east in the Gawler Block to Spencer Gulf where block-faulting on northerly lineaments has formed the Yorke Peninsula and the bounding gulfs.

The coastal trend in the west is essentially determined by the Darling Fault and its northward extensions, which form the marginal escarpment of the interior plateau, although this is fronted by a narrow coastal lowland formed on sedimentary rocks of the Carnarvon and Perth Basins.

The Carpentaria and Murray Basin components of the Central Basin formerly gave rise to embayments. The northern one persists in the Gulf of Carpentaria, where a low unindented shoreline and gentle offshore gradients denote a downwarped coast of subsidence; in the south, however, the Murray Basin has been sealed off through uplift along the Padthaway Horst and by the growth of beach barriers, and has been filled by river deposits.

The east coast is the result of differential block subsidence within the Eastern Uplands. These movements have occurred since the mid-Tertiary, and their recency is reflected in the lack of large indentations, the steep fall with restricted coastal plains, and the narrow drowned-valley

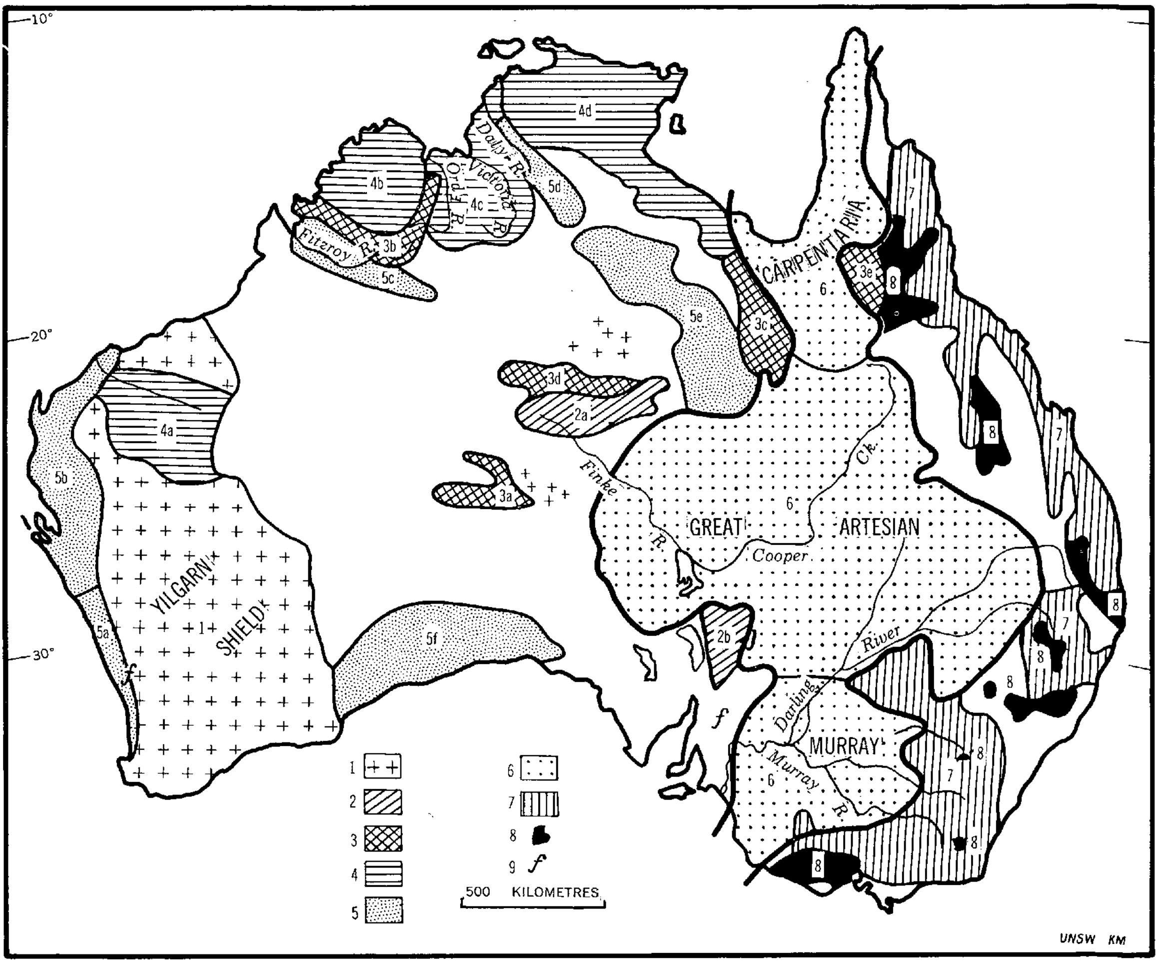


Fig. 2 : 1 Structural divisions and components
1 Shield
2 Folded belts (a) Macdonnell Ranges (b) Flinders Ranges
3 Hill belts of igneous and metamorphic rocks (a) Everard Ranges (b) Halls Creek hill belt (c) Isa Highlands (d) Northern Macdonnells (e) Einasleigh Uplands
4 Plateau blocks (a) Pilbara (Hamersley Ranges) (b) Kimberley (c) Ord–Victoria (d) Arnhem Land
5 Basin plainlands (a) Perth (b) Carnarvon (c) Fitzroy (d) Daly (e) Barkly-Georgina (f) Eucla
6 Central basin division
7 Structural highs of Eastern Uplands
8 Tertiary basalts
9 Tectonic relief

embayments. In the south, as along the west coast of Tasmania, the coast trends somewhat obliquely to the northerly grain of the Palaeozoic folding and there is a close alternation of rocky headlands and narrow inlets; in contrast, the coast north of Cape Byron runs mainly with the structure, and there are broad, north-facing embayments where basins meet the coast—for instance Princess Charlotte Bay on the Laura Basin—and protective promontories and intervening rocky sectors formed on faulted blocks. Deltaic plains, as of the Burdekin, occur on some structural lowland shores.

Drainage Patterns

The down-faulting or subsidence which has determined the outlines of the continent in the Western Platform and Eastern Uplands is

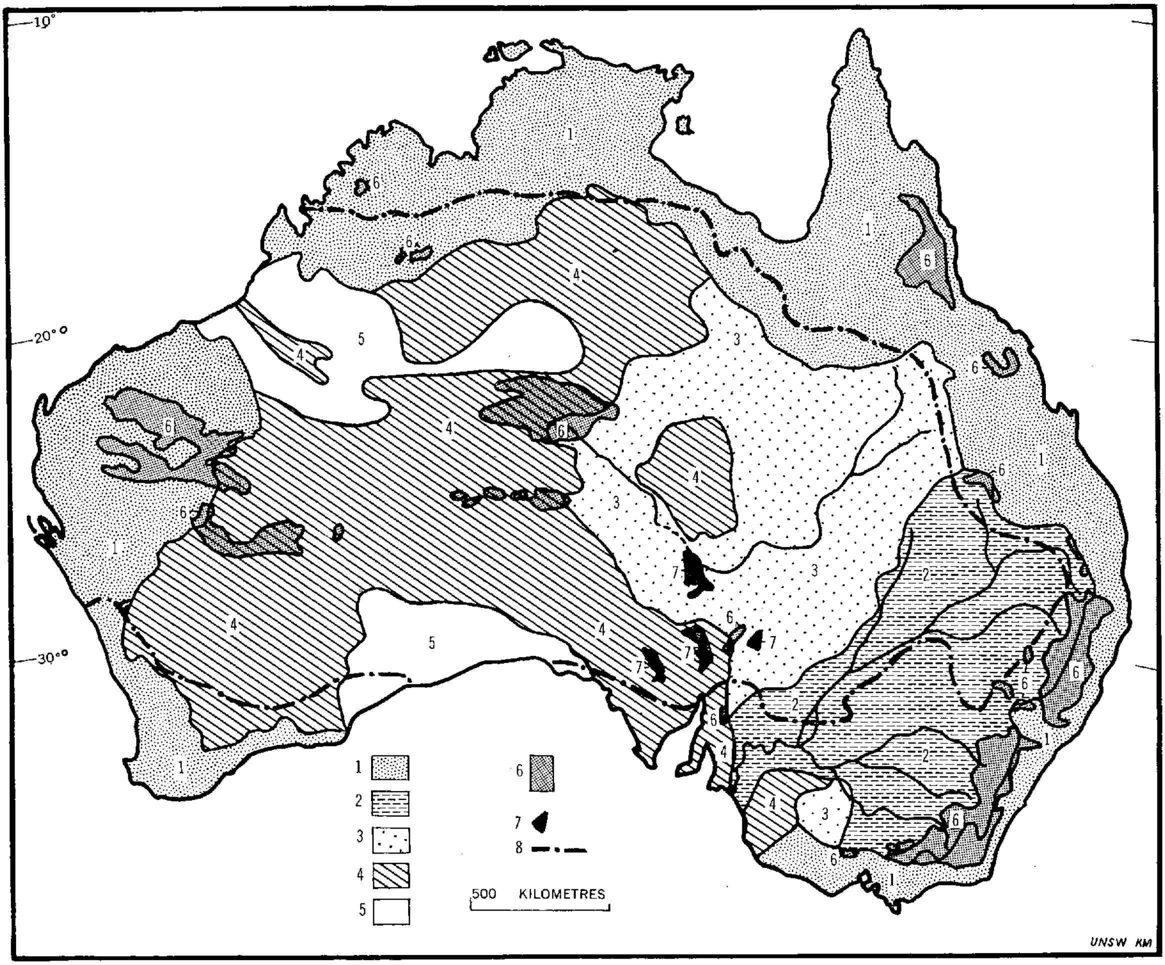


Fig. 2 : 2 Drainage classes
1 Direct external
2 Indirect external
3 Co-ordinated interior
4 Unco-ordinated interior
5 Riverless areas
6 Areas above 600 m
7 Large playa lakes
8 Limit of arid and semi-arid zone

commonly marginal upon broad flexures running parallel with the coast. This is best demonstrated in, and is indeed characteristic of, the Eastern Uplands, where the rise in plateau elevations denotes an up-arching in a belt between 100 and 300 miles (150 and 500 km) wide, with its inland limb beginning the tectonic fall to the Central Basin. As a result, the highest ground here generally occurs within 200 miles (300 km) of the coast (Fig. 2 : 2). The Main Divide between the Pacific drainage and the rivers flowing westwards is typically a broad summit for which the name 'Great Dividing Range' is inappropriate. The eastern rivers, as exemplified by the Shoalhaven, characteristically have wide upper valleys which commonly follow meridional structural trends, and deeply incised transverse lower courses. Some stretches of the Divide lie inland from the belt of maximum elevation, which is then traversed in spectacular gorges by antecedent streams like the Burdekin (Qld) or the Grose (N.S.W.).

To a lesser degree, marginal faulting on the Western Platform has also been accompanied by upwarping. In the south-west, the Darling Range rises some 130 ft (40 m) above the interior plateau and forms a watershed for minor streams, although traversed by the larger rivers such as the Avon. The uplifted blocks of the Hamersley and Kimberley Ranges and of the Arnhem Land Plateau also form peripheral watersheds in the north-west. In the north, too, the Pine Creek Upwarp (Hays 1967) separates the short rivers of the Gulf slopes from the interior drainage of the Barkly Tableland. The only large river systems which head far inland in this sector of the continent are those which occupy the major structural basins, for example the Fitzroy, the Ord, and the Daly.

Figure 2 : 2 shows the peripheral distribution of high ground and the associated position of the Main Divide resulting from marginal uplift in the Western Platform and Eastern Upland divisions. Only a relatively narrow belt, comprising less than one-third of the continent, is drained directly seawards. Contrasted with this exoreic zone of moderate-sized or small catchments are the two large inward-directed systems of the Central Basin, their centripetal patterns reflecting tectonic slopes in the Great Artesian and Murray Basins. The Murray-Darling system, with a maximum length of 3260 miles (5250 km), ranks fourth in the world, and its catchment of more than 440,000 sq miles (1,140,500 km^2) is the sixth largest; the basin tributary to Lake Eyre is somewhat larger, but its drainage has broken into separate systems through the combined effects of aridity and the differential earth movements which have carried Lake Eyre 23 ft (7 m) below sea level. The Gulf drainage in the north, separated from the interior drainage only by the low Selwyn Upwarp (Twidale 1966), can be recognised as a third centripetal system within the Carpentaria Basin, now drowned in its lower part.

Drainage Status

The two large inward-directed systems are equal in extent to the zone of exoreic drainage; the remaining third of Australia has disorganised river systems or lacks surface drainage, largely as a result of aridity. More than two-thirds of Australia is arid or semi-arid by accepted criteria (see Chapters 1 and 17), and as in other deserts the present drainage represents the truncated and disorganised relicts of river systems initiated in a moister Tertiary Era.

There is a striking accordance between the limits of direct exoreic drainage and the boundary of the Australian arid and semi-arid zone, a fact of major importance in that it severely restricts the amount of supplemental water received from the humid borderlands. The close association of aridity and interior drainage is a complex one. Partly, it results from the rain shadow effect of the Eastern Uplands, whereby the Main Divide is also a climatic limit. In part, it reflects the tendency, with an unfavourable water balance, for river systems of low gradient readily to become disorganised, as on the interior plains of the Western Platform. Locally, as on the northern edge of the Barkly Tableland, the divide has been pushed inland towards the desert zone by more vigorous, better-watered exoreic systems. Additionally, aridity is associated with the extension of pervious aeolian sands which do not generate runoff. Finally, tectonic derangement of drainage, as in the Great Artesian Basin, tends to persist under an arid regime.

The mere classification of drainage basins as exoreic or endoreic is inadequate in that it fails to express the status of drainage, that is the extent to which the topographic basins are effectively occupied by their drainage nets. Drainage status has been classified by Hills (1953) and later writers in the following or similar terms:

direct external drainage
indirect external drainage
co-ordinated interior drainage
disorganised interior drainage
riverless areas.

The distribution of these classes, as shown in Fig. 2 : 2, demonstrates that drainage status is only partly a function of climate; it also reflects differences of major relief and in surface properties as controlled by regional geology and geomorphic history.

The zone of direct external drainage contains most of the perennial rivers of Australia, for these, with the exception of a small area in the south-west, are dependent on the heavier rainfall of the Eastern Uplands. Nevertheless, the seaward fall has been adequate to maintain integrated drainage in the northern belt of seasonal rivers and in the north-western sector of ephemeral streams; in the former area, indeed, the direct external systems have enlarged their province at the expense of interior drainage.

The Murray-Darling system is the special case of external drainage initially directed inland, and it probably owes its status, in contrast to the Lake Eyre drainage further north, to the higher effective rainfall in the southern part of the Eastern Uplands. With an average rainfall of only 17 in.(440 mm), its average annual discharge is a modest 12 million acre ft (14,800 million m^3) (cf. runoff, Chapter 18), despite its extensive catchment. This discharge is subject to great variations, and in fact the northernmost tributaries, the Paroo and Warrego, have regimes midway between seasonal and ephemeral. However, the system as a whole is perennial, and in fact provides the sole Australian example of a successful allogenic river system—one which has its source partly in the humid zone and which successfully maintains its course to the sea across an intervening arid and semi-arid tract.

The Great Artesian Basin provides the only significant area of co-ordinated interior drainage. Large drainage units have survived intact here, despite regional aridity, because of the favourable structural disposition of peripheral uplands and centripetal lowland slopes on soft impervious Mesozoic rocks. Moreover, the upland catchments of the north and north-east—where the Cooper Creek drainage extends slightly beyond the desert margin—receive more effective rainfall than elsewhere in the arid zone. The river systems of the Channel Country closely approach a seasonal regime, with substantial flows in most summers and extensive flooding at intervals of about five years. Such flows reach Lake Eyre each decade or so, but it appears that the lake is filled only once or twice each century, after successive exceptional seasons as in the 1949–50 flooding.

Over most of the remaining third of Australia, and falling entirely within the arid zone, there is a disorganised interior drainage of ephemeral channels, the prior river nets having broken into separate systems within the topographic basins, each with its own terminal and isolated by areas without surface drainage. In central Australia, with its plains and island mountains, there are separate radial nets about each upland mass; only the steep rocky hillslopes generate significant stream flow, and for want of tributary recharge the channels generally die out on the adjoining plains before linking into larger systems. On the Western Australian part of the Platform, which consists of vast plains and featureless sandy divides, a Tertiary drainage which formerly reached the Bight has degenerated into several interior systems.

There remain the riverless areas, which lack surface drainage due to low relief and permeable surfaces. They comprise the limestone Nullarbor Plain and those parts of the sand deserts distant from entering drainage and lacking upland sources of local runoff.

LANDFORMS OF THE WESTERN PLATFORM

Landforms on the Shield

The core of this structural unit, which constitutes almost two-thirds of Australia, is the Yilgarn Shield in the south-west, a vast updomed area of Archaean gneiss and granite with belts of metamorphic rock. The homogeneity of these igneous rocks is reflected in the extensive plains, mainly between 1000 and 1700 ft (300 and 500 m) above sea level, which predominate in the south of Western Australia. Schists and quartzites traverse the area as low ridges and belts of rounded hills trending a little west of north, with the structural grain.

By the middle of the Tertiary Era the Shield had been reduced to a plain and the granitic rocks laterised to depths of between 50 and 85 ft (15 and 25 m). This ancient land surface, termed the Old Plateau (Jutson 1934), still survives extensively, protected by its lateritic duricrust, and forms low divides with extensive sandplain cover. The regional drainage was rejuvenated by the marginal uplift of the Platform and erosion of the Old Plateau was initiated under an arid climate. The 'weathering front', or contact between fresh and weathered rock, has exercised a dominant control over this erosional phase, and a younger land surface, the New Plateau, has formed by stripping of the weathered profile. This etchplain on little weathered granite is separated from the Old Plateau by long, low breakaways. Stripping is far advanced in the marginal exoreic zone, but the Old Plateau becomes more extensive inland and dominates in the area of disorganised interior drainage.

The sandy Old Plateau surfaces generate little runoff and the local drainage originates at the laterite breakaways and in the hill belts. The trunk valleys, remnants of wide-branching systems which once connected and led southwards to the Bight, have become choked by alluvium and wind-blown sand under increasing aridity and are now occupied by aligned series of elongate playas, each acting as the focus of a local drainage system. The prior fluvial ancestry of these 'river lakes' is only apparent from the air or when they connect at times of heavy flooding.

The alluvial fills in the main valleys are commonly cemented with chalcedonic limestone. These outcrop as low platforms a metre or two above the alluvial flats and as much as a kilometre long, and commonly extend in a broad terrace where drainage enters the salt lakes.

In its higher parts, below the laterite breakaways, the New Plateau consists of undulating stony plains locally dotted with low granite domes and tors exhumed from the weathering profile (Pl. 1). In the lower sectors the rock surface commonly passes beneath alluvial sheets subject to sheetflow.

Much of the area is masked by windblown sand, mainly as sandplain on Old Plateau remnants, but also as irregular dunes about the salt lakes. Jutson (1934) noted that the lakes commonly lie close to the escarpment bordering the valley on the west, whilst they are dune-rimmed on the east, and suggested that they may have been wind-planed and have migrated westwards, upwind, through the deposition of wind-borne materials on their lee margins. Locally, crusted gypseous dunes rim the salt lakes as lunette barriers, and parna sheets may extend for several kilometres downwind (Bettenay 1962).

Sand cover diminishes westwards, where the drainage has remained competent to evacuate the sediment supplied and where the erosional New Plateau surface is particularly extensive. In these areas, lower tracts on the New Plateau consist of rhythmic alternations of low aeolian sand banks ('wanderrie banks') and alluvial flats which vary in pattern with drainage direc-

Plate 1 Lateritic breakaway separating Old and New Plateau surfaces on the Yilgarn Shield, near Meekatharra, Western Australia, with granite tors exhumed from the weathered profile (University of New South Wales photo)

tion (Mabbutt 1963).

There is a general increase in salinity in alluvial deposits and in groundwater towards the lower parts of the area. However, salt crusts in the lakes are thin, partly because of periodic flushing and in part because the lakes do not constitute groundwater terminals, since movement continues through the alluvial fills.

The Yilgarn Shield is by far the largest exposure of crystalline basement on the Western Platform, but there are smaller recurrences in central Australia north of the Macdonnells, and also in the south of the Northern Territory. These differ from the Western Australian landscapes in that lateritic crusts are largely lacking. They are high-lying piedmont plains with competent through-drainage, and there is a predominance of erosional surfaces fashioned in little-weathered granite, with domes and tors on a larger scale than in Western Australia. These areas provide fine examples of pedimented landscapes, with thinly mantled rock surfaces of low gradient which extend smoothly to the piedmont angle.

Landforms on Uplifted Cratonic Blocks

Outside the shield areas the crystalline basement is concealed beneath a mosaic of cratonic blocks and basins with a variety of structures and forms, but which commonly attest to a remote geologic history of greater crustal mobility and later episodes of mainly vertical movement controlled by the older lineaments.

Belts of highly deformed igneous and metamorphic basement rocks traverse the Platform, as in the Isa Highlands (Twidale 1966), the northern Macdonnells (Mabbutt 1962), the Halls Creek Ranges (Wright 1964), and the Everard Ranges. They are the roots of geosynclines and tend to occur along the margins of folded cratonic blocks. They have been differentially eroded into ranges and hill belts with a variety of upland forms corresponding to the wide range of rock types; these include domes and tors on massive granite and gneiss, quartzite ridges and plateaux, and rugged country on schists and phyllites. The pronounced structural grain is strongly expressed in relief, with closely-spaced strike ridges and valleys and rectangular or dendritic tributary systems. Relief characteristically ranges up to 1000 ft (300 m).

Other belts contain moderately or closely folded rocks of Proterozoic and Palaeozoic age in which the structures have later been etched under an arid regime to form spectacular ranges with maximum relief of between 1000 and 2600 ft (300 and 800 m). Such are the Davenport, southern Macdonnell, James, and Krichauff Ranges in the Northern Territory and the Flinders Ranges in South Australia. For the most part the ridge-builders are massive quartzites and sandstones, and there is commonly a degree of relief inversion, the anticlines giving rise to closely spaced ridges-and-vales about axial lowlands and the synclines forming plateaux or perched basins as in Wilpena Pound in the Flinders Ranges.

The Platform also includes several cratonic blocks of relatively unfolded resistant rocks which have been periodically uplifted and which now form bold plateau relief, commonly up to 1000 ft (300 m). In some the basin structure persists in relief, with a lower central tableland tract and a higher plateau rim, locally with strike ridges around the basin margin. The drainage typically occupies a rectangular net of narrowly incised valleys due to control by jointing in the sub-horizontal strata. The main relief builders are Proterozoic sandstones and quartzites, with minor areas of volcanic rocks, and the characteristic landforms are plateaux and gorges.

These features are best exemplified in the Kimberley and Arnhem Land plateaux. In the Pilbara Block there has been stronger dissection into ridges which in the Hamersley Ranges are up to 2000 ft (600 m). high In part this reflects base-level control of erosion by the antecedent Fortescue River, which crosses the block in a deep graben gorge, and in part the greater structural and lithologic complexity, for gentle folding in the south of the area has exposed a variety of rocks.

The structural components of the Ord-Victoria Basin correspond topographically to the two drainage units of the same names. There is a plateau surround of Palaeozoic basalts, as in the Antrim Plateau, and in the central part of the smaller Ord Basin these are in turn capped by plateau-building sandstone. The inner area of the Victoria River Basin consists of extensive tablelands and low plateaux of gently-folded Proterozoic sandstone. Maximum relief in this area is between 350 and 700 ft (100 and 200 m).

Many of these Platform uplands bear evidence of prior planation, involving a reduction of structural relief to a degree not achieved in later erosion cycles, in the form of summit bevels or smoothed crestal surfaces which contrast with rugged lower slopes and indicate a more humid regime at the time of their shaping. The relief-building rocks, for the main part quartzites and sandstones, are not susceptible to deep weathering, but nevertheless bear signs of imperfect laterisation or secondary silicification. Such features have been described from the Macdonnell and Ashburton Ranges in the Northern Territory (Mabbutt 1966; Hays 1967), beyond the limits of Mesozoic transgression, but the equivalent bevel in the Isa Highlands has been identified with the sub-Cretaceous unconformity (Twidale 1966). In most areas the older summit plane occurs distinctly above the more widespread duricrusted erosion surface for which the name 'Australian' has been proposed (King 1951) and which is generally regarded as being of Tertiary age; this formed piedmont and intermont plains which have in turn been dissected into terraces and benchlands. In the Mt Isa area the duricrust remnants cap Cretaceous outliers upon the exhumed older surface.

The long history of subaerial planation on these uplands is also indicated locally by inherited master drainage transgressive of structure as in the Finke system in central Australia (Mabbutt 1966).

Despite the stable tectonic setting, many such desert uplands are flanked by dissected intermont fills, fans, and pediments which indicate periodic sequences of downcutting, planation, deposition, and weathering in piedmont zones (cf. Twidale 1967). Such features in the Macdonnells have been attributed to alternating wetter and drier phases superimposed on a general trend towards increasing aridity during the later Cainozoic and preceding the maximum extension of dune sands (Mabbutt 1966).

Intercratonic Basins

Younger basins of unfolded, mainly weak rocks ranging in age from Mesozoic to Palaeozoic form extensive plainlands around the margins of the Platform. The rock types include thin-bedded limestone and shale which form lowlands with extensive clay soils, and minor sandstones which build plateaux and mesas, generally with less than 170 ft (50 m) of relief. The structural units commonly accord with major drainage basins, as with the Daly and Fitzroy Rivers. The Fitzroy Basin also includes the Limestone Ranges, with unusual development of monsoonal karst on massive reef limestones, with rectangular systems of solution corridors and 'box valleys', and limestone pediments (Jennings and Sweeting 1963). The Barkly Basin has been marginally dissected into the Barkly Tableland, a mosaic of black soil plains and low sandy islands of laterised sandstone with a centripetal interior drainage. In the west of the Platform the Perth and Carnarvon Basins form a narrow coastal lowland with extensive dunefields and alluvial plains, broken by sandstone plateaux up to 350 ft (100 m) high. On the south, Tertiary limestones of the Eucla Basin build the structural Nullarbor Plain, a monotonous surface rising from 170 ft (50 m) above sea level at the cliff margin of the Bight to 600 ft (180 m) at the inland edge. There are no marked valleys or surface drainage lines, but moderately extensive underground systems with large caverns.

Tectonic Relief

Youthful tectonic relief is limited to areas of Cainozoic block-faulting along ancient lineaments, as in the Gulfs region of South Australia at the south-eastern extremity of the Platform. This consists of parallel tilted blocks trending meridionally along axes of the Adelaidean fold belt, and affects a wide range of sedimentary rocks with Archaean granitised sediments in anticlinal cores. Maximum vertical disruption, as measured by the summit plane of the Mt Lofty Ranges, exceeds 2300 ft (700 m). The Yorke and eastern Eyre Peninsulas are also uplifted and tilted blocks, whilst Spencer and St Vincent Gulfs are complex grabens; the fault scarps on the peninsulas face east and those on the Mt Lofty blocks face west, suggesting a broad crustal arch, the crest of which has undergone differential collapse. The movements, which have disrupted a laterised land surface, are geologically youthful, and this is also evidenced by the freshness and lack of dissection of the bounding fault scarps.

Aeolian Sand Surfaces

Large parts of the interior plains of Australia are masked by wind-blown sand, which covers almost 965,000 sq miles (2,500,000 km^2) of the arid zone in roughly equal areas of dunefield and sandplain. Although sand cover is also extensive in the Central Basin, notably in the Simpson Desert, the main areas occur on the Platform and the subject is accordingly treated here as a whole.

It will be seen from Map 1 that the extension of sand surfaces is not simply a reflection of climatic gradients within arid Australia; they occur mainly in lowlands where prior alluvial deposits have been exposed to wind-sorting following the retraction of drainage systems with declining rainfall. Other sources are relict sandy soils associated with laterised granite and sandstone on Tertiary land surfaces.

Sandplain consists of flat or gently undulating expanses of grit-veneered red clayey sands which have undergone only limited aeolian reworking as shown by shallow unsorted horizons. It is associated with sands containing a high content (10–20 per cent) of binding clay, for instance those derived directly from granite, as north of the Macdonnell Ranges, or from weathered land surfaces as on the Old Plateau of the Yilgarn Shield. It commonly forms the margins of dunefields where drainage enters, as north of the Simpson Desert, where wind action may have been hindered by periodic flooding, with its implications for vegetation cover and for the texture of alluvial deposits. Sandplain with regular broad undulations less than a metre high and showing the trend and spacing of the regional dune systems occurs in the north of the arid zone, for instance south of the Barkly Tableland, where incipient dune growth may have been arrested by close vegetation under a relatively moist climate. Finally, the relationship of sandplain and developing dunes in south-west Queensland shows the former to be an initial form, but one which may well persist in areas of limited wind fetch.

Plate 2 Strike range of steeply-dipping Palaeozoic sandstone in central Australia, with summit bevel of possible Mesozoic age. The piedmont plain on the north has an isolated drainage net, characteristic of the arid zone; partly vegetated sand ridges encroach on the south side (CSIRO photo)

By far the commonest dunes are longitudinal ridges (Pl. 2) which are developed on a greater scale in Australia than elsewhere (cf. Madigan 1936; D. King 1960; Mabbutt 1968). These are parallel ridges, generally between 30 and 100 ft (10 and 30 m) high and continuous over tens of kilometres, although occasionally linking in Y-shaped junctions. Their spacing (1000–1300 ft, 300–400 m) and direction are remarkably consistent in any region, but on a continental scale they trend in a vast arc through the Great Victoria, Simpson, and Great Sandy Deserts with extension in an anticlockwise sense and with junctions mainly pointing in this same direction (Map 1).

The ridges generally have vegetated flanks and a crestal belt of live sand with changing slip faces and blowouts; the body of the ridge is commonly asymmetrical, for instance the eastern flank is the steeper in most of the Simpson Desert. The crest sands, as in other dune types, are well-sorted with median diameters 0·3–0·5 mm; the swale sands are less sorted, with a tendency to bimodality. Many ridges have cemented cores resulting from illuviation of clay.

The swales are generally sandy, but may be flat with clay pans near the drainage lines, and there are floors of gibber plain, alluvium, or pan limestone, particularly on the margins of the Channel Country.

Regional trends and directions of elongation are closely but not exactly related to resultants of present-day effective winds (Brookfield, in press), but the palaeoclimatic significance of this is not clear, since the relationship to the formative winds is not known beyond the general fact that longitudinal dunes are the products of closely bi-directional wind regimes without excessive sand supply. The ridges are equilibrium forms as indicated by their constant geometry, for instance the inverse relation between height and spacing, but they have been fossilised in varying degree and there is a progressive increase in the amount of stabilising vegetation from the relatively mobile ridges in the arid core near Lake Eyre to the rounded, completely vegetated forms of the pindan desert slightly beyond the present north-western limit of the arid zone. It would appear that most ridges formed during one or more past periods of enhanced aridity when the arid zone expanded, particularly northwards, about its present core, but without major changes in the continental pressure and wind systems. No conclusions can be stated as to age, but it is known that deflation operated at Lake Eyre between 20,000 and 40,000 years ago (Johns 1962) and that sand ridges extended into what is now the tidal zone near Derby, W.A., some 7000 years ago (J. N. Jennings, unpublished data); the majority of the dunes are likely to be older than a so-called 'mid-Recent arid period' (5000–8000 B.P.) to which some earlier writers had consigned them (cf. Gill 1955).

The sand ridges appear to be the most evolved dune form; they occur in open desert plains free from interference by relief or drainage and they are found towards the eastern margin of the continental high pressure cell, in the area of strongest and most persistent winds, with less regular forms towards the central zone of lighter, more variable winds. This relative maturity is borne out by the deep red colour of the ridge sands, the well-developed clay cores, and by the transition to other forms in areas of continuing sand movement. For instance, chains of small crescentic dunes currently forming along the Finke River channel on the north-west margin of the Simpson Desert pass eastwards into linked crescentic dunes which in turn pass into longitudinal ridges by gradual increase in length of the paired crescentic arms and a decrease in the frequency of transverse links.

Reticulate or network dunes characteristically occur in areas of entering drainage, where the dune net commonly incorporates small claypans, but in some areas, as around Lake Amadeus, the pattern also appears to arise from the intersection of dune trends which are represented separately in adjoining sand-ridge systems (Mabbutt 1968). The least evolved form is the keel-shaped dune, which may or may not show regional alignment with the formative wind. These are characteristic of intermont basins with restricted wind fetch and also occur in the area of more variable winds towards the west of the arid zone, as isolated short ridges in predominant sandplain.

LANDFORMS OF THE CENTRAL BASIN

The unity and shared history of this structural division impose certain common traits on its landscapes. Being a relatively downwarped part of the continent, elevations rarely exceed 1000 ft (300 m) above sea level. The bedrock consists mainly of weak claystones, lithic sandstones, and limestones which have undergone moderate warping at most and which give rise to extensive rolling plains broken by tablelands and mesas rarely more than 350 ft (100 m high). In each basin compartment—the Carpentaria, Great Artesian, and Murray Basins—the structure is expressed in a centripetal drainage pattern directed to a point west of centre, the area of maximum subsidence. Through a combination of climate and tectonic movements the lower basin tracts are characterised by extensive alluvial plains with clay soils reflecting the fine texture of parent materials, and with anastomosing channel systems.

By the middle of the Tertiary Era the Cretaceous rocks of the Basin, together with a partial cover of younger terrestrial sediments, had been planed, deeply weathered, and duricrusted, as with the equivalent Old Plateau surface of the Western Platform. The duricrust here is generally a hard silcrete up to about 30 ft (10 m) thick, depending upon the amount of arenaceous sediments above the non-quartzose Cretaceous beds, and best developed in the central and western areas. It is underlain by a hardened reddish brecciated horizon, also up to 30 ft (10 m) thick, which is the main relief preserver where the silcrete is least massive, as in the north and east. Ferruginisation of the upper profile generally increases northwards and eastwards within the Basin, suggesting a transition towards the laterites of the Eastern Uplands (Langford-Smith and Dury 1965). The lowest horizon consists of pallid rock to a depth of 170 ft (50 m) commonly with a complex zone of ferruginisation towards the base. The duricrusted surface was thrown into shallow folds as a result of block movements in the underlying basement towards the end of the Tertiary Era and has been extensively strip-

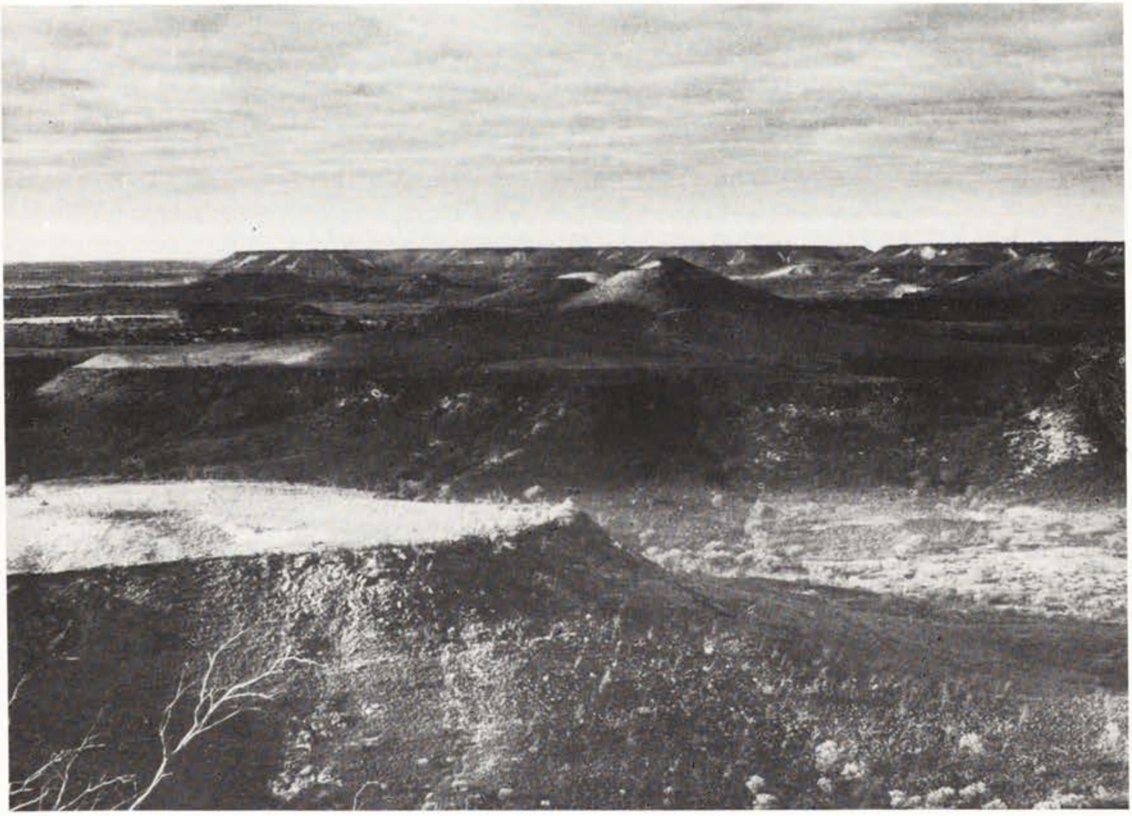


Plate 3 Plateaux and plains characteristic of the Central Basin, Rumbalara Hills, Northern Territory. The summit plane is a Tertiary land surface with silcrete duricrust; the steep slopes below are formed in pallid Cretaceous sandstone (University of New South Wales photo)

ped or dissected into tabular relief (Pl. 3). From this stage, however, each basin compartment has had its own history; accordingly, they are described separately below, with emphasis upon the landforms characteristic of each.

Carpentaria Plains

Two factors which lend character to the Carpentaria Plains (Twidale 1966) are the dominance of the confining uplands—the Isa Highlands in the west and the Einasleigh Uplands in the east—and the down-tilting of the unit northwards beneath the Gulf of Carpentaria. These combine to yield essentially erosional landscapes in the south and along the borders, and depositional surfaces in the central and northern part. The duricrusted surface, here lateritic, survives only locally as low tablelands in the north-west (Donors Plateau) and in the south (Kynuna Plateau) on the gently warped divide against the inland Diamantina drainage. Extensive undulating plains, the 'Rolling Downs', have been fashioned on little-weathered Cretaceous claystone across the south of the area. In the north, the eastern part of the plains is a featureless panfan of indurated and argillaceous sands sloping gently from the Einasleigh Uplands. The central part consists mainly of the alluvial clay plains of the lower Flinders and Leichhardt Rivers, extensively gilgaid and poorly drained, with prominent sump basins in the backplains. The main river channels are slightly braiding, sandy trenches similar to others in northern Australia, but with incised anastomosing distributaries like those of the Channel Country. They develop striking meanders across the tidal coastal plains, a marine terrace formed on a low bench cut into the downwarped lateritic land surface.

Landforms of the Great Artesian Basin

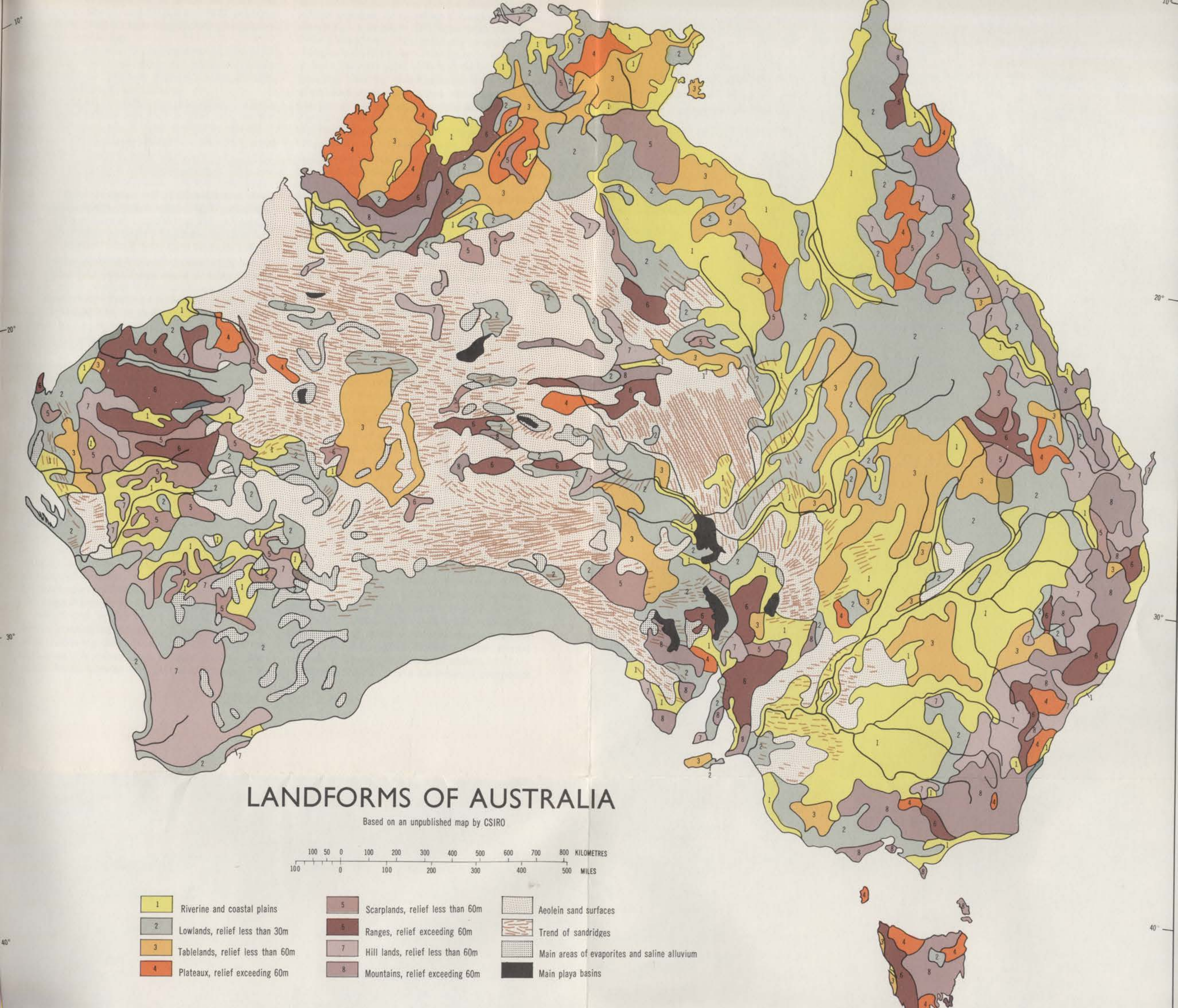
There is a concentric zonation of landscapes expressive of the basin structure, with erosional landforms predominant towards the rim, downslope an increasing proportion of the depositional river plains for which the Channel Country is named, and a central area with the dunefields of the Simpson Desert, already described, in the north, and Lake Eyre and its adjacent plains in the south.

Patterns of upland and lowland in the erosional landscapes have been determined by the gentle folding on mainly north-south lines which deformed the duricrusted land surface and initiated its destruction. The folds range from elongate domes to arches more than 60 miles (100 km) long, as in the Grey Range. The anticlines have mainly been breached and reduced to axial lowlands with flanking duricrusted tablelands, and the amplitude of the folds, a few hundred metres at most, has thereby limited the possible range of relief. In this outer zone the main drainage is often confined to narrow synclinal belts in notably straight floodplain tracts, for instance the Thompson above its confluence with the Cooper. Since the tectonic slope of the basin exceeds the topographic fall, as shown by increasing depositional surfaces towards the centre, structures generally stand higher with respect to baselevel in this outer zone, and relief inversion with synclinal uplands occurs locally, whilst the silcrete was commonly stripped from downfolded tracts prior to alluviation; in contrast, intact or incompletely breached domes may protrude with only moderate elevation above depositional levels in the inner lowlands, where the duricrust may be found at considerable depth beneath the alluvium, as in the Cooper plain at Windorah.

The duricrusted residual uplands are mainly mesas and plateaux, and cuestas locally where dips are above normal, with prominent breakaway-rimmed escarpments facing into axial lowlands and with summits declining gently downdip to the depositional plains which characterise the synclinal tracts. The upland surfaces are of three types: bare, stony tablelands where a well-developed silcrete caps weathered claystone, as in the west of the area; wooded tablelands with dusty red earth soils and minor silcrete outcrop where the brecciated zone forms the capping, as in the north-east; and sandplain with some silcrete where the duricrust is associated with thick sequences of Tertiary sands, as along the Bulloo trough below Quilpie.

The escarpments, formed in the weathered profile, provide classic examples of slope retreat where a hard caprock is undermined in a soft underlayer. Rock fall is best seen where the breakaway is in the massive brecciated zone, with its well-developed vertical jointing; blocky breakdown of silcrete provides the abundant gibbers which mantle the scarp and its fronting lowlands. Saturation of the soft pallid rock may produce mass movements on a scale unusual in a desert, including giant slips of blocks hundreds

MAP No. 1



LANDFORMS OF AUSTRALIA

Based on an unpublished map by CSIRO

of metres in dimension, as in the Mt Felix area (Gregory, Senior, and Galloway 1967), bouldery mudflows, and the slow creep which gives rise to boulder terracettes.

Where erosion in anticlinal tracts has penetrated to fresh rock, there are gently undulating open plains—'Rolling Downs'—with strongly gilgaid gibber-strewn surfaces.

The major river plains are characterised by low gradients, of the order of 1:5000, and by the fine-textured alluvia from the Mesozoic basin rocks. The Channel Country is named for the closely meshed channels of these rivers, which occur in straight-sided tracts between 1000 and 2000 yd (1 and 2 km) wide. They are predominantly deep channels of suspended-load type (Schumm 1963), often with small meanders, which anastomose in regular, rather rectangular patterns; these are crossed by sinuous, shallower flood channels which feed from and into them. The anastomosing channels occasionally link in straight, deep billabongs up to 3 miles (5 km) long, which commonly lie near the margins of the channel tract. The tract forms the highest part of the plain and is distinguished, particularly from the air, by its reddish silty soils and by the many meander scrolls.

The backplain is a featureless expanse of dark, cracking clays, sloping down towards the floodplain margin. Here in the lowest parts are sump basins with particularly heavy soils and gilgai nets; these are regularly flooded from the main channel by distributaries or by back channels associated with billabongs along the plain margins. Prior channel tracts form higher-lying islands in the backplain, and the old channel deposits have commonly been worked into islands of sand dunes.

Widenings of the plain occur in tectonic basins, as below the Cooper-Wilson confluence, and in the lowermost river tracts where the systems flood out within the barriers of their own alluvium; these wider, flatter sectors are characterised by extensive swamp basins fed by large, fan-shaped distributary systems termed 'deltoids' (Whitehouse 1944) which are well seen along the Warrego River below Cunnamulla.

Landforms in the lowest part of the Basin record continuing tectonic subsidence and deposition following deformation and erosion of the duricrust (Wopfner and Twidale 1967). The latter forms cuestas and plateaux between 100 and 170 ft (30 and 50 m) above a plain capped by a hard gypseous layer, which extends northwestwards for more than 250 miles (400 km) from Lake Callabonna at the north end of the Flinders Ranges to the latitude of Oodnadatta and which is more than 60 miles (100 km) wide. This surface was built by rivers entering from the west after fault-subsidence along the south-eastern margin of the Basin, probably at the time of closure of a former southerly exit seawards, and the ancestors of the present playas were sited along its lower, eastern margin. The gypcreted surface has in turn been faulted along the south and west margins of Lake Eyre, where it is dissected into tablelands up to 130 ft (40 m) high. Mound springs occur here and along other fault lines to the west and north. Although the playas occupy deflation hollows, their siting and even their outlines are seen to be partly tectonically controlled. The adjoining gypseous plains have also been wind-eroded on lee margins of the lakes and mantled with two generations of sand dunes, the older with calcareous concretions.

Landforms of the Murray Basin

This Basin is characterised by the dominance of depositional forms and it falls into two main sections, the Mallee in the south-west, an area of aeolian landforms, and the Riverine Plains in the north-east. For purposes of regional description we here treat the Murray-Darling system as a unit, although the Darling catchment falls into the Great Artesian Basin structure.

Mallee. This area of some 39,000 sq miles (100,000 km^2) is a broadly undulating plain less than 350 ft (100 m) above sea level, underlain by Tertiary marine limestone capped by Pliocene sands which formed in the developing estuary of the Murray River. The plain has been deeply trenched by the Murray in its lower course. The surface consists of red sand dunes trending east-west, a complex of longitudinal dunes subjected to periodic erosion and mobilisation during past arid phases (Churchward 1963), and extensively modified into parabolic forms by westerly winds. There is widespread development of calcrete crusts and pans in the swales and also on the flanks of the dunes, attributed by Churchward to the advent of windblown calcareous clay or 'parna' in dry phases between more humid periods of leaching and soil formation.

Riverine Plains. These constitute a composite alluvial fan sloping westwards from points of entry of the larger rivers, from about 570 ft (175 m) above sea level, with an initial gradient of about 1 : 1500 declining to below 1 : 5000 in the lower parts. The fan was built by one or more systems of prior rivers across which the present drainage is superimposed. These are traceable on airphotos due to the woodland vegetation which occupies the sandy channel fills, and with less clarity on the ground as low levee rises with or without a subdued channel depression. They are broadly meandering distributary systems. The patterns of alluvial deposits on the plains follow these drainage lines and the accordant topography of the plains, with coarser-textured materials on the upper plain near the Upland border, silty and loamy alluvium on prior levee slopes, and heavy grey clays with gilgais in the lowermost backplains, which may be swampy.

The prior stream systems have been held to indicate a more humid past because of the amplitude of their meanders and the indicated dimensions of their channels (Langford-Smith 1960). On the other hand, soil layering has indicated a close association in time between the prior channel deposits and sheets of parna derived from areas to westward during arid phases (Butler 1958). Pels (1964) has distinguished between prior and ancestral streams, the latter occupying tracts entrenched below the older plains and being more closely associated with the present river channels, which are in turn incised within the finer alluvial deposits of the ancestral stream tracts. He dates the prior streams as Pleistocene and the ancestral streams as uppermost Pleistocene to Recent.

The present channels resemble the ancestral streams in that they are smaller and more tightly meandering than the prior channels, and they anastomose in elongate rectangular networks due to the deferment of channel links by levee barriers. Billabongs, back-channels, and swamps are numerous in the highly uneven frontages of the present-day channels.

Recent study by Schumm (1967) of channel forms and their sediments has indicated that prior channels were trench-like with abundant coarse bed-loads and that they could reflect periodic high discharges in a semi-arid regime, whilst the smaller but relatively deeper ancestral channels, with suspended-load sediment more prominent, may represent more equable discharges and conditions more humid than now. The present channels, according to Schumm, indicate a slight reversal towards the drier conditions of the prior streams.

There is abundant evidence of drier conditions on the plains in the past. In the south and east this takes the form of small source-bordering dunes on the north-east lee margins of prior channels; these are rounded and vegetated and often show developed soil profiles indicative of current stability. In the drier north-west, where the regime of the Darling is more markedly seasonal and where its tributaries the Paroo and Warrego meet the main channel only in floods at intervals of a year or two, the impress of aridity is clearer and more widespread. Longitudinal dunes trending east-west occur on both sides of the lower Darling, although more notably on the west, and there are large wind-eroded playas, comprising claypans and salt lakes, with crescentic barriers or lunettes on their north-eastern rims. These latter features, generally not more than 30 ft (10 m) high, consist of silt and clay swept from the exposed lake floor during dry stages, or less commonly of sand from the lake beaches. The lunette lakes are commonly aligned in series along deranged former river courses.

These depositional landscapes are not free from tectonic forms; for instance, it is claimed by Hills (1956) that the south-westerly courses of the Lachlan and Darling and the north-east trend of the upper Murray are determined by lineaments in the underlying basement. More definite, however, is the uptilting by some 50 ft (15 m) of the Cadell Fault Block with its east-facing scarp, which has defeated the Murray and forced it to swing northwards upstream from Deniliquin (Harris 1939). Green Gully continues in prolongation of the Murray beyond the point of diversion and has been related by Pels (1964) to a prior stream phase.

LANDFORMS OF THE EASTERN OROGEN

This geologically complex division is a mosaic of cratonic blocks or ‘structural highs’ and intervening basins of subsidence. The blocks consist of highly deformed lower Palaeozoic sediments and volcanics, metamorphosed in varying degree, and intrusive granites; the basins contain a range of moderately folded to flat-lying sedimentary rocks which form structural lowlands or plateaux according to lithology. The meridional or north-westerly grain of the Palaeozoic orogenies which created the belt is still evident in relief and drainage trends, particularly inland. Because of the variety of relief resulting from this structural complexity, regional subdivision is not possible in the space available, and this account will accordingly be confined to general landform traits.

Present relief is a function of differential uplift from the Mesozoic onwards, with episodes of dissection and planation, and the overall distribution of elevation in the upland belt reflects regional contrasts in the amount of this uplift. It has been greatest in the south, where there are extensive uplands above 5000 ft (1500 m) in the Australian Alps and plateaux above 4000 ft (1250 m) in Tasmania and New England and only slightly lower in the Blue Mountains; in contrast, the Queensland sector is lower, and only in the Atherton Tableland are there extensive areas above 2100 ft (650 m).

Prior Planation Surfaces

Many of the plateau surfaces are inherited from prior planation (Pl. 4), as on the granite tablelands of New England (Voisey 1956). Such interior upland surfaces show low gradients and senile drainage features indicative of advanced age, as on the Main Divide in central Queensland where perched Lakes Galilee and Buchanan are the centres of interior drainage systems. Many such surfaces are marked by laterite duricrust or show deep rotting of bedrock, as in the granites of the Snowy Mountains. The upland valleys are generally broad and open, in contrast to incised lower sectors, suggestive of the rejuvenation of older landscapes.

However, such surfaces are found at several levels in any area, and the controversy remains as to whether they represent successive bevels

Plate 4 Tableland forms characterise the Eastern Uplands, as in these bevelled steeply-folded Palaeozoic strata west of Cooktown, Queensland (CSIRO photo)

formed during staged uplift, or one or two master surfaces tectonically disrupted, or merely differences in resistance to erosion, whereby older lineaments have been exhumed. The problem of the origin of Lake George, an interior basin on the Main Divide north of Canberra, is symptomatic. Is the Cullarin scarp west of the lake a fault scarp (T.G. Taylor 1907), in which case the lake may have been dammed by block uplift across a westerly stream course, or is it a fault-line scarp, and the lake lowland merely an erosional feature in which ponding may have occurred through back-tilting, as suggested by Craft (1928)? The question remains open.

Craft (1933 a, b) has invoked faulting and warping to account for differences in elevations of land surfaces of the Blue Mountains and the Monaro, whilst J. L. Davies (1959) and Voisey (1956) regard the stepped surfaces of Tasmania and New England as reflecting staged bevelling due to intermittent epeirogenesis with faulting. On the tablelands west of the Divide, van Dijk (1959) has related stepped pediment embayments of the Yass and Canberra areas to stages in the downcutting of the Murrumbidgee and its tributaries, the embayments extending down-valley as straths separated by nickpoints.

A recent account of the Nogoa-Belyando area in central Queensland (Galloway 1967a) reveals the possible complexities. The oldest land surface recognised here is of Mesozoic age, a surface of appreciable relief which was buried beneath basalts in the lower Tertiary. This lava cover was stripped following uplift and rejuvenation of drainage, and over large areas the Mesozoic surface was exhumed, albeit with somewhat reduced relief. Planation was resumed, but the eventual formation of an early Tertiary surface of low relief was equally the result of deposition in lowland areas. This Tertiary surface, both erosional and constructional, was deeply weathered and duricrusted. Renewed erosion set in, the Tertiary weathering profiles were stripped or dissected into tablelands, and relief features on the more resistant rocks of the uplands were rejuvenated. At least two further episodes of deposition have followed this erosional phase, although without further deep weathering.

Structural Plateaux

Other upland levels are purely structural, the expression of little-disturbed resistant strata of the basins. The Hawkesbury Sandstone of the Sydney Basin, upwarped in the Blue Mountains and in the coastal plateaux without important folding, yields bold plateau relief through which the main rivers pass in deep gorges. The tabular relief of eastern Tasmania is largely the expression of dolerite sills in little-disturbed strata, in strong contrast to the rugged country formed on dissected fold structures in the western half of the island (J. L. Davies 1967).

Volcanic Landscapes

An additional plateau element is contributed to the relief by basalt cappings which form extensive upland plains from Queensland to Victoria. Almost the whole length of the belt was subjected to volcanism at some period during the Tertiary, and activity has persisted into Pleistocene and Recent times in northern Queensland and western Victoria. As evidenced by the auriferous 'deep leads', the lavas often drowned landscapes of appreciable relief and so effected a general levelling which in many areas was emphasised by planation and laterisation during the early Tertiary (Voisey 1956; Galloway 1967b). Little remains of initial volcanic forms in such areas. These older basalts have since been extensively dissected and stripped following uplift with minor deformation; in many watershed areas they remain as broad plateaux, as in the Liverpool Range; elsewhere, as in the Blue Mountains they have been reduced to widely-separated mesa cappings. Erosion of trachytic plugs has produced the spectacular forms of the Warrumbungles and Glass House Mountains. Hence, over large areas of the uplands the present-day relief has been exhumed from beneath a former lava cover and certain transgressive drainage elements, for instance the upper Hunter River, are explicable as having been superposed.

The older basalts are of considerable importance for the fertility of the soils formed on them. In contrast, the areas of most recent volcanic activity have little-weathered basalt surfaces with freshly preserved details of the eruptive centres and of the lava flows. Scoria and lava cones, explosion craters and maars, flow-front scarps, tumuli, lava caves, and many other features have been described from western Victoria (Ollier 1967) and from the Hughenden area of north Queensland (Twidale 1966). Where such flows entered valleys, as in the

Loddon and Campaspe valleys of Victoria and the Einasleigh valley in Queensland, drainage diversion has occurred, often with the initiation of lateral streams along the flow margins, with eventual relief inversion through incision of the channels into the former valley sides.

Glaciated Landscapes

The Uplands contain the only parts of Australia to have been directly affected by Pleistocene glaciation, at a time when mean annual temperatures were some 10°C lower than today. In Tasmania, more than 1900 sq miles (5000 km^2) were glaciated. The central plateau above Lake St Clair was occupied by a small ice sheet which scoured innumerable small rock basins, whilst its outlet valley glaciers eroded valley troughs with hanging tributaries, rock steps, and lake basins, and formed moraines in the piedmont zone. Cirques formed on the ranges in the west, as in the Frankland Range. In the Snowy Mountains a glacier occupied the upper Snowy valley down to 5500 ft (1675 m) (Galloway 1963), but by far the most striking landforms in this area are the cirques, with their tarns and morainic loops, incised into the lee side of the summit ridge from Mt Townsend to Mt Twynham. Both in Tasmania and in the Australian Alps, these glacial features are now regarded as marking stages of a single glacial episode which is correlated with the last advance of the Würm ice elsewhere.

Periglaciation was extensive beyond the ice margins; in Tasmania, for instance, its traces are found down to 1500 ft (450 m), and more than one-fifth of the island must have been subject to strong frost action. It takes the form of stone polygons, solifluction mantles, and block streams at higher levels in areas of dolerite occurrence. Periglaciation also affected the Snowy Mountains down to 3500 ft (1075 m), and higher summits everywhere in the Uplands as far north as New England. The evidence again consists of solifluction phenomena and pattern ground. The lower limit of periglaciation is difficult to ascertain here, since the solifluction deposits are confused with widespread slope mantles and soil layering developed in past episodes of drier climate (Butler 1967).

Periglaciation in a mild form persists in Tasmania above 3300 ft (1000 m), as shown by active sorting of stone nets through frost heaving, and in the area immediately below Mt Kosciusko, where snow-patch erosion is taking place and where terracettes are being actively developed.

ACKNOWLEDGMENTS

The author gratefully acknowledges the help of Kevin Maynard in drawing the text figures. Map 1 is based on an unpublished map prepared by Bryan Ruxton and Ernst Loeffler of the CSIRO Division of Land Research.

3

SOILS

G. D. HUBBLE

Over the continental area of almost 3 million square miles, extending from the tropics to mid-southern latitude, Australia has a great variety of soils and soil-forming environments. Climate varies from alpine and humid tropical with annual rainfall of 152 to 432 cm, through the sub-humid and semi-arid of both summer and winter rainfall zones, to the arid inland deserts. Rocks of all types and degrees of weathering provide a full range of soil parent materials; elevation and topography range from steep mountain slopes to low plains; and there is a varied and, in many respects, distinctive vegetation including eucalypt and acacia-dominant forests and woodlands, and extensive grasslands, shrub steppes, tropical rainforests, and heaths.

Most of the major soil groups (Prescott 1931; Stace *et al.* 1968) have equivalents in some other part of the world (Stephens 1950); yet the soil cover of the continent presents a number of features that together give it some distinctive character in comparison with those of the northern hemisphere. Among these are:

1. generally low nutrient status with widespread and severe deficiencies of phosphorus and nitrogen, and varying deficiencies of several trace elements (see Chapter 21);
2. poor physical condition of surface soils which, over large areas, are massive or weakly structured with low macroporosity, set hard on drying and tend to surface sealing;
3. large areas of soils with strongly-weathered or differentiated profiles, particularly those with strong texture contrast;
4. lack of correlation of the distribution of many soils with climate, especially in the sub-humid and drier regions (Jackson 1957); and
5. the prominence and variety of soil micro-relief or gilgai (Hallsworth, Robertson, and Gibbons 1955)—the curious patterns of mounds and hollows with associated soil profile differences which affect both the distribution of plant species in the native vegetation and the growth of crops.

SOME FACTORS CONTROLLING SOIL CHARACTER AND DISTRIBUTION

The explanation of some of these features lies in the long geomorphic and weathering histories of the major landsurfaces leading to the progressive degradation of soil materials. Much of the surface of the continent dates from Tertiary geological times when widespread peneplanation and intense weathering produced a cover of deeply weathered laterite profiles, in places reaching the extreme thickness of 200 ft (61 m). The character and distribution of the present-day soils depend on the extent of later modification and stripping of the ancient soil cover and the geomorphic and pedological history of the younger land surfaces formed since.

At one extreme are the extensive low tablelands of the stable Great Plateau, which comprises much of the western two-thirds of the continent, and the widely-distributed smaller plateaux along the belt of eastern highlands. These landscapes are dominated by variously modified relict lateritic soils—both the podzolic form with its prominent horizon of ironstone nodules or massive laterite, and the red and yellow earthy forms, either sandy or clayey, with varying pisolitic, cellular, or massive laterite. At the other extreme are such landscapes as the undulating ‘downs’ of central western Queensland—a modern peneplain with a cover of moderately fertile self-mulching grey and brown clays formed from underlying fresh Cretaceous sediments following complete stripping of the old weathered profile. Between these extremes are large areas of soils formed *in situ* on the deeper horizons of the weathered profile exposed by truncation, and on lower plains of redistributed weathered detritus, or on mixtures of these materials and fresh parent rock. The characteristics of these old materials have been the dominant factor in subsequent soil formation on them (Stephens 1946), modifying and largely overriding the expected effects of climate.

The earlier intense weathering and leaching have largely determined the nutrient status and fertility of the relict and younger soils formed wholly or dominantly of materials of the deep weathered profile (Stephens 1951). In addition to the leaching of bases and some trace elements it seems likely that much of the phosphorus of the parent rock was lost at the same time (Wild 1958). The concentration of molybdenum and zinc in lateritic nodules (Oertel and Prescott 1944) is also undoubtedly a factor in soil deficiencies of these elements.

A number of more recent influences deserve mention for their effects on the present soil cover. Important among these are widespread salinisation, solonisation, and solodisation. The salinisation has been considered to be the result of atmospheric accession of oceanic salts (Prescott 1931) and to have occurred mainly during the Recent Arid period (Downes 1954), but later studies in south-eastern Australia (Hutton and Leslie 1958) have shown that the proportion of oceanic salts in rain water falls rapidly with distance from the coast. Whatever the source of the salts, large areas of soils in the sub-humid to semi-arid hinterland show the effects of solonisation in their poor physical properties and low fertility. Many still contain large amounts of salts.

In many parts of the continent, major landscapes of widely different ages have been affected by later major and minor episodes of erosion and deposition alternating with periods of stability during which soils have formed on the newly-established surfaces. These periodic phenomena (Butler 1967), mainly the result of climatic changes, have usually affected only parts of the landscapes and have further complicated soil distribution. They are best documented in south-eastern Australia but are undoubtedly more extensive in the arid regions where deflation accompanied by the accumulation of dune systems and sand sheets have played a major role in modifying old soil formations and initiating new ones.

The more fertile Australian soils occur mainly in the broad belt of eastern highlands extending from Tasmania to Cape York Peninsula. In this geologically complex zone, dissection following earth movements and widespread outpourings of basalt has exposed a wide range of fresh rock materials to soil formation. Under the moister regimes in this zone the influence of climate on soil distribution is more apparent in some zonal arrangement inland from the coast. However, over the continent as a whole, and even in the eastern highlands, soil parent materials and past conditions have been the main determinants of soil character and distribution.

Generally the native vegetation seems to have been more a dependent variable than an important factor affecting soil formation. Low soil nutrient contents, low and erratic moisture supply, and long isolation of the continent, have produced specialised xerophytic plants that seem to have had very limited effects on soils through nutrient cycling and litter return, but few detailed studies have been made. The generally dry soil surface conditions, poor meso-fauna, and woody nature of much of the litter have tended to limit its incorporation in the surface soil.

Until European settlement less than two hundred years ago, Australian soils were undisturbed and apparently in equilibrium with their environments, although in many regions the balance seems to have been a very delicate one. Pastoral and agricultural development have upset this, greatly changing soil dynamics and leading firstly to losses of organic matter and some further nutrient depletion but mainly to widespread accelerated erosion. This trend is now being reversed in many areas through the increasing use of fertilisers, the development of sown pastures based on introduced legumes and grasses, irrigation, and the establishment of forest plantations. Some significant regrading of soils under fertilised pastures and forests is already evident.

AUSTRALIAN SOIL GROUPS

Of the forty-three groups of Australian soils at present recognised only thirty-two occur as dominants in the soil units shown in Map 2. The following statement concerns only these dominant groups and is limited to their essential characteristics and the more interesting features of their occurrence and use. Groups of lesser importance that occur as associate or minor soils in the units mapped—although some occur as dominants in patterns too small to be shown separately at this scale—are listed in the text and map legend to preserve the reference numbers used in *A Handbook of Australian Soils* (Stace *et al.* 1968). Full descriptions of the morphology of all the soil groups with supporting laboratory data and colour illustrations of representative profiles are presented in the *Handbook*.

Soils Showing No Profile Development

1. *Solonchaks.* These highly saline soils lack distinctive morphology except for their characteristic surface features which vary with soil texture and salt content. They include whitish fragile crusts and flakes, loose puffy moist soil containing salt crystals, and polygonally cracked, polished dense crusts of sodium clays grading below into massive or blocky saline soil. Their subsoil characteristics are largely those of the parent materials which are mostly sediments.

Two main forms of solonchaks are common. Those of the coastal salt pans and estuarine plains are usually clays with prominently mottled grey, ochreous, and red gleyed subsoils over the shallow, saline groundwater. Those associated with the claypans, playas, and dry valley floors of the semi-arid and arid lands are generally brown to grey sandy clay loams to clays that are seldom moistened below 10 to 15 cm depth.

The solonchaks are infertile soils and vegetation is either absent or restricted to patches of such halophytes as saltwater couch grass, samphires, and saltbushes which provide very little grazing. The extensive claypans common in the semi-arid grazing lands can be reclaimed by contour or checkerboard furrowing to hold water and seed on the surface, and locally leach some of the salt.

2. *Alluvial soils.* Alluvial soils largely retain the textures, sedimentary fabric, and layering of their parent materials which include riverine, deltaic, lacustrine, and alluvial fan deposits. They are commonly near-neutral in reaction, moderately porous, and range in texture from gravelly sands to clays. Soil profile development is mainly restricted to the formation of a fairly thick, darker, A_1 horizon. Most are sandy to loamy soils, and moderately fertile except when formed from materials eroded from severely-weathered soil formations.

Alluvial soils occur in all parts of Australia but generally in areas too small to be shown separately on small-scale maps. The Burdekin River delta on the north-east coast is one of the larger occurrences: its soils have relatively high phosphorus contents and are highly productive for sugar cane.

3. *Lithosols.* Lithosols are stony or gravelly soils lacking profile differentiation except for the formation of a darker A_1 horizon. Generally they are formed from hard rocks and gravelly sediments. Characteristically they are shallow soils, but in many areas weathering and soil formation extend to depths of one or two metres. Soil texture and fertility are dependent on the nature of the parent rocks and degree of weathering. Generally they are leached, mildly acid, sandy and loamy soils of low fertility and carry woodland or forest cover. Some areas have yielded valuable timbers but most support sparse grazing only.

Most occurrences are on the steep slopes and narrow crests of hilly to mountainous lands found in all States.

4. *Calcareous sands.* Deep profiles of calcareous sands are found on the younger systems of shelly beach ridges and coastal dunes associated with extensive beaches along lower parts of the coastline of the southern half of the continent. These soils are mildly acid to alkaline and show no profile development except for a moderately thick A_1 horizon of grey-brown to grey sand with some organic matter and some leaching and deposition of secondary carbonates in the deeper subsoil. Isolated occurrences under rainforest vegetation along the north-eastern coastline have dark brown surface soils up to 2 ft (61 cm) thick.

Large areas of the calcareous sands carry a shrub vegetation and are virtually unused. Where the cover is dominantly grassy—as on the islands of Bass Strait and parts of the South Australian coast—sheep and cattle have been grazed and coast disease, due to deficiencies of cobalt and copper, has proved a problem (see Chapter 25). This is now corrected with fertilisers or by direct treatment of the animals. Wind erosion is a serious hazard and drifts of bare sand quickly develop when the cover is broken.

5. *Siliceous sands.* Deep siliceous sands, leached and neutral to acid in reaction, are widespread and are associated with environments ranging from the moist coastal fringe to those of the deserts. Four distinct sub-groups are recognised, three of them occurring as dune formations. Profile differentiation is generally restricted to a varying weak to prominent development of an A_1 horizon.

Pale siliceous sands are associated with the older dune systems with heath cover occurring mainly along the coastline of the northern half of the continent. Their brownish grey surface soils are underlain by very pale yellow to whitish leached fine sands which often continue to depths exceeding 20 ft (6 m).

Coarse gritty sands occur as deep sedentary and colluvial accumulations weathered mainly from acid granites in the humid to semi-arid regions. They are also strongly leached and pale yellow to whitish below a grey-brown coarse sand A horizon, but are generally less than 6 ft (1·8 m) deep and the subsoils are both increasingly gritty and clayey with depth.

Brown siliceous sands occur mainly as scattered groups of modified dunes of alluvial sands in the shallow valleys and riverine plains of the sub-humid to semi-arid inland. They are generally loamy sands with a weakly defined A horizon overlying light grey-brown to reddish-brown sands which become more clayey and yellowish with increasing depth.

Red siliceous sands are characteristic of the extensive sandy deserts of Central and Western Australia. They are uniformly-coloured, loose to weakly coherent sands leached free of salts and carbonates and may have an increasing clay content at depth. The crests of the dunes are bare but a shrub vegetation usually covers the slopes.

All of the siliceous sands have low to extremely low fertility due to several nutrient deficiencies and droughtiness and are very liable to wind erosion. In the irrigation areas of south-eastern Australia small areas of brown sands are used for citrus crops: elsewhere the sands provide only sparse grazing or are unused.

6. *Earthy sands.* The earthy sands have uniform profiles of red, or sometimes yellow, massive, coherent sands and sandy loams with a characteristic 'earthy' appearance on the broken face due to coating and bridging of sand grains by clay and iron oxides. They are very porous, acid soils, range from shallow to deep, and have weakly defined A horizons of dull brown to reddish sand. Some contain scattered ferromanganiferous nodules.

The main occurrences lie in a broad arc from south Western Australia through the Northern Territory to north-eastern Queensland. Most are on extensive sand plains and low tablelands, as in the Gibson and Great Sandy Deserts of Western Australia where large areas are underlain by ironstone nodules or laterite at shallow depths, or on plains bordering ranges as in central Australia.

They are infertile soils with very low nutrient status. The large areas in the deserts are unused but elsewhere they provide some grazing for cattle and sheep on sparse vegetation which includes Acacia shrublands and arid hummock grasslands of spinifex.

Soils Showing Minimal Profile Development

7. *Grey-brown and red calcareous soils.* Where limestones and highly calcareous sedimentary rocks are exposed in the arid and semi-arid regions, shallow sedentary soils have developed, containing much finely-divided carbonate and fragments of parent rock.

These soils vary from grey-brown to red and are soft, powdery or weakly structured, calcareous loams, clay loams, and light clays up to about 15 in. (38 cm) thick. Texture and structure vary with depth from pulverulent massive loams at the surface to weak to moderate medium blocky clays in the subsoil.

Generally they carry a shrub steppe vegetation. The largest area—the Nullarbor Plain—is largely unused but other occurrences in central South Australia are sparsely grazed. The soils are very susceptible to wind and water erosion.

8. *Desert loams.* Desert loams have weakly-differentiated profiles consisting of 5 to 10 cm of brown to reddish, neutral to alkaline, loamy surface—usually massive with a thin crust—grading into a paler, vesicular A_2 horizon clearly separated from generally red, finely-structured alkaline clay subsoils. Commonly the surface is protected by a cover of dominantly siliceous ironstained gravel up to 6 in. (15 cm) in size, and smaller gravel occurs through the A horizon

with lower amounts in the subsoil. Some finely divided carbonate may be present in the surface soil; the clay B horizons contain both carbonates and gypsum and are saline and moderately solonised. They are moderately deep soils.

Desert loams occur in arid regions with generally less than 10 in. (254 mm) rainfall, on wide alluvial plains and associated low stony uplands. The largest areas are in northern South Australia extending into adjoining States. Soil fertility is low, being limited by moisture supply, and the shrub steppe vegetation of saltbush and bluebushes provides only sparse grazing for sheep and cattle (see Chapter 17).

9. *Red and brown hardpan soils.* Important areas in the arid lands of central Western Australia and lesser areas in South Australia and south-western Queensland have shallow to moderately deep profiles of red, massive earthy soil abruptly overlying indurated pans apparently cemented by deposition of silica and clay.

The earthy soil above the pan is very porous, acid and non-saline, varies from 2 to 5 ft (61–152 cm) thick, and generally is of uniform texture ranging from sandy loam to sandy clay loam. Some rounded siliceous gravel with a coating of desert varnish often occurs on the surface. The underlying reddish-brown to red hardpan is typically laminar with coarse sandy texture and vesicular pores alternating with finer, denser bands and irregular siliceous crusts. Black manganiferous segregations occur as flecks within the pan and as coatings on its surface and cleavage faces.

These soils occur mainly on gentle slopes and plains below old plateau remnants. Their fertility is low and they are used only for very sparse grazing of the ephemeral herbage and shrub cover. Associated Acacia shrublands provide valuable drought feed.

Plate 5 Grey and brown members of the grey, brown, and red clays occurring in the depression and on the bank of melon-hole gilgai common in brigalow (*Acacia harpophylla*) forest (CSIRO photo)

10. *Grey, brown, and red clays.* Among the more important Australian soils is a range of uniform clays that crack deeply on drying and characteristically have a self-mulching granular surface grading into coarser lenticular structured subsoils with large slip planes. Their major occurrences are on broad riverine plains and on gently rolling uplands overlying sedimentary rocks, and they form a broad arc through the sub-humid to arid lands of the eastern States from south-eastern South Australia to the Northern Territory. The larger areas are true grasslands dominantly of Mitchell and Flinders grasses (see Chapter 17), especially important to the grazing industry for wool production. In the arid lands they support a shrub steppe of saltbushes and bluebushes: in eastern Queensland and northern New South Wales important areas carried forests of the acacia species, brigalow and gidgee.

Typically they are brown and grey clays—the latter with some ochreous and rusty spotting where surface drainage is poor—but red-brown to red soils are common in the more arid occurrences. Soil reaction is generally slightly acid to slightly alkaline at the surface, becoming moderately to strongly alkaline in the subsoil which is also moderately saline and usually contains small nodules or soft segregations of carbonates and some gypsum, especially in arid regions. However, a high proportion of the clays of the brigalow lands and some of associated grasslands are alkaline and calcareous in the upper profile, becoming strongly acid below, or are strongly acid throughout.

Plate 6 An oblique aerial photograph of melon-hole gilgai characteristic of the grey and brown clays of the (cleared) brigalow forest lands of eastern Australia. A ring of herbaceous plants marks the margin of ponding in the large depressions following earlier rains: the banks are almost bare.

The clays vary from moderately to extremely deep and are generally moderately fertile although phosphorus contents particularly are very variable and usually low. The clays of the brigalow lands have high total nitrogen constants possibly due to symbiotic fixation of atmospheric N in root nodules. Gilgai is a feature of most of the soils, varying from a weak development of small puffy mounds with carbonate nodules on the surface to the large banks and depressions of the melon-hole formations of the brigalow and gidgee forest lands with a vertical interval of 2 to 6 ft (61–183 cm) and banks and depressions up to 60 ft (18 m) across (Pls. 5 and 6). In addition to their widespread use for grazing for sheep and cattle the clays have proved highly productive under both dry and irrigation farming for a wide range of crops and for sown pastures.

The Mildly Leached Dark Soils

11. *Black earths.* Black earths are uniform clay soils similar in general form to the grey, brown, and red clays but dark grey, very dark brown, or almost black in the upper profile. They are also much less extensive in area but widely distributed in the 20 to 40 in. (508–1016 mm) rainfall zone between southern Tasmania and north Queensland. The main occurrences are on plains of clay alluvium and low hilly lands of basic igneous rocks and sedimentary rocks of high calcium status. They are essentially grassland soils, the native vegetation being tall grass or open grassy woodlands.

The surface clay is self-mulching, granular, and slightly acid to neutral, grading through blocky clay to alkaline and calcareous subsoils with well-developed lenticular structure and shear planes. These soils crack deeply on drying. The shallower sedentary soils less than 2 ft (61 cm) thick contain little salt and carbonate segregations and below the dark soil grade through several centimetres of brown clay into friable weathered parent material. The deeper soils on colluvium and alluvium have about 3 ft (91 cm) of dark clay, with soft and nodular carbonate segregations and low to moderate salt contents in the lower part, merging into yellowish brown or light grey-brown deep subsoil clays with carbonates and moderate salt contents. Gilgais are characteristic features.

The black earths are among the more fertile arable soils of Australia although phosphorus contents range from high to low and deficiencies of zinc and sulphur sometimes occur (Chapter 21). Their total nitrogen and organic contents are moderately high but with continued cropping nitrogen deficiency develops. Large areas still provide valuable native grazing lands for sheep and cattle. The more favoured areas, for example the Darling Downs of south-eastern Queensland, are now intensively farmed using moisture conserving practices and some irrigation and are highly productive for a wide range of summer and winter crops including sorghum, maize, cotton, wheat, barley, linseed, and lucerne (see Chapter 12).

12. *Rendzinas*

13. *Chernozems.* Chernozems are of minor importance, apparently being limited to exposures in sub-humid regions of basic parent materials that weather to textures not heavier than light clay. Small areas are irregularly distributed in the sub-coastal lands from south-eastern South Australia to northern New South Wales.

They are generally similar to the black earths but have much lower clay contents, soft friable consistence, and are much more permeable. Typically the surface soil is deep, dark grey-brown to black, and ranges from fine sandy loams to heavy clay loams with strong fine crumb to polyhedral structure. It grades below into grey-brown to grey deep subsoil which is usually not heavier than light clay, has blocky structure, and contains a few carbonate segregations or nodules. Chernozems are seldom more than 40 in. (102 cm) deep and grade from slightly acid at the surface to alkaline in the deep subsoil.

The chernozems are very fertile soils and in places have produced high yields without the addition of phosphate fertilisers. Originally they carried woodland vegetation and are now used for a wide range of crops, irrigated sown pastures and fodders.

14. *Prairie soils.* Prairie soils are also limited to small occurrences in the sub-humid regions of southern Queensland and south-eastern Australia.

They are weakly leached, mildly acid to mildly alkaline soils with moderately organic dark A horizons of friable loam to light clay of crumb, granular, or blocky structure. The heavier soils have the thicker A horizons grading into yellow-grey, yellow-brown, or reddish blocky clay subsoils. Where the surface soil is loamy it is usually only 6 to 8 in. (15–20 cm) thick with gradual to clear boundary to brighter, medium or heavy clay subsoils which have firm moist consistence and medium blocky to prismatic structure. The profile is normally 30 to 40 in. (76–102 cm) deep and lacks carbonate segregations.

The prairie soils are fertile and highly productive for sown pastures and a range of crops, often with little addition of fertilisers.

15. *Wiesenboden*

The Mildly Leached Brown Soils

16. *Solonetz*

17. *Solodised solonetz and solodic soils.* These soils are found in all States, mainly within the 15 to 40 in. (381–1016 mm) rainfall zone, with large areas in sub-coastal regions of Queensland, south-eastern Australia, and the south-west of Western Australia. They occur on extensive plains, valley floors, mid to lower hillslopes, and lower areas of the coastal plain overlying parent material ranging from medium-textured alluvium to acid and intermediate igneous rocks. The native vegetation is usually woodland or forest.

The soils have moderately acid, grey to brown, loose sandy and platy loamy A horizons with a strongly bleached A_2, sharply separated from dense clay subsoils (Pl. 7) that are acid in the upper part but become strongly alkaline below where there are moderate contents of exchangeable sodium. This deeper subsoil usually contains some carbonate nodules or soft segregations and low to moderate accumulations of soluble salts. The clays are variously coloured grey, grey-brown, yellow-brown, and red or mottled, with strongly developed structure ranging from coarse columns and prisms (solodised solonetz) to blocky (solodics). Ferromanganiferous nodules and segregations may occur in the A_2 horizon and top of the clay.

In the natural state these soils are generally infertile owing to severe deficiencies of nitrogen and phosphorus, varying lesser deficiencies of trace elements, calcium, and in some areas, potassium, and poor moisture relationships. They are used mainly for cattle and sheep grazing of the native herbage, but considerable areas are now being developed for sown pastures and some cropping (see Chapter 12). With adequate fertilisation they are moderately productive, and pastures based on subterranean clover in the south and Townsville lucerne in northern Australia are transforming the use of the poorer soils. Some areas of the better soils are cultivated for cereal crops. In southern Queensland large areas of the virgin forests are reserved for the production of cypress pine.

18. *Soloths*. These soils have texture-contrast profiles with bleached A_2 horizons very similar to those of the solonetz and solodic soils, but they differ in being moderately to strongly acid throughout the solum. The boundary between the A and B horizons is also commonly not as sharp and the clay subsoils usually have a stronger medium blocky structure, a lower degree of sodium saturation, and are not as tough or hard. Although the acidity and lower base saturation suggest stronger leaching of the deeper subsoil, many have moderate soluble salt contents and the acidity probably inherited from

Plate 7 Solodised solonetz showing the distinctive coarse columnar structure and bleached A_2 horizon penetrating between the columns. The strong and abrupt texture change from A to B horizons is common to a wide range of texture-contrast soils (CSIRO photo)

pre-weathered parent materials.

The soloths occur mainly as small areas associated with the solodised solonetz and solodic soils but extending into the moister subhumid regions with annual rainfall as high as 50 in. (1270 mm). They have similar nutrient deficiencies but higher potential productivity owing to their more favourable moisture regime. In the natural state they carry forest or woodland and have been used mainly for grazing, but increasingly are being used with fertilisers for sown pastures and some cropping.

19. *Solonised brown soils.* These soils—formerly called mallee soils because of the dominance of mallee eucalypts in their low shrubland vegetation—occur extensively in the 10 to 16 in. (254–406 mm) winter rainfall zone from south-western Australia to western New South Wales (see Chapters 14 and 15).

They vary widely from red-brown deep sandy soils to red-brown, brown, and grey-brown sandy loams to clay loams increasing in texture with depth to sandy clay loams and clays. All contain large amounts of carbonates both throughout the fine earth and as soft to hard segregations forming prominent subsoil horizons often with pans or nodule concentrations in the upper part. They are commonly massive, and neutral to alkaline at the surface, becoming strongly alkaline in the subsoils which usually contain much soluble salt and sometimes manganiferous segregations.

These soils have low organic contents and low inherent fertility due to phosphorus and nitrogen deficiency. Following clearing they have been widely used with additions of superphosphate for mixed farming on a bare fallow-cereal crop—volunteer annual pasture rotation in which medics are often sown with the crop and contribute to the pastures grazed by sheep. Their productivity is usually limited by moisture deficiency, and wind erosion is a hazard, especially on the lighter soils. Where irrigated, as along the Murray River, they can be highly productive for vine, deciduous fruit, and citrus crops but water-table and salinity problems have developed in many areas and there are some zinc and manganese deficiencies.

20. *Red-brown earths.* The major areas of these soils also lie in the winter-dominant rainfall zone of south-eastern Australia under 16 to 25 in. (406–635 mm) annual rainfalls. Smaller areas occur through north-eastern Australia with summer-dominant rainfall up to 35 in. (889 mm) per annum and under drier conditions in north-western Queensland and Western Australia. They have formed on a variety of parent materials including old alluvia, fine metamorphic rocks, and intermediate igneous rocks, under woodland vegetation (see Chapter 12).

They have reddish-brown to grey-brown, massive or weakly structured, loamy A horizons, sometimes with a paler A_2, with an abrupt to clear boundary to reddish-brown to red clay subsoils of strong medium blocky to prismatic structure. The surface soil sets hard on drying and is mildly acid to neutral, reaction becoming alkaline in the B horizons which usually contain soft or nodular carbonate segregations and some soluble salts in the lower part. Profiles range from 30 to 50 in. (76–127 cm) thick.

In the natural state red-brown earths are moderately fertile soils but deficient in phosphorus and nitrogen. They are widely used for mixed farming based on wheat and sheep, cattle raising on native grazing lands, and some irrigated horticulture and sown pastures. With moisture conservation and additions of superphosphate they are moderately productive but liable to erosion which has reduced fertility in farmed lands through loss of the more organic surface soil.

21. *Non-calcic brown soils.* These soils are very similar to the red-brown earths but lack paler A_2 horizon, and have neutral to mildly alkaline B horizons with lower base saturation and no carbonate segregations.

Their loamy surface soils are darker with higher organic content than the red-brown earths, have weak blocky to crumb structure, and, although friable when moist, set hard on drying. There is a clear boundary to reddish brown to red or weakly mottled clay subsoils which characteristically have moderate medium blocky structure. Generally they are thinner and more leached than the red-brown earths, varying from 20 to 36 in. (51–91 cm) deep.

They are fairly widely distributed in south-eastern and eastern Australia as smaller areas associated with the red-brown earths on the moister side of their climatic range and have the same range of uses. Their inherent fertility is a little higher but phosphorus and nitrogen are deficient: the native vegetation is woodland and in the north-eastern occurrences is used for beef cattle grazing.

22. *Chocolate soils.* The chocolate soils have restricted area and distribution and occur mainly on basalt in the sub-humid tablelands of northern New South Wales with scattered smaller areas in south-eastern Queensland. Typically they are crumbly, dark chocolate to brown friable clay loams and clays grading into grey-brown to yellowish or reddish chocolate firmer clay subsoils. Reaction is moderately to mildly acid at the surface, becoming neutral with depth. Floaters of basalt may occur throughout the soil which varies from 2 to 5 ft (61–152 cm) thick. They are moderately fertile but where used for cereal crops, sown pastures, and such crops as potatoes and peas they respond to phosphatic and nitrogenous fertilisers. Under native grazing lands their carrying capacity is low to moderate.

23. *Brown earths*

Soils with Profiles Dominated by Sesquioxides

24. *Calcareous red earths.* These soils are associated with red earth of the arid regions but are much smaller in area. They occur on undulating plains often formed from red materials eroded from older lateritic landsurfaces. In western New South Wales and Queensland they form part of the red mulga country.

They are red, massive but porous, sandy and loamy soils with characteristic earthy fabric, weak horizon differentiation and some carbonates in the deep subsoil. Below the slightly darker dull red-brown surface soil of low organic content, changes are gradual with texture usually increasing to sandy clay loam, sandy clay or light clay in the deep subsoil which may contain a few ferromanganiferous nodules. Reaction grades from mildly acid to alkaline in the calcareous subsoil. Carbonates occur as isolated soft segregations or nodules, or larger diffuse patches, but usually in small amounts and at depths varying with texture from 2 to 5 ft (61–152 cm).

Their fertility is limited by the arid environment and by major deficiencies of phosphorus and nitrogen. Generally they are used only for sparse grazing by sheep and cattle.

25. *Red earths.* Red earths cover large areas and are widely distributed north of an arc from south-eastern New South Wales, through northern South Australia to Geraldton in Western Australia. They occur in all climatic zones from arid to humid, on materials ranging from red earthy detritus to quartzose sandstones and granite, and on undulating plains, old stream levees, hill slopes, and modified tableland remnants of old land surfaces. The native vegetation includes arid shrublands, eucalypt woodlands and forests, and rainforests.

Although they vary considerably, the red earths are essentially red-brown to red, porous sandy to loamy soils with earthy fabric, weak horizon differentiation, and gradually increasing texture with depth. Texture usually reaches a maximum of sandy clay loam to clay a metre or two below the surface; the deeper subsoil of very deep types is commonly very light grey mottled with red and has polyhedral structure. Surface soils range from massive, hard-setting forms with low organic contents to dark crumb-structured types with high organic contents. Generally red earths are mildly acid, becoming increasingly acid with depth, and may contain small amounts of ferromanganiferous nodules. Three main forms of red earths are recognised; normal, podzolic with a pale subsurface horizon which is common in sub-coastal regions, and lateritic with a horizon of ironstone nodules or reticulate sandy laterite.

Most of the red earths are used for cattle and sheep grazing of the native herbage but increasing areas in the sub-humid lands are used for a great variety of crops including tropical fruits, sugar cane, tobacco, peanuts, and citrus. Deficiencies of phosphorus, nitrogen, trace elements, and occasionally potassium are common but the soils respond to fertilisation and good management.

26. *Yellow earths.* These soils are more restricted in area and distribution than red earths. The larger occurrences are in the sub-humid hinterland of Queensland and New South Wales, but minor areas are probably associated with most areas of red earths in the moister regions. Most occurrences are on remnants of old land surfaces or transported materials from such formations, but they are found on a similar range of parent materials as the red earths, mostly in association

with eucalypt woodlands and forests.

They differ from red earths mainly in their predominantly yellow to yellow-brown colour and sometimes a more pronounced increasing texture gradient with depth. Generally they are massive, highly porous, earthy soils with moderately acid profiles and a similar range of texture and other properties as the red earths. The surface soils are grey-brown to brown with varying organic contents and massive to weak crumb structure. Some ironstone or black manganiferous nodules are common in the subsoils and many profiles have red and grey mottling in the deeper subsoil. There are also lateritic and podzolic variants. Their fertility and use are as for the red earths: most are used for cattle and sheep grazing of their inferior native grazing lands.

27. *Terra rossa soils.* These are well-drained, predominantly red, friable sandy to clayey soils overlying highly calcareous parent materials in sub-humid or moister regions. They are generally shallow, neutral or slightly acid at the surface, becoming alkaline below. Where formed from shelly sands they have greyish-brown sandy loam surfaces grading into red friable sandy loam to sandy clay subsoils with weak blocky structure. Their largest area is in the south-east of South Australia with smaller occurrences on the Bass Strait islands and north-west Tasmania. Generally they have low fertility and are used mainly for grazing of both grazing lands and sown pastures with small areas of tree and vine crops.

Those formed from hard limestones as in east-central Queensland and New South Wales have dark red-brown, crumbly clay loam to clay surface soils grading into red, fine polyhedral to blocky clay subsoils, and often contain much stone and outcropping rock that limits their usefulness. However, they are moderately fertile soils and small areas have been used for field crops, tropical fruits, and dairying.

28. *Euchrozems.* Euchrozems have a restricted distribution in the sub-humid lands of northern New South Wales and south-eastern Queensland where they occur on gentle slopes in hilly basalt country and have formed from both strongly-weathered old materials and freshly-weathered basalt.

The surface soil is dark brown friable clay loam to clay with crumb or fine blocky structure and grades into red to yellow-red blocky clay subsoils that are compact with firm to friable consistence. Euchrozems are mildly acid at the surface, becoming neutral to mildly alkaline in the subsoil. Depth ranges from 3 to 5 ft (61–152 cm).

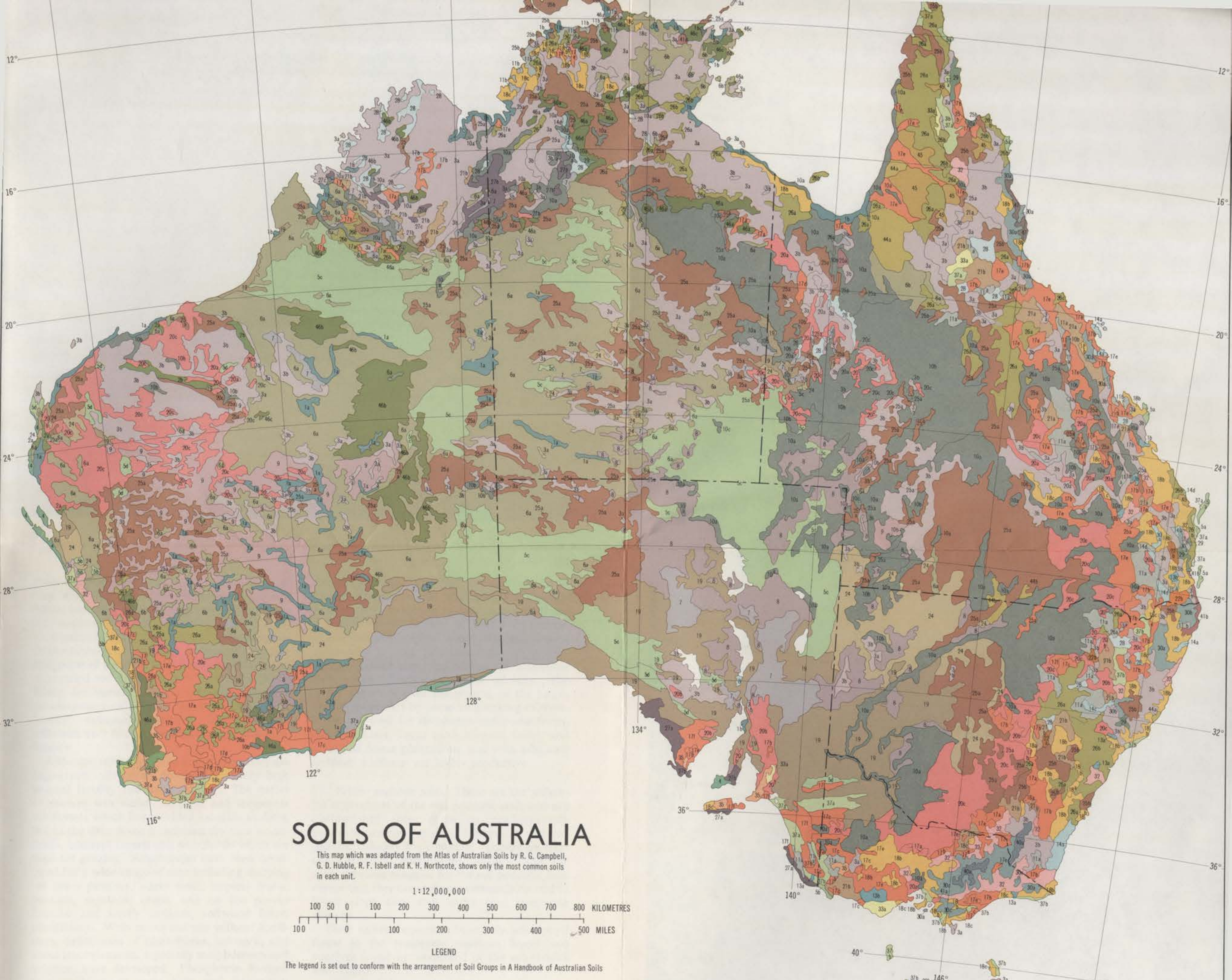
They are moderately fertile and are used for grain cropping, dairying, and for beef cattle grazing on the grazing lands of eucalypt woodlands. Where cropped they respond to superphosphate and nitrogenous fertilisers if moisture is not limiting.

29. *Xanthozems.* These are yellow-brown, friable and strongly structured clay soils which occur in association with the similar but red kraznozems on a range of basic igneous and metamorphic rocks. Small areas are scattered through the sub-humid summer rainfall zone from northern New South Wales to Cape York, occurring mainly on hilly lands and on lower slopes where drainage is slow.

Xanthozems are deep, acid soils with gradual horizon changes and increasing texture with depth. The moderately-organic surface soil is dark grey-brown friable clay loam with crumb to fine polyhedral structure, grading into yellow-brown to reddish-yellow clay subsoils that have strong fine polyhedral structure and are porous and friable when moist. Varying amounts of dark ferromanganiferous nodules occur in the subsoil which is often mottled with red. Xanthozems are moderately fertile soils mainly providing native grasses for beef cattle grazing eucalypt woodland or forest, but smaller areas are used with the kraznozems for the wider range of crops grown on those soils.

30. *Kraznozems.* These red, friable clay soils are formed mainly from basalt, but in the tropics on a wider range of less basic rocks including fine-textured metamorphics. Occurrences are spread through the sub-humid to humid hinterland of eastern Australia on plateaux, hilly lands, and some plains, with annual rainfalls from 30 to 150 in. (762–3810 mm). They are deep soils, well drained, strongly acid and with low base saturation except in the surface soils which are normally less acid and have moderate to high organic contents.

The A horizon, 6 to 8 in. (15–20 cm) thick, is



SOILS OF AUSTRALIA

This map which was adapted from the Atlas of Australian Soils by R. G. Campbell, G. D. Hubble, R. F. Isbell and K. H. Northcote, shows only the most common soils in each unit.

1:12,000,000

100 50 0 100 200 300 400 500 600 700 800 KILOMETRES

100 0 100 200 300 400 500 MILES

LEGEND

The legend is set out to conform with the arrangement of Soil Groups in A Handbook of Australian Soils

1 — SOLONCHAKS
🟦 1a Saline loams
1b Saline clays

2 — ALLUVIAL SOILS[1]
🟩 2a Loamy soils
2b Clayey soils

3 — LITHOSOLS

14 — PRAIRIE SOILS
🟦 14a Brown friable earths[4]
14b Dark, neutral, friable earths[4]
14c Dark, friable, porous earths[4]
14d Dark, structured loams and clays

15 — WIESENBODEN[2]

16 — SOLONETZ[2] [3]

26 — YELLOW EARTHS[4]
🟨 26a Acid and neutral yellow earths
26b Acid and neutral yellow earths with bleached A_2 horizons
26c Yellow-brown earths

27 — TERRA ROSSA SOILS
🟪 27a Shallow red sandy soils
27b Shallow red loamy soils
27c Deep red loamy soils

SOILS OF AUSTRALIA

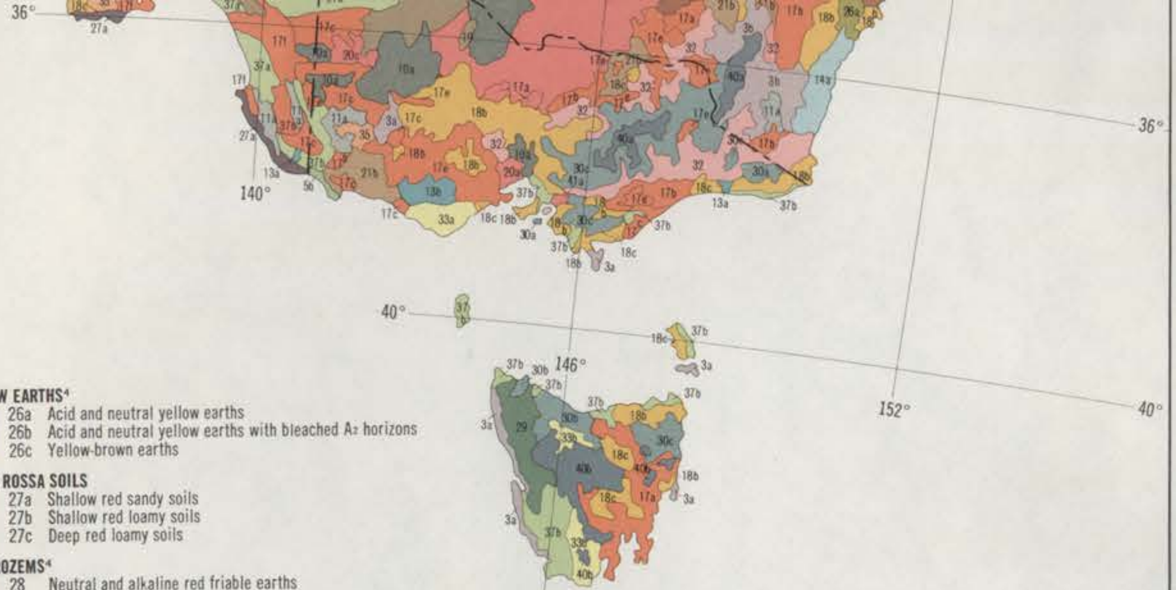
This map which was adapted from the Atlas of Australian Soils by R. G. Campbell, G. D. Hubble, R. F. Isbell and K. H. Northcote, shows only the most common soils in each unit.

1:12,000,000

100 50 0 100 200 300 400 500 600 700 800 KILOMETRES
100 0 100 200 300 400 500 MILES

LEGEND

The legend is set out to conform with the arrangement of Soil Groups in A Handbook of Australian Soils



1 — SOLONCHAKS
▨ 1a Saline loams
1b Saline clays

2 — ALLUVIAL SOILS[1]
▨ 2a Loamy soils
2b Clayey soils

3 — LITHOSOLS
▨ 3a Shallow sandy soils
3b Shallow loamy soils

4 — CALCAREOUS SANDS
▨ 4 Pale coloured calcareous sands

5 — SILICEOUS SANDS
▨ 5a Pale coloured siliceous sands
5b Yellow siliceous sands
5c Red siliceous sands
5d Brown sands

6 — EARTHY SANDS
▨ 6a Red earthy sands
6b Yellow earthy sands

7 — GREY-BROWN AND RED CALCAREOUS SOILS
▨ 7 Shallow calcareous loamy soils

8 — DESERT LOAMS[3]
▨ 8 Crusty red soils

9 — RED AND BROWN HARDPAN SOILS
▨ 9 Shallow loams

10 — GREY, BROWN AND RED CLAYS
▨ 10a Grey cracking clays with self-mulching surfaces
10b Brown and red cracking clays with self-mulching surfaces
10c Grey cracking clays with massive surfaces

11 — BLACK EARTHS
▨ 11a Dark cracking clays with self-mulching surfaces
11b Dark cracking clays with massive surfaces

12 — RENDZINAS[2]

13 — CHERNOZEMS
▨ 13a Dark deep structured loams
13b Dark, alkaline, friable earths[4]

14 — PRAIRIE SOILS
▨ 14a Brown friable earths[4]
14b Dark, neutral, friable earths[4]
14c Dark, friable, porous earths[4]
14d Dark, structured loams and clays

15 — WIESENBODEN[2]

16 — SOLONETZ[2, 3]

17 — SOLODIZED SOLONETZ AND SOLODIC SOILS[3]
▨ 17a Hard neutral red and brown bleached form
17b Hard neutral yellow bleached form
17c Sandy neutral yellow bleached form
17d Hard alkaline red and brown bleached form
17e Hard alkaline yellow and dark bleached form
17f Sandy alkaline yellow bleached form

18 — SOLOTHS[3]
▨ 18a Hard acid red bleached form
18b Hard acid yellow bleached form
18c Sandy acid yellow bleached form

19 — SOLONIZED BROWN SOILS[4]
▨ 19 Calcareous earths and sandy earths

20 — RED-BROWN EARTHS
▨ 20a Hard alkaline red and brown form
20b Hard alkaline red form
20c Hard alkaline red and brown bleached form

21 — NON-CALCIC BROWN SOILS[3]
▨ 21a Hard neutral red form
21b Hard neutral red and brown form

22 — CHOCOLATE SOILS[3]
▨ 22a Friable red form
22b Friable brown form

23 — BROWN EARTHS[2]

24 — CALCAREOUS RED EARTHS[4]
▨ 24 Alkaline red earths

25 — RED EARTHS
▨ 25a Acid and neutral red earths
25b Acid and neutral red earths with dark A_1 and paler A_2 horizons

26 — YELLOW EARTHS[4]
▨ 26a Acid and neutral yellow earths
26b Acid and neutral yellow earths with bleached A_2 horizons
26c Yellow-brown earths

27 — TERRA ROSSA SOILS
▨ 27a Shallow red sandy soils
27b Shallow red loamy soils
27c Deep red loamy soils

28 — EUCHROZEMS[4]
▨ 28 Neutral and alkaline red friable earths

29 — XANTHOZEMS[4]
▨ 29 Acid and neutral yellow and brown friable earths

30 — KRASNOZEMS[4]
▨ 30a Acid red friable earths, some have A_2 horizons
30b Acid red friable porous earths
30c Acid brown friable porous earths, some have A_2 horizons

31 — GREY-BROWN PODZOLIC SOILS[2]

32 — RED PODZOLIC SOILS[3]
▨ 32 Hard acid red soils

33 — YELLOW PODZOLIC SOILS[3]
▨ 33a Hard acid and neutral yellow form
33b Sandy acid yellow form

34 — BROWN PODZOLIC SOILS[2, 3]

35 — LATERITIC PODZOLIC SOILS[3]
▨ 35 Ironstone gravelly, hard acid and neutral yellow soils

36 — GLEYED PODZOLIC SOILS[2]

37 — PODZOLS[6]
▨ 37a Sands with bleached A_2 horizon over a colour B horizon
37b Sands with bleached A_2 horizon over a cemented B horizon

38 — HUMUS PODZOLS[2]

39 — PEATY PODZOLS[2]

40 — ALPINE HUMUS SOILS
▨ 40a Organic loamy soils
40b Organic loamy soils with peaty surface

41 — HUMIC GLEYS
▨ 41a Organic clay soils
41b Friable acid form[3]

42 — NEUTRAL TO ALKALINE PEATS[2]

43 — ACID PEATS[2]

44 ————[4, 5]
▨ 44a Acid grey earths
44b Alkaline grey earths

45 ————[4, 5]
▨ 45 Acid bleached grey earths

46 ————[5]
▨ 46a Ironstone gravels in a sand matrix[4]
46b Ironstone gravels in an earthy sand matrix[4]
46c Ironstone gravels in a red earth matrix[4]
46d Ironstone gravels in a yellow matrix[3]

47 ————[4, 5]
▨ 47 Deep red and yellow friable loams

NOTES
1. Most areas of these soils are too small to be shown.
2. All areas of these soils are too small to be shown.
3. Soils in which a marked texture-contrast exists between surface soil and subsoil.
4. Soils in which texture gradually increases with depth.
5. Only limited studies have been made of these soils.
6. As mapped, Humus Podzols are included.

Map originally presented in A Handbook of Australian Soils.

dark reddish-brown friable clay loam to light clay with strong crumb structure and grades below into red, strongly polyhedral clay which may continue to depths exceeding 15 ft (457 cm) to weathered rock. Fine black ferromanganiferous nodules are common in the upper profile and some of the deep soils have a thick horizon of mottled red and light grey clay at the base. There are variants with a weak A_2 horizon, concretionary or massive laterite horizon, and 'snuffy', extremely-weathered, loamy surface soils with very fine crumb structure and low bulk density.

Although their total area is not great they are important soils owing to their relatively high natural fertility and good rainfall. The native vegetation was mainly tropical and temperate rainforests which have yielded valuable timbers, but in the drier areas it included dry vine woodlands, eucalypt forests and woodlands which are used for grazing. Kraznozems have been developed for a wide range of uses including dairying on sown pastures, sugar cane, tropical fruits, peanuts, vegetable crops, and on the poorer lateritic and snuffy variants, softwood forest plantations. With continued use without fertilisers, deficiencies of phosphorus, nitrogen, and some trace elements, especially molybdenum and sulphur, have developed. Phosphorus fixation is a problem on some soils and manganese toxicity sometimes occurs on the more acid types.

Moderately to Strongly Leached Highly Differentiated Soils

31. *Grey-brown podzolic soils*

32. *Red podzolic soils.* Red podzolic soils are most common in the seasonally-humid coastal regions and hinterland of eastern and northern Australia. Occurrences are mostly on well-drained slopes in hilly country on a wide range of parent materials excluding siliceous and basic extremes. Their vegetation cover is usually dry sclerophyll forest but in places is rainforest or woodland.

Essentially they are acid, leached soils with a prominent texture contrast and clear boundary between pale sandy to loamy A horizons and red, friable strongly structured clay subsoils. The surface soils are brownish-grey to grey-brown and massive or weakly structured grading into palder A_2 horizons which are porous, sometimes strongly bleached, and may contain some ferromanganiferous nodules. The red clay B horizons have varying moderate to low base saturation.

Their natural fertility is low with general deficiencies of phosphorus and nitrogen, varying deficiencies of trace elements including molybdenum, copper, zinc, and boron, and occasional deficiencies of potassium and calcium. The larger areas are used for grazing of the native grasses improved by some ringbarking of trees. Some are used for deciduous and pome fruits, sown pastures, sugar cane, tropical fruits, and softwood forest plantations, and with adequate fertiliser additions are highly productive.

33. *Yellow podzolic soils.* These are the yellowish equivalents of the red podzolic soils and are distinguished from them by predominantly yellow-brown clay subsoils. Intergrades with red mottled subsoils are common. Otherwise their characteristics, distribution, fertility, and use span the same range as for the red podzolic soils except that they occur more commonly on mid to lower slope sites and under cool temperate climates.

Their native vegetation is mainly sclerophyll forest in the temperate southern States and eucalypt forest or woodland in the sub-tropics and tropics.

34. *Brown podzolic soils*

35. *Lateritic podzolic soils.* These are deeply-weathered soils with acid, texture-contrast profiles generally similar to sandier yellow podzolic soils with red-mottled subsoils. The essential differences are a horizon of nodular, pisolitic, or massive ironstone in the lower part of the thick sandy A_2 and top of the mottled yellow-brown and red clay B horizon, and below the main B, a thick zone of white - and red-mottled heavy clay grading into white clay and kaolinised rock (Pl. 8). The full profile depth ranges from 5 ft (152 cm) to more than 20 ft (610 cm). They are found in all States but especially in the sub-humid regions of south Western Australia, South Australia, and the eastern States. Most occurrences are on old land surfaces ranging from undulating plains to low mesas and extensive tablelands. The native vegetation is commonly sclerophyll forest or heath.

These soils are very infertile due to similar but

Plate 8 Lateritic podzolic soil more than 20 ft (610 cm) deep with a well-developed horizon of laterite nodules in the thick sandy A_2 horizon and upper B horizon, and a thick white and red mottled zone of kaolin clay below

more extreme deficiencies than the other podzolic soils. Earlier, most of them provided only sparse grazing and a little timber, but considerable areas in both temperate and sub-tropical regions are now being developed, with heavy fertiliser additions including superphosphate, lime, potassium, molybdenum, copper, and zinc, for legume-based sown pastures (see Chapter 11). Softwood forest plantations have also been established in several States, and with the addition of phosphates and sometimes zinc, are growing satisfactorily.

36. *Gleyed podzolic soils*

37. *Podzols.* Podzols are restricted to the more humid coastal regions and well-drained sites on highly siliceous sands. Their main occurrences are on the older dune systems and sandy plains of coastal regions of southern and eastern Australia. The native vegetation is heath, open sclerophyll woodland or forest.

They are strongly leached, acid sands with grey, slightly loamy A_1 horizons of varying thickness and organic content, generally thicker whitish sand A_2 horizons, and somewhat loamy coherent B horizons with accumulations of a little clay, sesquioxides, and/or organic matter and varying from reddish and yellowish-brown to black. Organic matter is often concentrated in the top of the B horizon forming a weak pan below the very irregular boundary with the A_2 horizon.

Podzols are very infertile soils with gross deficiencies of phosphorus, nitrogen, and several trace elements. Generally they are unused or provide sparse grazing, and where they occur on dunes are very liable to wind erosion. With correction of the nutrient deficiencies some areas are used for plantations of exotic softwoods, and development with legume-based sown pastures is increasing.

38. *Humus podzols*

39. *Peaty podzols*

The Organic Soils

40. *Alpine humus soils.* These soils are found only on the highlands of south-eastern Australia where they occur on sloping sites with good surface drainage over comminuted parent materials derived from acidic and basic igneous rocks, metamorphosed sediments, and other rocks. Their natural vegetation is mainly alpine heathland and sub-alpine woodlands (see Chapter 13).

They are strongly acid soils with thick A horizons of dark grey to brownish-black crumbly organic loams grading below through yellow-brown porous and friable loams into coarser-textured, stony and gravelly C horizons. The surface soils have high contents of well-humified organic matter intimately mixed with the mineral soil. Generally the subsoil contains recognisable rock fragments and weathering minerals. Some stones and occasional boulders usually occur throughout the profile.

The organic surface soils have high total nitrogen contents and some accumulation of potassium and phosphorus, but the mineral soils below are strongly leached and base unsaturated. Phosphorus status varies greatly with the parent rocks. Previously these highlands have been used for summer grazing, stock being moved to lower lands during winter when much of the area may be snow-covered. With their increasing importance as a source of water for hydro-electric power and irrigation schemes the emphasis is now on conservation and protection from erosion.

41. *Humic gleys.* Humic gleys are restricted to low-lying areas with high groundwater tables. They are formed in unconsolidated sediments ranging from sands to clays and are best developed on coastal and estuarine plains in subhumid or moister regions, extending inland along valley floors. The native vegetation is grassy woodland or herbaceous marsh.

They are strongly acid to neutral with thick, moderately organic, dark surface soils (sandy loams and clay loams) grading into grey, wet subsoils of weakly structured clayey sand or coarsely prismatic clay mottled with rusty and ochreous streaks and patches. The deeper subsoil is permanently waterlogged and grey or bluish grey. All forms usually contain some harder ferruginous segregations as nodules and tubules.

In the natural state humic gleys have low fertility due to varying nutrient deficiencies and intermittent waterlogging. Where artificially drained and adequately fertilised, mainly with phosphates and trace elements, they have proved highly productive for sown pastures, vegetables, and sugar cane. Along the coastal fringe excessive salinity is sometimes a problem, but with assured soil moisture from their high watertables they provide valuable grazing, especially during drought periods.

42. *Neutral to alkaline peats*

43. *Acid peats*

Other Soils

Four units shown on the soil map are dominated by soils that have not yet been fully described and recognised as groups. In the following statement descriptive names are used for convenience.

44. *Acid and alkaline grey earths.* These are deep sandy soils with earthy fabric, gradually increasing texture with depth, and pale greyish to yellowish-brown or mottled subsoils. The acid form occurs both with and without a pale A_2 horizon and is generally similar to very sandy yellow podzolic soils but lacks a clear texture contrast and a well-defined colour B horizon. Some ironstone nodules or pans often occur in the subsoils. The largest occurrences are on extensive plains with woodland cover south-east of the Gulf of Carpentaria. The alkaline form includes both sandy and loamy soils with soil reaction increasing to at least pH 8 in the deep subsoil. Occurrences are restricted to plains on the central New South Wales-Queensland border under open woodland vegetation with some patches of gidgee.

All are infertile soils with severe deficiencies of phosphorus and nitrogen and provide only sparse grazing.

45. *Acid bleached grey earths.* These differ from the acid grey earths in having a prominent bleached A_2 horizon and include both sandy and loamy soils with mottled pale grey and pale yellowish-brown deep subsoils. Ironstone nodules are common in the subsoils and sometimes occur as shallow cemented pans. There are extensive areas of these soils on Cape York Peninsula carrying poor woodland and forest vegetation which provides sparse grazing for beef cattle. Despite very low nutrient contents and moisture-holding capacity, the productivity of all tropical areas of the acid grey earths could be greatly increased by the introduction of Townsville lucerne, especially with some addition of superphosphate (see Chapter 8).

46. *Ironstone gravel soils.* From the south-west, through central Western Australia and the Kimberley region, to the 'Top End' of the Northern Territory there are extensive areas of soils whose dominant feature is large accumulations of ironstone gravel with some massive laterite. The fine earth matrix is commonly sand or earthy sand, sometimes red earth material and, in more restricted occurrences, sandy texture-contrast soils with yellow or mottled heavier subsoils that are neutral or slightly alkaline.

They occur on broad undulating tablelands, or dissected tablelands and lower undulating plains, in environments ranging from sub-humid temperate and tropical to arid, and are the modified remnants or transported detritus of relict soils associated with old lateritic land surfaces. Most are shallow, and those with sand matrix are often underlain by various mottled and pallid zone clays of the laterite profile. Their native vegetation includes sclerophyll forests, open woodlands, mulga shrublands, and hummock grassland. All are very infertile owing both to gross nutrient deficiencies and droughtiness. The forests in the higher-rainfall areas of south-western Australia yield valuable timber; other areas provide sparse grazing or, in arid regions, are unused.

47. *Deep red and yellow friable loams.* These soils have affinities with the red and yellow earths but have weak A_2 horizons and uniform loam texture profiles with strongly structured subsoils. They have formed from fine-textured metamorphic rocks and are weakly weathered, containing recognisable micas and other minerals. They occur on mountains, high hills, and elevated plateaux—with shallow stony variants on the steeper slopes and scarps—along the humid tropical coast near Cairns with annual rainfall of almost 100 in. (2540 mm). Most are still under rainforests which have been exploited for timber. Fringing areas on gentle slopes are used for pastures and some sugar cane and are highly productive with the addition of fertilisers.

4

VEGETATION

R. MILTON MOORE AND R. A. PERRY

According to Beadle (1966) 189 of the 307 families of plants in the world are found in Australia. Most of the families not represented occur in places remote from Australia and only 14 are in the near tropics to the north. All of the tribes of the Gramineae except the Maydeae, and all of the Compositae except the Helenieae and the Mutisieae are represented.

Distinctive characteristics of the Australian vegetation are the few deciduous trees, the widespread sclerophylly, the relatively minor occurrence of conifers and other softwoods, and the predominance of the genera Eucalyptus and Acacia in forests, woodlands, and shrublands.

The 500 or more species of Eucalyptus occupy a wide range of soils and climates in both tropical and temperate zones. The genus is confined almost entirely to Australia and in the words of Pryor (1959) is 'overwhelmingly an Australian endemic'. Although relatively uniform morphologically there is a wide range of physiological variation within the genus. Except for a few deciduous species in the tropics eucalypts are evergreen and, even at tree lines in alpine areas, retain their leaves in winter. The genus exceeding Eucalyptus in number of species in Australia is Acacia which occurs throughout the arid parts of the continent and is associated with eucalypts in shrub woodlands and in forests of the high rainfall areas.

In eastern Australia eucalypts are popularly called gums if the dead bark is shed leaving the trunk and branches smooth, boxes if the dead bark on the upper part of the tree is shed but retained on the branches and lower trunk, stringybarks if the bark is retained at least on the trunk and main branches and is fibrous, ironbarks if the bark is mostly persistent and is hard and deeply furrowed. In Western Australia any eucalypt may be called a gum. Acacias have a variety of names—mulga, gidgee, blackwood, myall, brigalow, and even jam—but those with showy yellow flowers are commonly called wattles.

There are three principal elements in the Australian flora: an Indo-Malaysian, an autochthonian or Australian, and an Antarctican (Gardner 1944). These elements and the phytogeography of the Australian flora are discussed by Burbidge (1960).

The broad climatic zones in Australia are tropical, temperate and alpine and eremean. The north-eastern tropical zone characterised by a dry monsoonal climate is rich in Indo-Malaysian floristic elements. The eremean zone differs from most other arid regions in the high proportion of low trees and shrubs and in the absence of cactaceae and other large succulents.

Sclerophylly, a feature of the Australian element, occurs in about twenty families in eastern Australia and to a high degree in the flora of the south-west. It is common in the Epacridaceae, Myrtaceae, Papilionaceae, and Proteaceae which usually grow on soils of low fertility. Beadle (1966) separates xeromorphic heaths and sclerophyll forests from rainforests on the basis of soil phosphorus, most xeromorphic communities having less than 200 ppm HCl soluble soil phosphorus.

Other features of the sclerophyllous vegetation are adaptation to fire and capacity to regenerate following mechanical injury. Most eucalypts will regenerate from epicormic buds or from lignotubers after a fire. A high proportion of other species in dry sclerophyll forests, tropical woodlands, heaths, and mallee will also tolerate fire and some, for example the species of Acacia, are stimulated to germinate by fire. Regeneration of woody plants following mechanical injury is often a cost factor in the clearing of land for pastoral purposes.

As in northern Europe there is an increase in the proportion of hemicryptophytes, and chamaephytes with increasing cold. The affinities of the alpine and sub-alpine vegetation are Antarctican (Costin 1959).

In this book Australian vegetation is classified into heaths, forests, woodlands, shrublands, and grasslands. The distribution of these formations is shown in Map 3.

Boundaries are approximate only as many formations intergrade, and even where the dividing lines between formations and sub-formations are relatively sharp few have been accurately surveyed. Also within areas designated as one formation there may be outliers of other formations too small to include in the map even if information were available to enable this to be done with accuracy. The structure of a floristic group may change but unless the area in which the change has occurred is extensive, it is not differentiated from the larger formation. Thus, in places, a woodland or shrubland dominant species may have a forest form but unless the area is large, the change in community structure may not be shown on the map.

Some departures are made from the structural units defined by Beadle and Costin (1952) and R.J. Williams (1955). Australian terms such as mallee and brigalow are retained because they provide direct reference to pastures and grazing lands, but 'scrub', popularly applied to a number of different formations, is replaced by less confusing and we believe more specific terms. Brigalow, the layered scrub formation of Williams (1955), is classified as Brigalow Forest, arid scrub (Williams 1955) and dry scrub (Beadle and Costin 1952) are called Acacia Shrubland, and mallee scrub (Williams 1955) is classed as Eucalypt Shrubland (Mallee). Shrubs are defined as many-stemmed or low branching woody plants not generally exceeding 25 ft (8 m).

Formations are subdivided mainly on a humidity-aridity basis. The humid and sub-humid are further separated into tropical and temperate and where relevant into alpine or sub-alpine. Arid shrublands and grasslands are classified on the bases of the growth habits and floristics of the dominant species.

A large area of Australian vegetation has not been surveyed for classification purposes. For this reason and because of uncertainties about different authors' concepts, we have avoided the terms association and alliance.

Descriptions of the formations and sub-formations that follow are intended to serve as explanatory notes for the vegetation map and are therefore brief. Further descriptions of plant communities are given in chapters on pastures and grazing lands.

HEATHS

Communities of shrubs, often less than 6 ft (2 m) tall, with ericoid, microphyllous or sclerophyllous leaves, and few or no herbaceous species. Common genera of lowland heaths are Banksia, Leptospermum, Calytrix, and Hakea.

Tropical Heaths

In the tropics and sub-tropics heaths are confined to wet coastal areas and in Map 3 include the wallum proper (see Chapter 7).

Temperate Heaths

In temperate areas heaths may be coastal (wet) or sub-coastal (dry). Dry heaths frequently intergrade with dry sclerophyll forests forming a shrub understorey to the forest eucalypts (see Pls. 9 and 10).

Mallee Heaths

Sometimes stunted eucalypts less than 12 ft

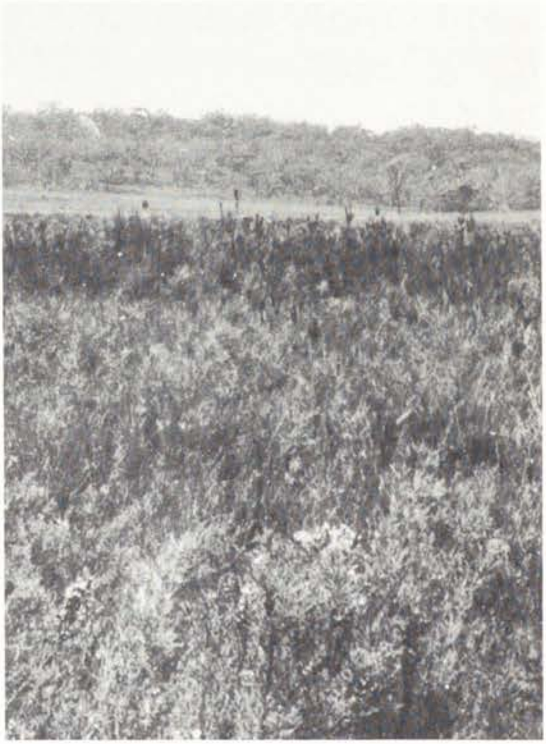


Plate 9 Temperate wet heath. *Banksia marginata* (dwarf honeysuckle) with *Melaleuca* spp. (tea trees) and *Leptospermum* spp., north-western Tasmania (Department of Agriculture, Tasmania, photo)

Plate 10 Temperate heath associated with dry sclerophyll forest. The principal species are *Banksia* spp., *Leptospermum* sp., *Pultenaea* sp., *Hibbertia* spp., *Astroloma* sp., and *Persoonia* sp., Western Victoria (Department of Agriculture, Victoria, photo)

(4 m) tall occur in heaths and when these are of the mallee form (multi-stemmed) the communities are classed as mallee heaths.

Alpine Heaths

At elevations of more than 5000 ft (1524 m) there are small areas of heath usually less than 2 ft (60 cm) tall. Genera with high frequencies are Oxylobium, Podocarpus, Hovea, Orites, Prostanthera, and Phebalium. At lower elevations there are sub-alpine heaths of *Epacris serpyllifolia* and *Kunzea muelleri*.

FORESTS

Forests occupy principally the landforms classified as ranges, hill lands, and mountains (see Map 1).

Rainforests

Communities of two or more tree strata with densely interlacing canopies, lianes, epiphytes and sparse ground layers of ferns. Australian rainforests have been classified by Webb (1959). The southern boundary of Webb's sub-tropical rainforest is south of Kiama, New South Wales (lat 34°30′S), but for reasons associated with the distribution of tropical and sub-tropical pasture species our sub-tropical-temperate boundary has been drawn at Taree (lat 31°54′S). The leaf size of tropical and sub-tropical rainforests is large to small mesophyll (> 12·7 cm). Species of Araucaria are prominent in sub-tropical (Pl. 12) and large woody lianes and vascular epiphytes in tropical rainforests. The large family Dipterocarpaceae, so highly represented in the tropics to the north, does not occur in Australia.

Temperate rainforests have microphyll leaf sizes (< 7·6 cm) and a flora with Antarctic affinities. *Notofagus cunninghamii* (myrtle beech) is the typical tree and mosses are common (Pl. 13).

Plate 11 Tropical rainforest (Mesophyll vine forest), north Queensland. Note abundance of lianes including *Calamus* spp. (lawyer vine) (CSIRO photo)

Plate 12 Sub-tropical rainforest: *Araucaria bidwellii* (bunya pine) with *Argyrodendron* spp. and *Castanospermum australe* (black bean), Bunya Mountains, Queensland (Queensland Forest Service photo)

Plate 13 Temperate rainforest, western Tasmania. Dominants are *Notofagus cunninghamii* (myrtle beech), *Atherosperma moschatum* (sassafras), and *Phyllocladus aspleniifolius* (celery-top pine). Understorey species are *Dicksonia antarctica* (tree fern) and *Anodopetalum biglandulosum* (University of Tasmania photo)

Wet Sclerophyll Forests

Communities of eucalypts usually more than 100 ft (30 m) and in parts of Tasmania and Victoria more than 200 ft (60 m) tall. There is commonly an understorey of shrubs (Pl. 14), and in wet places of tree ferns (Dicksonia and Cyathea). In coastal areas adjacent to rainforests in Tasmania and Victoria the herbaceous stratum is often poorly developed, but further north and in the mountain ranges the canopy is often more open and *Themeda australis* and other grasses may form a discontinuous ground layer.

Characteristic trees of wet sclerophyll forests are *Eucalyptus grandis*, *E. pilularis*, Queensland; *E. saligna*, *E. pilularis*, *E. dalrympleana*, *E. delegatensis*, New South Wales; *E. regnans*, Victoria and Tasmania; and *E. diversicolor*, Western Australia.

Dry Sclerophyll Forests

Communities of eucalypts usually less than 100 ft (30 m) tall with xeromorphic shrub layers of variable densities (Pl. 15). There is some evidence that repeated burning may have increased shrub densities. The grass layer, too, varies markedly in density. Dry sclerophyll forests occur on infertile and skeletal soils in Western Australia, South Australia, Victoria, and New South Wales.

Typical dry sclerophyll forests are *E. macrorrhyncha-E. rossii*, *E. sideroxylon-E. dealbata*, New South Wales; *E. baxteri-E. obliqua*, Victoria and South Australia; and *E. marginata*, Western Australia.

Brigalow Forest

Williams (1955) classes brigalow as layered scrub because of the high density of the dominant

Plate 14 Temperate wet sclerophyll forest: *Eucalyptus regnans* (mountain ash) with an understorey of *Acacia dealbata*, *Bedfordia salicina*, *Pomaderris apetala*, *Olearia* spp., and *Cassinia* spp., north-eastern Tasmania (Department of Agriculture, Tasmania, photo)

Acacia harpophylla and the presence of a subordinate layer of shorter shrubs. The community varies in structure but for the most part appears to be forest in form and has usually a sparse herbaceous layer (Pl. 35).

WOODLANDS

Sub-humid Woodlands

Tropical and sub-tropical. Principally communities of eucalypts but also including extensive areas of *Melaleuca viridiflora* (tea-tree) in north Queensland (Pl. 53).

Because of the forest form of many of the eucalypts some of the communities classified as woodlands in Queensland could be classified perhaps as open forests, but there is much variation in both tree and shrub density and we believe that the relatively high density of the herbaceous layer justifies placing them with woodlands (Pl. 16). In sub-tropical Queensland, also, we have mapped as woodlands communities floristically related to temperate dry sclerophyll forests, again because of the density of their herbaceous layers.

The area mapped as tropical and sub-tropical woodland includes the following communities of Williams (1955), tropical layered woodland, tropical deciduous woodland, coastal woodland, tropical scrub, tropical layered forest, and his northern dry sclerophyll forests.

Temperate. Communities dominated by species of Eucalyptus and occasionally by Casuarina and Acacia. Trees usually have a woodland form, that is the length of the bole is equal to or less than the depth of the crown which is rounded rather than flat as in forest trees. Shrubs are rare and the herbaceous layer is relatively dense (Pl. 43).

As mapped, temperate woodlands include the

Plate 15 Temperate dry sclerophyll forest on a sandy acid soil. *Eucalyptus baxteri* (brown stringybark) and *Eucalyptus obliqua* (messmate) with *Pteridium esculentum* (bracken fern) and *Hibbertia* sp., western Victoria (Department of Agriculture, Victoria, photo)

savannah woodlands of Williams (1955) and others, the tall woodland of Beadle and Costin (1952), and in part the sub-alpine woodland of Pryor (1939).

Typical communities are *Eucalyptus melliodora—E. blakelyi* and *E. woollsiana*, New South Wales; *E. camaldulensis—E. ovata* and *E. hemiphloia—C. leuhmannii*, Victoria; *E. pauciflora—E. salicifolia—E. ovata*, Tasmania; *E. leucoxylon* and *E. odorata*, South Australia; *E. loxophleba—Acacia acuminata*, Western Australia.

Sub-alpine. Communities of mainly single-stemmed trees and relatively dense layers of grasses. Except in parts of Tasmania where *Notofagus cunninghamii* is the treeline species, eucalypts ascend to the upper limit of tree growth. This is 6500 ft (1982 m) on Mt Kosciusko (lat. 36°27′S) and 5500 ft (1676 m) further south on Mt Buller (lat. 37°3′S).

Sub-alpine woodlands of *E. pauciflora*, *E. stellulata*, and *E. rubida* occur at lower elevations (4500 ft, 1372 m) on the slopes of saucer-shaped valleys on the floors of which accumulation of cold air prevents the growth of trees (Pl. 28).

Semi-arid Shrub Woodlands

In these communities the woodland form is retained in the tree stratum but there is a discontinuous subordinate layer of low trees or shrubs, mostly less than 25 ft (8 m) tall (Pl. 17). River and creek fringing woodlands of *Eucalyptus largiflorens*, *E. camaldulensis*, *E. microtheca*, and *E. ochrophloia*, and woodlands of *E. melanophloia* classified by Beadle (1948) as savannah woodlands have been included with shrub woodlands because, except in the south, most have distinct though sparse shrub layers. The low shrub woodland of Williams (1955) is also included.

Plate 16 Tropical woodland, mainly *Eucalyptus crebra* (narrow-leaved ironbark) with an understorey of *Heteropogon contortus* (bunch spear grass), *Themeda australis* (kangaroo grass), and *Bothriochloa* spp.: Tropical Tallgrass grazing land, northern Queensland (CSIRO photo)

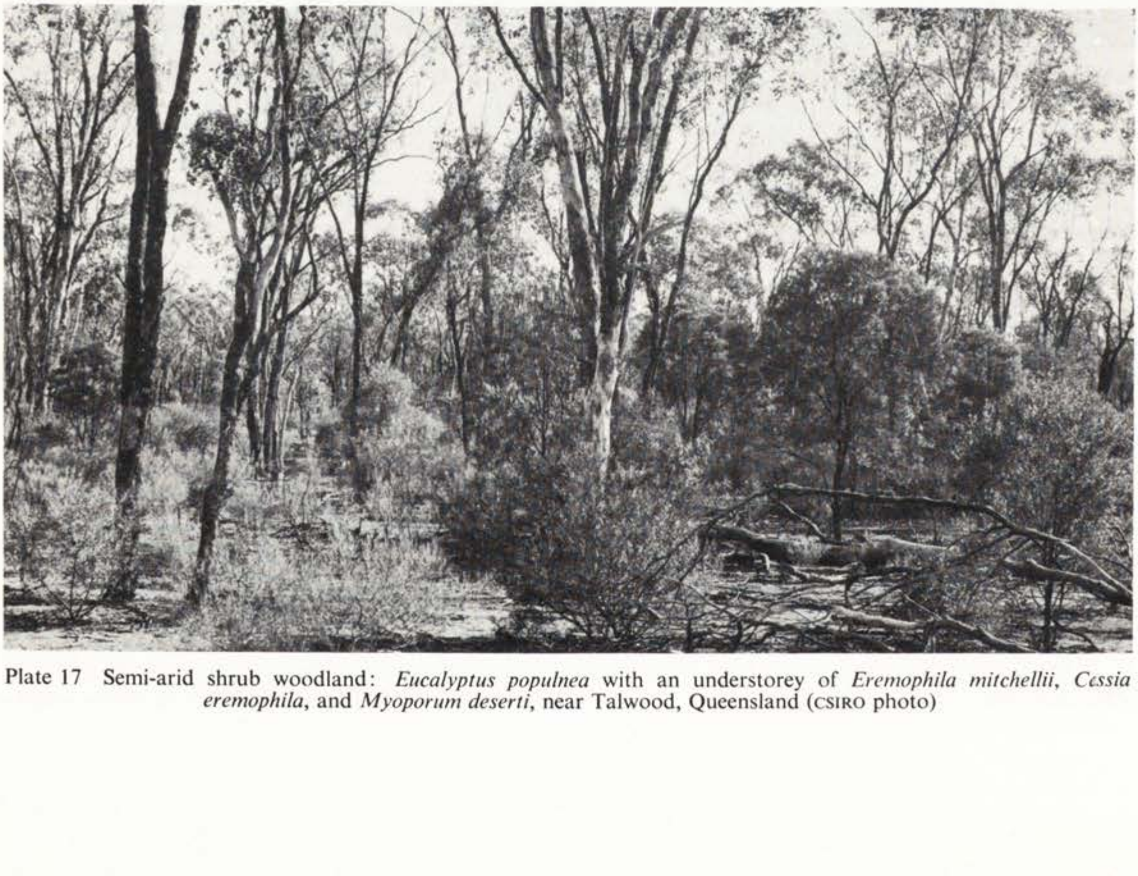


Plate 17 Semi-arid shrub woodland: *Eucalyptus populnea* with an understorey of *Eremophila mitchellii*, *Cassia eremophila*, and *Myoporum deserti*, near Talwood, Queensland (CSIRO photo)

The most typical communities are those dominated by *E. populnea*, *Acacia pendula*, *E. similis*, *E. brownii*, and *E. microneura*. Common shrubs are *Eremophila mitchellii*, *Atalaya hemiglauca*, *Geijera parviflora*, *Acacia homalophylla*, *A. excelsa*, *Myoporum desertii*, and *Canthium oleifolium*. The characteristic grasses are species of Aristida (Pl. 29) except near the southern limits of the sub-formation in southern New South Wales and northern Victoria where they are *Danthonia caespitosa* on clays and *Stipa variabilis* or *S. scabra* on light-textured soils.

Arid and Semi-arid Low Woodlands

The dominants in communities of this sub-formation are mostly of shrub height (less than 25 ft, 8 m) but mainly with a single principal stem (Pl. 18). In the south the principal species are *Casuarina cristata*, *Heterodendrum oleifolium*, and *Callitris columellaris*. This is the scrub formation of Beadle (1948). In north-western Queensland, the Northern Territory, and the north of Western Australia the communities are principally *Eucalyptus brevifolia*, the Sparse Low Woodland of Perry and Lazarides (1964), *E. argillacea—E. terminalis*, *E. pruinosa*, *E. dichromophloia*, and *Acacia shirleyi*. Low shrubs are common but sparse and in some respects the sub-formation resembles a stunted shrub woodland.

South and east of the Gulf of Carpentaria there are communities of *Melaleuca viridiflora* and of *Bauhinia cunninghamii* (bean tree) that vary in structure from tropical woodlands north of the 30 in. (762 mm) annual isohyet (see Chapter 8) to shrub woodlands and low woodlands in the lower rainfall areas (see Chapter 16). As in the shrub woodlands the dominant grasses of arid and semi-arid low woodlands are species of Aristida with Stipa becoming more frequent in the southernmost part of their distribution.

Plate 18 Semi-arid low woodland of *Eucalyptus terminalis* (bloodwood), Northern Territory (CSIRO photo)

SHRUBLANDS

Communities dominated by woody plants mostly less than 25 ft (8 m) tall and multi-stemmed. Included are the shrub steppe, the semi-arid mallee, sclerophyll mallee and, in part, the arid scrub of Williams (1955). In southern Australia shrublands are mostly on riverine plains and lowlands with relief less than 100 ft (30 m) (see Map 1).

Shrub Steppe

Communities of low chenopod shrubs 3–7 ft (1–2 m) tall with semi-succulent leaves. After rain, space between the shrubs is occupied by grasses, composites and crucifers. Typical species are *Atriplex vesicaria* and *Kochia sedifolia* (Pl. 19).

Acacia Shrublands

The dominants are *Acacia aneura*, *A. cambagei*, *A. sowdenii*, or *A. georginae*, all of which branch close to the ground and are usually less than 25 ft (8 m) tall excepting in parts of Queensland where *A. aneura* may be slightly taller.

A layer of low shrubs is often present. Common genera are Eremophila, Cassia, and Atriplex. There are widely spaced perennial tussock grasses and, after rains, numerous annuals (Pl. 20).

Eucalypt Shrublands (Mallee)

Communities of multi-stemmed eucalypts of shrub height, that is 7–25 ft (2–8 m) tall (Pl. 21). The hummock grass *Triodia irritans* (porcupine grass) is common in the ground stratum of some

Plate 19 Shrub steppe: *Atriplex vesicaria* (bladder saltbush), Saltbush-Xerophytic Midgrass grazing land, south-western New South Wales (CSIRO photo)

Plate 20 Acacia shrubland: *Acacia aneura* (mulga), Acacia Shrub-Shortgrass grazing land, Northern Territory (CSIRO photo)

communities. In others, low shrubs of *Melaleuca uncinata* (broombush) or *Callitris preissii* (mallee pine) are frequent. Chenopods (Atriplex, Enchylaena), become more prominent towards the arid limits of the mallee.

Common mallee eucalypts are *E. oleosa*, *E. dumosa*, *E. incrassata*, and *E. diversifolia*. Forest species that may assume a mallee form include *E. baxteri* and *E. cosmophylla*.

GRASSLANDS

Communities dominated by grasses and for the most part treeless.

Arid Tussock Grasslands

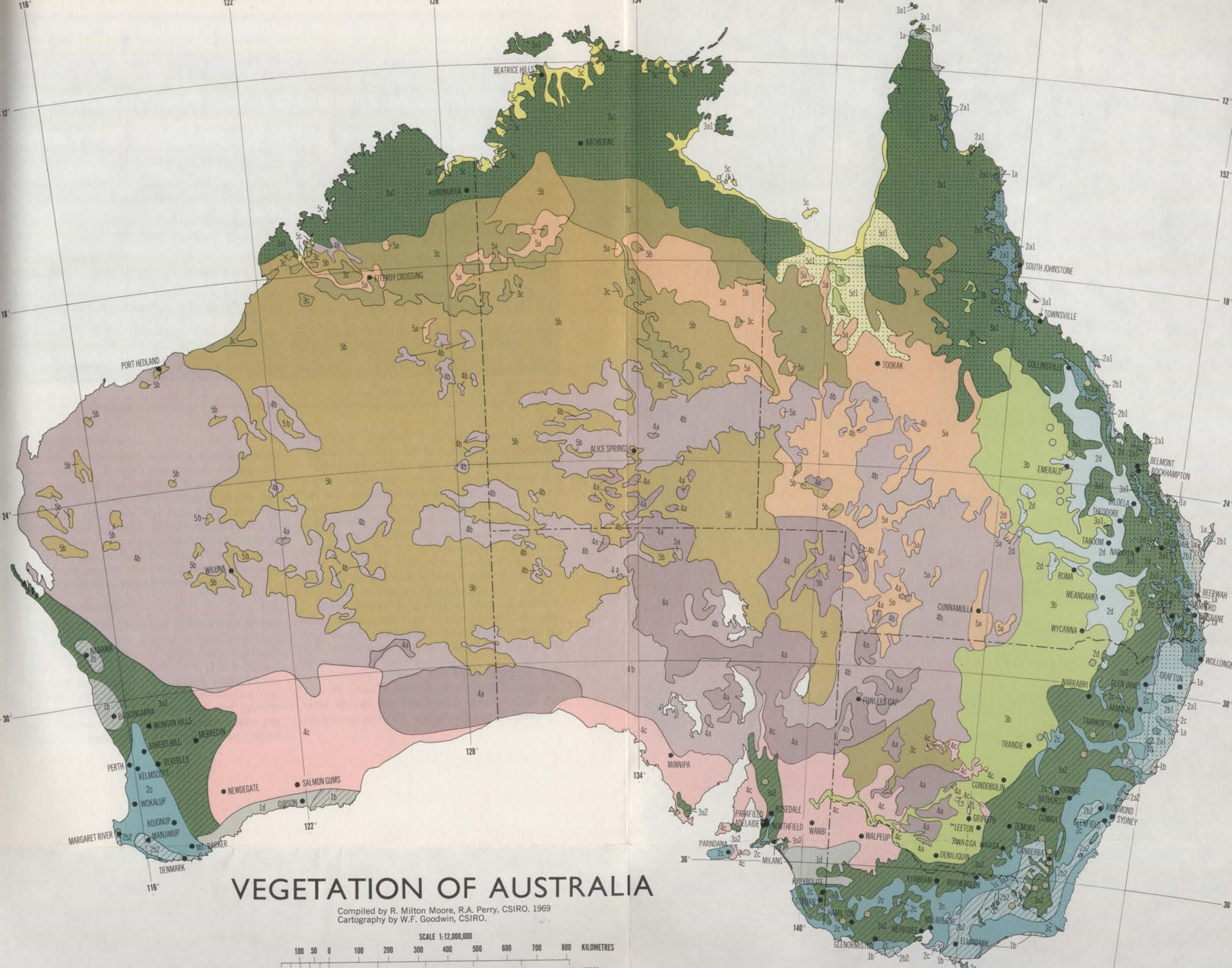
These are the Mitchell grass plains of Prescott (1931) and in part the semi-arid tussock grassland of Williams (1955). The dominants are perennial tussock grasses belonging to the genus Astrebla. The tussocks are 1·5 to 3 ft (0·5 to 1 m) tall and about 6 to 9 in. (15–23 cm) diameter at the base. Annual grasses, notably *Iseilema membranaceum*, *I. vaginiflorum*, and composites occupy the inter-tussock spaces after rains. Towards the higher rainfall limits of arid tussock grasslands *Dichanthium sericeum* becomes more frequent, and after a series of wet seasons may be co-dominant with *Astrebla* spp. (Pl. 22).

Arid Hummock Grasslands

Open grasslands of xeromorphic hummock-forming perennial grasses belonging to the genera Triodia and Plectrachne commonly called spinifex. Hummocks are from 3 to 5 ft (1 to 1·5 m) in diameter and often dead in the centre (Pl. 26). These are the sclerophyll hummock grasslands of Williams (1955). The inter-tussock areas are commonly bare except following rains when there is a dense population of annuals. Widely spaced low trees or shrubs are common in many of these grasslands which are mostly on aeolian sand surfaces (see Map 1).

Plate 21 Eucalypt shrubland (mallee): *Eucalyptus oleosa* and *Eucalyptus dumosa* on solonised brown soil, South Australia (Department of Agriculture, South Australia, photo)

Plate 22 Arid tussock grassland: *Astrebla* spp. (Mitchell grasses), Xerophytic Tussockgrass grazing land, Northern Territory (CSIRO photo)



VEGETATION OF AUSTRALIA

Compiled by R. Milton Moore, R.A. Perry, CSIRO. 1969
Cartography by W.F. Goodwin, CSIRO.

VEGETATION OF AUSTRALIA

Compiled by R. Milton Moore, R.A. Perry, CSIRO. 1969
Cartography by W.F. Goodwin, CSIRO.

SCALE 1:12,000,000

100 50 0 100 200 300 400 500 600 700 800 KILOMETRES

100 0 100 200 300 400 500 MILES

1. HEATHS

a. Tropical	1a
b. Temperate	1b
c. Alpine	1c
d. Mallee	1d

2. FORESTS

a. Rain forests. 1. Tropical and sub-tropical	2a1
2. Temperate	2a2
b. Wet sclerophyll forests. 1. Tropical and sub-tropical	2b1
2. Temperate	2b2
c. Dry sclerophyll forests	2c
d. Brigalow forests	2d

3. WOODLANDS

a. Sub-humid woodlands. 1. Tropical and sub-tropical	3a1
2. Temperate	3a2
3. Sub-alpine	3a3
b. Semi-arid shrub woodlands	3b
c. Arid and semi-arid low woodlands	3c

4. SHRUBLANDS

a. Shrub steppe	4a
b. Acacia	4b
c. Eucalypt (Mallee)	4c

GRASSLAND RESEARCH CENTRES

NARAYEN ●

5. GRASSLANDS

a. Arid tussock grasslands		5a
b. Arid hummock grasslands		5b
c. Coastal grasslands		5c
d. Sub-humid grasslands. 1. Tropical	○	5d1
2. Temperate	▨	5d2
3. Sub-alpine	▨	5d3

Symbol denotes grassland too small to map

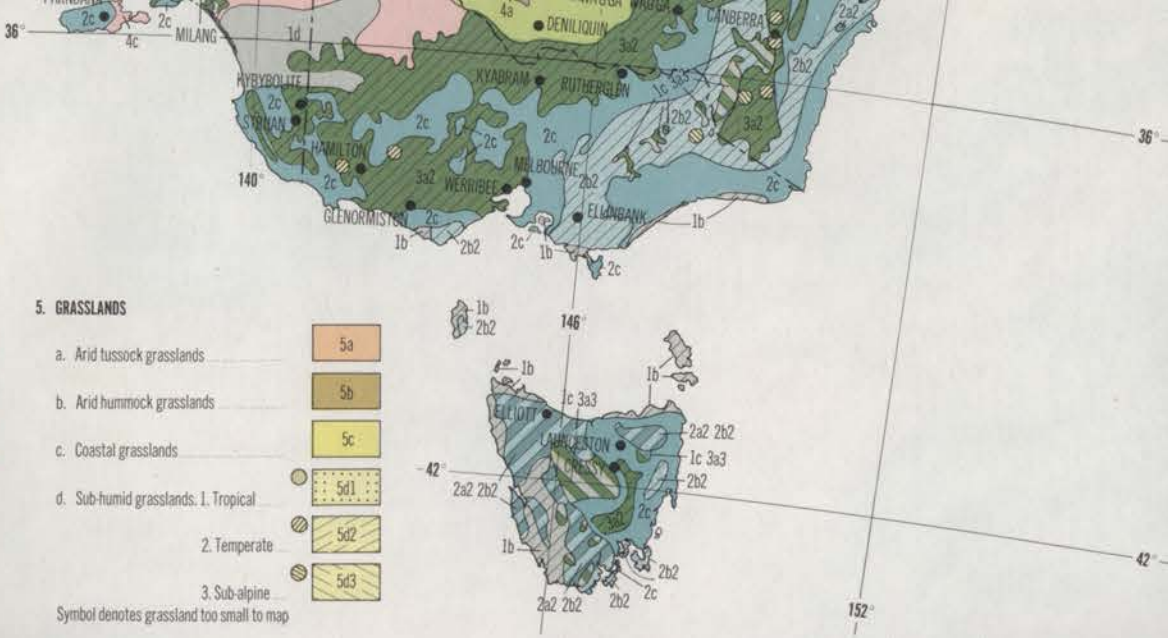


Plate 23 Coastal grasslands with saline mud flats: *Sporobolus virginicus* (salt-water couch) with *Arthrocnemum leiostachyum* (samphire) and *Suaeda australis*, Gulf of Carpentaria, Queensland (CSIRO photo)

Coastal Grasslands

These include saline, brackish, and freshwater communities. Saline communities occupy the inland edges of bare salt flats in coastal areas of northern Australia. The common species are *Sporobolus virginicus* and *Xerochloa imberbis*, grasses about 0·5 to 1 ft (15–30 cm) tall (Pl. 23).

In shallow fresh water and brackish swamps *Eleocharis* spp. or *Fimbristylis* spp. are dominant. Associated species are *Pseudoraphis spinescens*, *Leersia hexandra*, and *Oryza australis*.

Sub-humid Grasslands

Tropical. The principal community of this sub-formation is the *Eulalia fulva-Dichanthium fecundum* community of Perry and Christian (1954). The dominants are 3–5 ft (1–1·5 m) tall. Common associates are *Iseilema vaginiflorum*, *Aristida latifolia*, *Dichanthium tenuiculum* syn. *D. superciliatum*, *Bothriochloa* spp., and *Astrebla* spp. Further south and extending below the Tropic of Capricorn there are drier but related grasslands in which *Dichanthium sericeum* and *Bothriochloa erianthoides* are common species.

Temperate. There are two principal communities in this formation, one originally dominated by tall tussock-forming perennials, *Themeda australis*, *Poa caespitosa* sens. lat., and *Stipa aristiglumis*, and the other by *Stipa aristiglumis* and originally probably by *Themeda avenacea* (see Chapter 6). All of these species range from 3 to 7 ft (0·9 to 2 m) in height. As a result of grazing, the dominants are now short species of Stipa and Danthonia (see Chapter 12).

Other temperate grasslands with affinities to these two are one now dominated by *Lomandra* spp. (family Xanthorrhoeaceae) and *Danthonia* spp., and another near Cooma, N.S.W. (lat. 36°S) dominated by species of Stipa.

Sub-alpine. These are the sub-alpine sod-tussock grasslands of Costin (1954). The principal species are fine-leaved snow grasses *Poa caespitosa* sens. lat. and *Danthonia nudiflora*.

OTHER COMMUNITIES

Desert Sandhills

The communities typical of sandhills of the arid interior (see Map 1) are *Zygochloa paradoxa* (canegrass), *Triodia basedowii*, *Sida corrugata*, *Salsola kali*, *Plagiosetum refractum*, and *Eriachne aristidea*. In the interdune areas *Acacia* spp. and *Triodia basedowii* are the commonest species (Pl. 24).

Coastal Dunes

In northern Australia the principal species on foredunes are *Spinifex longifolius* and *Ipomoea pes-caprae*. The windward side of stabilised dunes has trees of *Casuarina equisetifolia* and bushes of *Salsola kali*, *Scaevola sericea*, and *Suriana maritima*. The lee side community is often a hummock grassland of *Triodia* spp.

In southern Australia the foredune plants are commonly *Atriplex cinerea*, *Cakile maritima*, or *Festuca littoralis*. On semi-stabilised dunes the rhizomatous grass, *Spinifex hirsutus*, is common. Other species that may be present are *Hibbertia volubilis*, *Lepidosperma* sp., *Scirpus nodosus*, and *Scaevola* sp. The plants of more stabilised dunes are *Acacia longifolia*, *Olearia axillaris*, *Leptospermum laevigatum*, *Correa alba*, and *Leucopogon* spp. Communities of these plants intergrade with Banksia heaths or with woodlands.

Mangroves

Shrub or low tree communities of tidal mudflats often showing species zonation particularly in northern Australia. From the water side landwards the principal species are those of Avicennia and Sonneratia, followed by Rhizophora, Bruguiera and finally by other species of Avicennia. In southern areas Avicennia occurs alone or with Aegiceras.

The common plants of salt flats both coastal and inland are *Arthrocnemum* spp. and *Salicornia* spp.

Plate 24 Arid hummock grassland (spinifex): *Triodia basedowii* (spinifex) foreground with *Zygochloa paradoxa* on dune ridge, Northern Territory (CSIRO photo)

OTHER ALPINE COMMUNITIES

Besides alpine and sub-alpine heaths, woodlands, and sod-tussock grasslands, there are bogs, feldmark (fjaeldmark), and herbfields in the alps of south-eastern Australia. The principal species of these communities are shown in Table 13 : 1.

INTRODUCED PLANTS

The modification of native plant communities by farming and grazing has provided habitats suited to alien species that have evolved in areas constantly disturbed by man. Except in the arid regions, disturbed sites in temperate Australia tend to be colonised by introduced species. The climatic ranges of many of these species appear to be wider in Australia than in the countries to which they are native. Perennial species believed to have originated in the Mediterranean appear to be better adapted to parts of Australia receiving rain in both summer and winter than to areas with a more typically Mediterranean climate (Moore 1967b).

Although many introduced species grow as well or even better in environments different to some degree from those where they originated, the naturalised plants of temperate Australia are largely European and north African, and those of northern Australia are mostly tropical and sub-tropical.

There are about 1300 introduced plants naturalised in Australia. These include some of the worst weeds and all of the sown pasture plants.

5

THE HERBIVOROUS WILD ANIMALS

H. J. FRITH

The Australian continent has been isolated from other land masses since the Cretaceous and the fauna which has developed in isolation is typically an island fauna. It includes a few endemic forms and lacks several basic animal types. The great majority of present-day animals developed from small ancestors that reached the continent by island hopping through the Indo-Malayan chain of islands from the Asiatic mainland. Several groups, particularly the marsupials and the rodents, have radiated widely to fill all or most available ecological niches.

The fauna in the Tertiary was unique among those of the continents in being dominated by herbivores with few attendant carnivorous species. There was a great development of herbivorous birds and mammals corresponding to the wide development of grasslands. These included several very large and browsing kangaroos, Sthenurus and Procoptodon; the largest, *P. goliath*, was 10 ft (3 m) tall. There was a family Diprotodontidae that included the largest marsupials that ever lived. They ranged in size from that of a sheep to *Diprotodon optatum* which was as large as a rhinoceros. There were two sorts of diprotodons; heavy browsing species, such as Diprotodon, on the one hand and more lightly built grazing forms on the other. The largest of the latter group was *Palorchestes azael* which was similar in size to an average heifer. There were also some very large emu-like birds including Genyornis and Dromornis.

The fossil record shows that there were few large carnivorous animals. The largest was a marsupial 'lion' (Thylacleo) but it is not known if it was a predator or scavenger. The most widespread predator was the thylacine or marsupial 'wolf' (*Thylacinus cynocephalus*), an animal that hunted in a solitary manner and could hardly have been a serious predator of the large herbivorous marsupials.

It is generally held that the Aborigines had little effect on the native fauna, but this cannot be so. They arrived from Asia accompanied by a highly developed placental predator, the dingo (*Canis familiaris dingo*), which rapidly replaced the thylacine on the mainland and preyed on the smaller marsupials. Tindale (1959) and Merrilees (1968) postulated that the widespread fires lit by Aborigines and allowed to burn uncontrolled probably caused considerable changes to the original vegetation over great areas and contributed greatly to the extinction of the giant herbivorous marsupials. The fauna was probably still adjusting to the Aborigines when European man arrived and introduced numerous placental herbivorous and carnivorous mammals and birds. Their effect on the native fauna has been profound and generally disastrous.

The present-day vertebrate fauna includes about 400 reptiles, 229 mammals and 700 birds. The mammals include 2 monotremes, 119 marsupials, and 108 placentals; among the placentals are over 50 rodents and 50 bats. In addition to the native fauna and the domestic stock there are now significant populations of at least 25 introduced birds and 12 introduced mammals living in the wild.

Although this chapter is concerned with the mammals and birds it should be recorded that among the insects there are very rich groups of termites, order Isoptera, ants, family Formicidae, and grasshoppers, family Acrididae, whose effect on grasslands is probably of greater significance than that of the vertebrate fauna.

The native wildlife has altered greatly due to settlement and the associated changes in habitat. Many animals of great scientific interest are now disappearing. Of the mammals the two monotremes remain abundant but of the marsupials five are possibly extinct and thirty-four endangered. It is probable, however, that critical taxonomic studies would reduce some of these forms to subspecies (Calaby 1963). The position with the placental mammals is similar, but due to a lack of data on distribution and to taxonomic difficulties, precise statements are difficult. The birds have survived better and none is known to be extinct, although a few have not been seen for a long time and groups associated with particular habitats have been greatly reduced in range and numbers. These include many birds that were associated with the grasslands before they were grazed by domestic stock. Despite the general decline in fauna a few species, including some important herbivorous ones, have been favoured by habitat changes and are expanding in range and numbers.

NATIVE HERBIVORES

The family Macropodidae includes about fifty marsupials ranging in size from the small musky rat-kangaroo (*Hypsiprymnodon moschatus*) weighing only about one pound (454 g), to the red kangaroo (*Megaleia rûfa*) and the grey kangaroos (*Macropus giganteus* and *M. fuliginosus*). Red kangaroos reach over 180 lb (82 kg) in weight and grey kangaroos a little less. The family is divided into two subfamilies; the rat-kangaroos, Potoroinae, include about ten species in five genera, the Macropodinae include eleven genera of wallabies, tree-kangaroos, and kangaroos. There is no real difference between a wallaby and a kangaroo; the smaller animals are called wallabies and the larger are called kangaroos. All are herbivorous with the exception of the musky rat-kangaroo, which is at least partly insectivorous.

Rat-kangaroos

Among the small marsupials known as rat-kangaroos are ten species in five genera. One Hypsiprymnodon is restricted to the rainforests of north Queensland but its status is unknown, one Caloprymnus is a rare species in arid grasslands, and the others are characteristic of open forest and woodland regions.

The rufous rat-kangaroo (*Aepyprymnus rufescens*) is still common in some places but has disappeared from most of the southern parts of its range. Of the four members of the genus Bettongia one, *B. gaimardi*, seems to be extinct on mainland Australia but survives as the subspecies *cuniculus* in Tasmania in satisfactory numbers. The ranges of the others have shrunk greatly.

Of the three members of the genus Potorous two are probably extinct but the other, the potoroo (*P. tridactylus*), remains in forests and long grass in Tasmania and some isolated colonies on the east and south-east coasts of the mainland.

Wallabies

There are about thirty species in nine genera on the mainland and a further five species in two genera in New Guinea.

The most important grassland wallabies are a group of large species of the genus Wallabia that range from the Kimberley Division of Western Australia in the coastal districts and adjacent highlands of northern and eastern Australia and along the south coast to south-east South Australia. Some replace one another geographically and others overlap in range but are separated ecologically.

The sandy wallaby (*W. agilis*) extends from the Kimberleys through northern Australia to about Rockhampton, Queensland, where it overlaps the red-necked wallaby (*W. rufogrisea*) which extends to south-east South Australia and throughout Tasmania where the local race is known as Bennett's wallaby. Sandy and red-necked wallabies are characteristic of forest country with some undergrowth; they graze in clearings both natural and man-made on the edges of the forest. The sandy wallaby throughout its range has established a reputation as a competitor with stock, especially where sown pastures are being established. Control is by shooting and poisoning (Tomlinson, Gooding, and Harrison 1954; Gooding 1963; Gooding and Long 1958). The red-necked wallaby has the reputation of being a nuisance on pastures in eastern Australia; in Tasmania it was reported as a serious hindrance to pasture establishment, and poisoning techniques using sodium fluoroacetate have been employed.

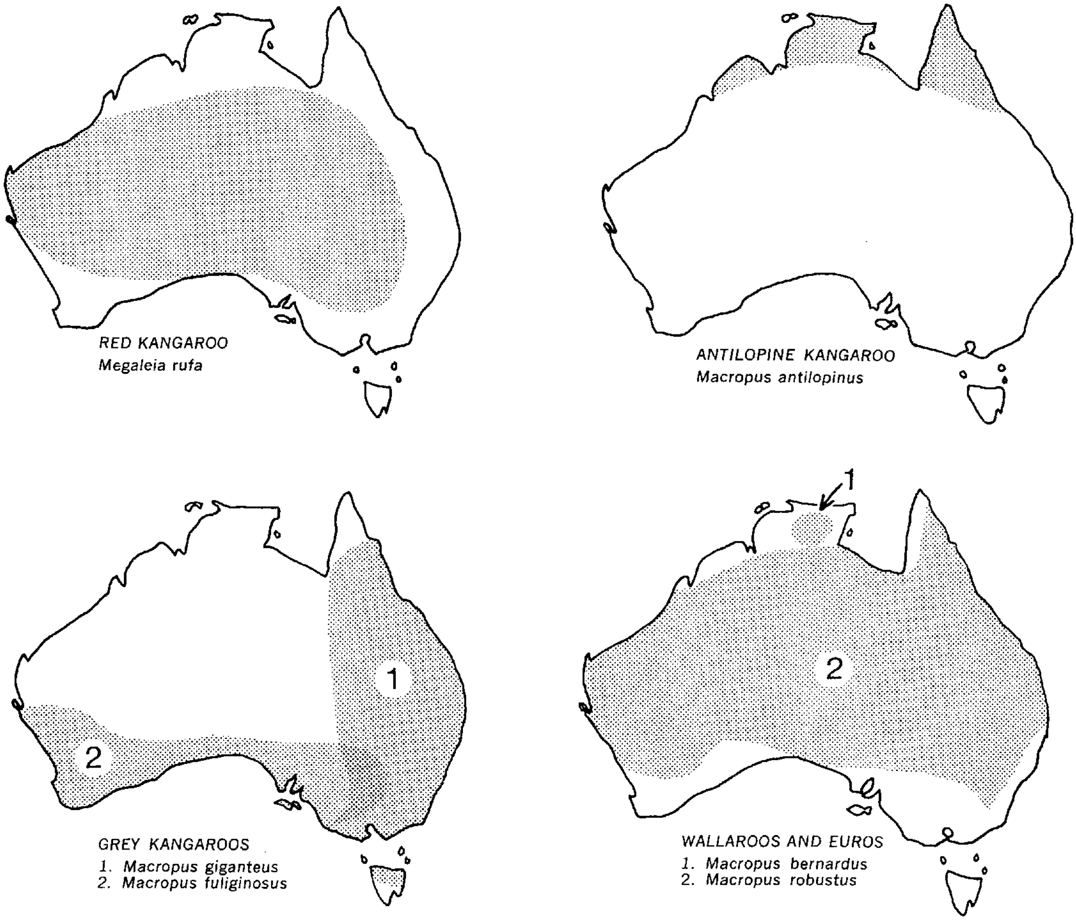
Although there has been no detailed study of the ecology of either of these wallabies, field observations strongly support the contention that they have increased greatly in abundance in some places due to partial clearing of the land and the establishment of more extensive grasslands within the forest zones. The same is not true of the other wallabies in the group, however.

The whiptail wallaby (*W. parryi*) extends from near Cooktown, Queensland, to the Clarence

River district, New South Wales. It overlaps in range both the sandy and the red-necked wallaby but favours more open forests and scattered timber with coarse native pastures. Forestry and cattle raising constitute the main landuse in these areas and, as at present practised, do not affect the wallabies greatly. Indiscriminate shooting in some districts has caused local decline in their numbers.

The swamp wallaby (*W. bicolor*) that extends along the east and south coasts from Cairns, Queensland, to south-east South Australia, and the black-gloved wallaby (*W. irma*) of south-west Western Australia, the black-striped wallaby (*W. dorsalis*), and the parma wallaby (*W. parma*) of eastern Australia are of little importance as herbivores as they are restricted to denser scrubs and forests and seldom emerge from them. The tammar (*W. eugenii*) is locally abundant on Kangaroo Island where it has apparently been favoured by partial clearing and the establishment of sown pastures. It has declined seriously in the rest of its range, mainland South Australia and south-western Australia.

The numerous other small macropodids were probably never of great significance to grasslands. Most are restricted to dense forests and scrubs and graze only the edge, like the pademelons (Thylogale). The tree kangaroos (Dendrolagus) are adapted to life in rainforest trees. *Setonix* inhabits dense coastal and swamp communities and the rock-wallabies (Petrogale) are



RED KANGAROO
Megaleia rufa

ANTILOPINE KANGAROO
Macropus antilopinus

GREY KANGAROOS
1. *Macropus giganteus*
2. *Macropus fuliginosus*

WALLAROOS AND EUROS
1. *Macropus bernardus*
2. *Macropus robustus*

Fig. 5 : 1 The distribution of the large kangaroos (from H. J. Frith and J. H. Calaby, *Kangaroos*, Melbourne, Cheshire, 1969)

characteristic of steep stony hills and cliffs. The nail-tailed wallabies (Onychogalea) and hare wallabies (Lagorchestes) have declined greatly. They were abundant in more open woodlands and savannahs but have suffered from changes to the ground cover caused by domestic stock and are now generally rare; some species are almost certainly extinct.

Kangaroos

The large kangaroos are found throughout the continent. There are five types, more or less divided by their habitat although there is considerable overlap. Their distribution is shown in the map (Fig. 5 : 1). The red kangaroo (*Megaleia rufa*) has a more or less continuous range throughout the drier parts of the mainland outside the forest and eucalyptus woodland zones. It is the characteristic animal of the open plains.

Grey kangaroos are characteristic of the forests and denser inland scrubs. The grey kangaroos range from Cape York Peninsula throughout eastern Queensland, New South Wales, Victoria, Tasmania, the southern part of South Australia, and south-western Western Australia. There are five fairly distinct colour varieties and opinion has differed as to their status. Some have considered them to be races of the one species (*Macropus giganteus*) and others have considered them distinct species. Recently, however, evidence has been produced, based on blood serum protein analysis and differences in gestation period, length of oestrus cycle and other biological characteristics, to show that at least two species exist. These are an eastern form, *Macropus giganteus*, and a western form *M. fuliginosus* (Kirsch and Poole 1967). The two overlap and live in sympatry in western New South Wales.

The euros or wallaroos are also known as hill kangaroos and are characteristic of stony and hilly regions. There are two species, one, *M. robustus*, is found throughout the continent wherever suitable habitat occurs except in the most northerly tropics, the extreme south-west of Western Australia, south-east South Australia, and the State of Victoria. The other, the black wallaroo (*M. bernardus*), is found only in Arnhem Land (Northern Territory).

The antilopine kangaroo (*Macropus antilopinus*) is a large animal, superficially similar to the red kangaroo in appearance. It is restricted to the tropical woodlands of the north and north-east, but little exact data have been recorded on its distribution and practically nothing is known of its biology.

An interesting feature of the biology of kangaroos is the occurrence of delayed implantation or embryonic diapause (Sharman 1959). Soon after giving birth the female experiences *post partum* oestrus and is usually fertilised again. The fertilised egg develops for a few days and then ceases development, remaining as a stored blastocyst in the uterus. Should the young already in the pouch perish or be lost, or in any case when it leaves the pouch of its own accord, this delayed blastocyst recommences development and in due course another young is born. Gestation periods are remarkably short, 33 days for the red kangaroo, 36 and 31 days for the eastern and western grey kangaroos respectively. The young is born in a very primitive state and continues its development for six months or more in the pouch.

The anatomy of the stomach and the physiology of digestion have many features similar to those of the ruminants (Griffiths and Barton 1966) and some species can very efficiently use low-quality forage in droughts or other times of stress. It has been shown that some kangaroos convert plant protein to animal protein more efficiently than do ruminants. The carcass has a higher proportion of protein (muscle) than other grazing animals (Tribe and Peele 1963).

As the largest of the native herbivorous mammals the kangaroos and wallabies are often thought to be competitors of stock and there has been some research on this aspect. Studies of the plants grazed by kangaroos and stock in the same place have shown that the animals are not in direct competition at all times. Each has distinct food preferences. In one such study with red kangaroos, grey kangaroos, and sheep in south-west Queensland it was shown that grey kangaroos ate more grasses and browsed more shrubs than did either sheep or red kangaroos. Although many plants were grazed both by sheep and by red kangaroos there were significant differences in the plants preferred in each month (Griffiths and Barker 1966). In north-west Australia Storr (1968) showed that when food was abundant the red kangaroos, euros, and sheep selected different plants, but although the differences in the plants eaten by the euros on the one hand and the sheep and red kangaroos on the other hand were considerable there was little difference in the grazing habits of the last two animals. In the dry summers there was little difference in the plants grazed by all three animals.

There is no doubt that several of the large kangaroos are animals that prefer a particular stage of botanical succession and have increased very greatly in abundance as a result of changes to the grasslands caused by domestic stock. There is, for example, evidence that in the early days of settlement, when much of the semi-arid plains of New South Wales carried shrub woodlands of *Acacia pendula* and other trees with saltbush, the animals were uncommon. As the woodlands were removed or thinned and the ground cover replaced by species of Danthonia, other grasses and annual herbs (see Chapters 6 and 12), the red kangaroos increased very greatly in numbers (Frith 1964).

Similarly with euros in north-west Western Australia, Ealey (1968) has shown that at the beginning of European settlement the valleys were well grassed and the stony hills were covered with spinifex (*Triodia* spp.). The valleys supported red kangaroos and the stony hills euros. Wrong grazing methods resulted in the destruction of the grasslands in the valleys and their invasion by spinifex. The effect of this change was that red kangaroos disappeared from the area and euros colonised the valleys and flat land and increased enormously in numbers. On one property of 211,000 acres (86,510 ha) that could carry only 2,300 sheep, 15,000 euros were poisoned between 1946 and 1951 yet 13,000 could still be poisoned in a three-month period on one half of the property in 1959 (Ealey and Richardson 1960).

Kangaroos have been used as a source of hides since the early days of settlement and have also been destroyed in great numbers as pastoral pests. Recently an export market was found for kangaroo meat and a considerable industry developed until at least one million kangaroos were being slaughtered each year. There have been few controls and the industry has been an exploitative one. The animals are harvested without regard to age, sex, or number. When one species, the red kangaroo, declined in numbers other species became more important and the annual harvest was only maintained by continually increasing the area of operation.

The combined effect of the industry and a serious drought which caused a cessation of breeding and increased the natural mortality resulted in a great decline in kangaroo numbers. In western New South Wales numbers of the red kangaroos were reduced by 75 per cent between 1960 and 1966 (Frith 1964) and around Alice Springs, Northern Territory, by 60 per cent (Newsome 1966). This is gross exploitation of a valuable resource as there is little doubt that the animals can be managed on a sustained yield basis. A long-term husbandry based on both domestic stock and kangaroos in arid zones would probably be less productive in the short term but certainly more permanent than one based on domestic stock alone.

Other Native Herbivores

There is a large group of native rats and mice. There are about fifty species in the one family, Muridae, and these have undergone radiation second only to the marsupials. Not a great deal is known of their biology. There are many desert species that could be important in the regeneration of arid grasslands because they eat seed. Among these are *Notomys alexis* and *Pseudomys hermannsburgensis* that are the most desert-adapted of rodents of any continent. They have a great ability to conserve water and to live on dry seed, producing very concentrated urine and dry faeces.

The plague rat (*Rattus villosissimus*) is found in the inland parts of the tropics and periodically irrupts. It moves in vast numbers destroying anything edible in its path. Little is known of its biology nor is there any real idea of what effect it has on pastoral production, but this is probably considerable. Closely related to *R. villosissimus* are two other species, *R. colletti* and *R. conatus*, that have shown a considerable ability to irrupt when reached by agriculture—the former in subcoastal Northern Territory and the latter in north-eastern Queensland. There is a good deal to be learned of the factors influencing animal irruptions in a study of this group of species.

There are many other herbivores, and some are widespread, but none is of great importance to grasslands except in local areas. They include the wombat (*Vombatus ursinus*) of the alpine and sub-alpine communities and some coastal areas and the two hairy-nosed wombats (*Lasiorhinus*) of some semi-arid shrub steppe limestone country of South Australia and parts of Queensland. The eastern populations have disappeared from New South Wales and only a remnant is left in Queensland.

The emu is a wide-ranging large herbivorous bird that is abundant in semi-arid grasslands and is clearly well adapted to live in them. Two grazing waterfowl, the wood duck (*Chenonetta jubata*) of the temperate regions and the grass whistle duck (*Dendrocygna eytoni*) of the tropics, have been benefited as a result of domestic stock altering tall grazing lands to short ones. Both are at times accused of grazing newly sown pastures. The same criticism is made about the Cape Barren goose (*Cereopsis novaehollandiae*), the black swan (*Cygnus atratus*), and the mountain duck (*Tadorna tadornoides*). In each case any damage done is generally minor.

Another bird of interest to grasslands is the Tasmanian native hen (*Tribonyx mortierii*), a flightless rail. Entirely herbivorous, it exists in large numbers in Tasmania and frequently causes damage to sown pastures and forage crops. The bird lives in swampy areas and in heavy cover along creeks, grazing out across adjacent pastures, and on the edges, close to cover, can remove up to 15 per cent of the production (Ridpath and Meldrum 1968 a and b). The related black-tailed native hen (*T. ventralis*) is a highly nomadic mainland species found in the inland. It periodically irrupts, sometimes extensively, and is said to damage pastures and crops.

INTRODUCED HERBIVORES

Although some native herbivores are at times in competition with stock, none is in the same class as pests as the animals deliberately introduced by European man and those that have been permitted to develop feral populations.

Rabbit

The rabbit (*Oryctolagus cuniculus*) of Europe came to Australia with the First Fleet in 1788 and in the next fifty years there were several further introductions. The rabbits were, however, domestic types. Due to this and to the fact that they were released in coastal districts enclosed by inhospitable eucalyptus forests they failed to spread, although colonies did become established.

There is little doubt that the real rabbit invasion began in 1859 with a shipment of rabbits that were released near Geelong in Victoria; this was in open woodlands that merged into the inland plains. These were genetically wild rabbits released into a suitable habitat with no serious barrier to their spread (Ratcliffe 1959). From Geelong they rapidly extended north and west. They had crossed the Murray River by 1881, they reached the Queensland border, 500 miles north, in 1886, and moved on to the Gulf of Carpentaria. To the west they reached Fowlers Bay in 1891 and Eucla inside the Western Australian border in 1894, and some arrived on the shores of the Indian Ocean in 1907. The westerly movement covered 1100 miles (1771 km) in 16 years. As the population became established at Geelong rabbits were carried to other places, including Adelaide, South Australia, and released there.

The initial spread was rapid and extensive but the animals did not become established throughout the whole of the early range. The next few decades were occupied in ecological consolidation. Rabbits now occupy about half the continent. The rabbit nowhere extends far north of the Tropic of Capricorn. In the temperate zone it is widespread but its distribution is affected by a number of ecological factors; it cannot live in the extensive eucalyptus forests, nor can it survive in the heavy black soil plains, and it is not abundant in regions of high summer rainfall. The present distribution is shown in Fig. 5 : 2.

Because of the paramount importance of the rabbit as a pest there has been a great deal of research on its behaviour, ecology, physiology and parasitology by CSIRO and other agencies. It is not proposed to describe this but to refer the reader to the convenient summaries of Ratcliffe 1959, Ratcliffe and Calaby 1958, Fenner and Ratcliffe 1965, and the extensive writings of K. Myers, R. Mykytowycz, W. Poole and their colleagues, mainly in the journal *CSIRO Wildlife Research*.

The introduction of rabbits was a disaster to the native fauna and to the grazing lands of the continent. It occurred at the time when settlers were stocking the inland and learning to manage the delicately balanced native vegetation. The sudden invasion of the area by hordes of rabbits

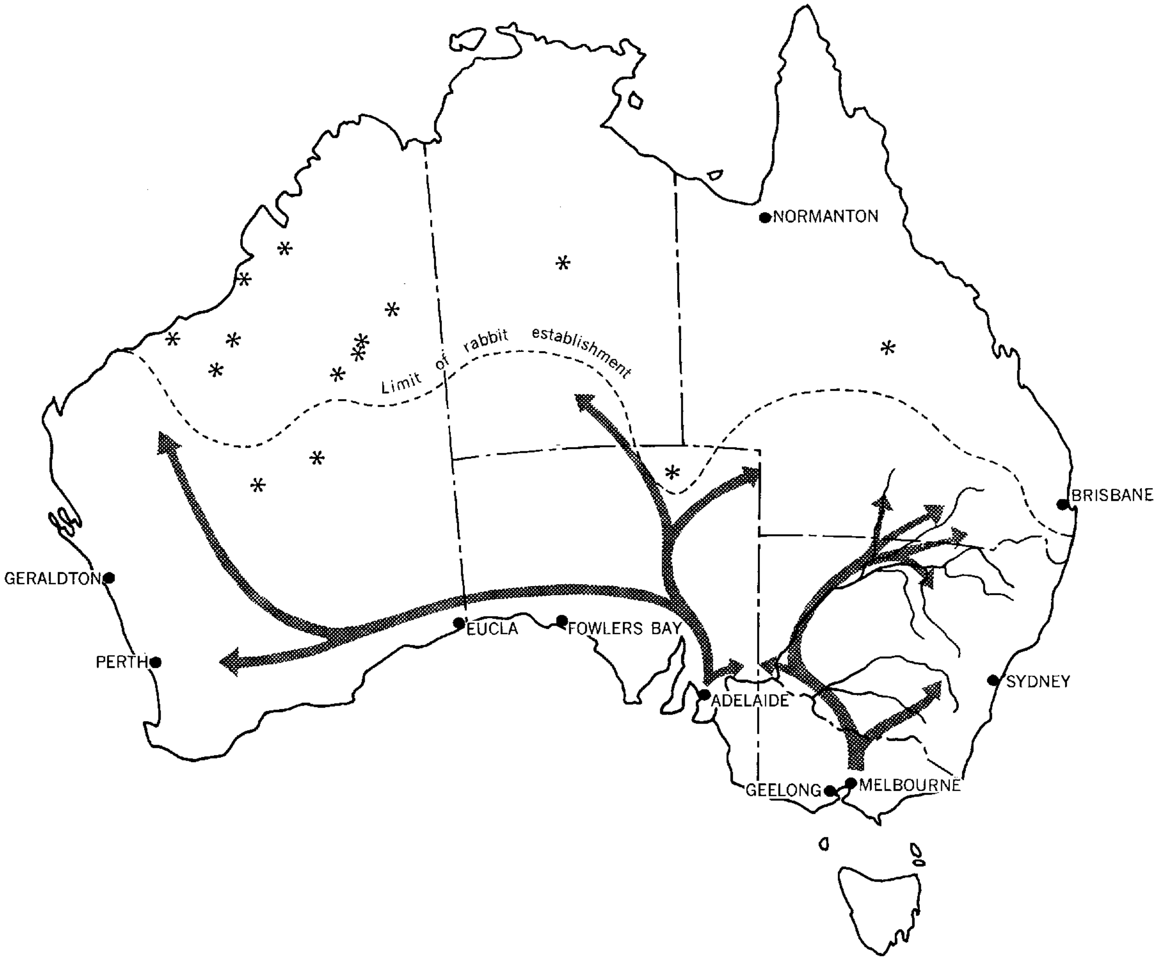


Fig. 5 : 2 The distribution of the rabbit in Australia. The arrows show the probable routes of its colonising spread on the mainland. The stars show the location of colonies that failed to become permanently established (from *Biological Science: The Web of Life*, Canberra, Australian Academy of Science, 1967)

led to gross over-grazing of herbage and edible shrubs and to permanent degradation of the grazing lands. It is not possible now to separate the effects of the rabbits and the sheep themselves but the combined result is shown by the decline in carrying capacity. In 1891 the Western Division of New South Wales carried 7,300,000 sheep, but by 1911 the number had fallen to 1,500,000, and something like this figure has been maintained ever since.

It has been difficult to measure losses in production due to rabbits but there were some striking improvements in the appearance and stock-carrying capacity of country when the disease myxomatosis swept through rabbit populations and caused a major decline in their numbers. Hills that had been bare and stony throughout living memory became green and well grassed; plains that had always been bare became covered with herbage several inches tall. It was estimated that in 1952–3 alone the removal of rabbits led to an increased production of wool of about 70 million lb (31,780,000 kg) (5·47 per cent of the total production in that year). The increase in the value of the production of wool and meat in 1952–3 was about $68 million.

In higher rainfall regions the effects of rabbits are less permanent and often less obvious but can be estimated by contrasting the productivity of areas from which rabbits have been eradicated with that from areas where they are uncontrolled. One such example has been well documented in the Central Western Slopes areas of New South Wales. A property became heavily infested with rabbits and its sheep-carrying capacity fell by 50 per cent in six years, while wool production fell by two-thirds. A major rabbit control program was instituted and within one year the carrying capacity had doubled and the wool production had trebled.

Myers and Poole (1963), working with enclosed populations of rabbits, have shown great changes in composition of rye grass and clover pastures when grazed by rabbits. The proportion of rye grass in the pasture was greatly reduced and that of less palatable grasses and weeds was increased. At rabbit densities of 10–20 rabbits per acre the changes were considerable and at this density pasture yield could be decreased by as much as 25 per cent. By comparing the numbers of rabbits that could be carried permanently with the local agronomic assessment of sheep-carrying capacity it was estimated that 7–10 rabbits per acre (17–25 per ha) were about equal to one sheep per acre (2·5 per ha) in grazing capacity. The rabbits were more competent than sheep in selecting from the pastures the seedlings, seed, and roots that are the basis of the ability of the pasture to maintain itself.

Soon after the rabbit began to spread it was obvious that it was going to become a major pest and efforts were made to contain it. The earliest attempts were by means of netted barrier fences. Many of these were built, particularly along State boundaries, and they totalled thousands of miles in length. One single fence in Western Australia covered 1100 miles (1771 km). Some of them were built through virtually unexplored desert country. Although some are still maintained and serve a useful purpose, in the main they were not effective in preventing the spread of rabbits. This was partly because of the impossibility of maintaining them in the state of effectiveness that was essential. In some cases the rabbit wave had reached the fence before it was completed. On individual properties well-maintained boundary fences are the basis of successful control; the animals are eradicated inside the fence which then serves as a barrier against reinfestation.

Rabbit eradication is difficult and expensive. It involves the use of poison baits, the fumigation of burrows, the destruction of warrens by ripping them up, the destruction of other cover, and the use of steel traps and dogs. Unfortunately not all landholders had the money or energy to complete such a campaign and in the inland where the holdings are large and of relatively low carrying capacity capital values were not sufficient to support the cost of fencing and eradication.

The first general control was achieved in late 1950 when, after many years' work, the disease myxomatosis was successfully established and was spread mainly by mosquitoes through the rabbit population. In the next three years the numbers of rabbits had been reduced by 80–90 per cent.

Since then there has been a biological adjustment between the host and the virus resulting in a decrease in its virulence and an increase in the resistance of the rabbit population. There have been large-scale inoculations of highly virulent laboratory strains of the virus in some States in an attempt to maintain the effectiveness of the disease. The rabbit flea, the principal vector of the disease in Europe, is now being introduced into Australia to assist the spread of the virus.

Against this background of a relatively low but increasing rabbit population traditional methods of control have been improved and intensified. Sodium fluoroacetate, a powerful poison, has been added to the armoury. Very extensive studies of rabbit ecology and behaviour in enclosed and in wild populations in the main climatic regions of the rabbit's range are increasing the effective strategy of rabbit control.

Hare

The hare (*Lepus europaeus*) was introduced into Victoria in the 1870s and is now widely spread in much of south-eastern Australia, particularly in the better-grassed areas. It has never caused much concern but there has been no study of its grazing habits and of the degree with which it competes with stock. Perhaps such a study would produce surprising results. It is quite mobile and travels greater distances to feed than does a rabbit and is twice as large. It can congregate to graze on small areas of newly sown or irrigated pasture and in these situations, at least, its effect might be severe.

There seems little doubt that since the reduction of rabbit populations the numbers of hares have increased in some places and this trend seems to be continuing. There is little or no organised control although in some districts a bonus is paid for each hare scalp and in some there is spasmodic shooting and trapping.

Equines

There are a number of feral populations of horses, ponies, and donkeys but none has been studied in any detail. Wild horses or brumbies (*Equus caballus*) are widespread in many thinly settled areas and in some, particularly in the Northern Territory, are a serious pest not only because of their impact on grazing lands but also because their presence has a disturbing effect on stock and they break fences and generally complicate management.

Timor ponies (*E. caballus*) are common on Cobourg Peninsula, Northern Territory, where they were introduced as domestic animals, but they have not spread from that peninsula.

During much of the early settlement and exploration of the inland, donkeys (*E. asinus*) were widely used as draught animals and considerable populations of feral animals now exist in north-western Western Australia and the Northern Territory. They are considered a very serious pest in some marginal grazing lands.

Cattle

Water buffaloes (*Bubalus bubalis*) were brought from Timor to the Northern Territory between 1825 and 1838. They were landed at Melville Island, Raffles Bay, and Port Essington to provide domestic stock. Some escaped and some were released when these settlements were abandoned. The animals spread and are now abundant on the coastal and sub-coastal plains between Darwin and Arnhem Land where they are the dominant grazing animal. Smaller numbers extended westward to Port Keats and a few have strayed east to the shores of the Gulf of Carpentaria.

The animals are well adapted to coastal grasslands and the populations are very successful. Those on the plains between Darwin and Arnhem Land have been studied by Tulloch (1967). In the wet season the animals, which live in social units, tend to leave the plains and disperse more widely through the eucalptus woodland, but in the dry season they are largely congregated on the black soil plains. The average densities varied seasonally from 11 to 46 per square mile in the one year, but in particularly favourable areas there were as many as 1–2 buffaloes to the acre (2·5 ha). Little is known of the effects of buffalo grazing on the grasslands but many areas are very closely grazed and it is certain that there have been profound changes.

Until World War II buffaloes were hunted for their hides and there was a profitable industry. However, in the early 1950s the industry became uneconomic and collapsed. In 1959 a new industry based on buffalo meat developed and is now well established. The Northern Territory Administration has protected the industry and afforded it meat inspection facilities. Some areas are now managed specifically for buffalo production. In 1965–6 17,000 animals were slaughtered to provide products worth $885,000.

The banteng (*Bos javanicus*) was originally introduced to Port Essington, Northern Territory, and has since become very numerous on Cobourg Peninsula although it has failed to spread beyond it. Within this area it occurs in all habitats but for preference grazes the plains of *Fimbristylis* spp. behind the coastal dunes. The closely grazed nature of these plains as well as a very distinct browse line on some trees suggests that the grasslands are over-utilised. As the area is a sanctuary for native wildlife the presence of these exotic animals is most unfortunate.

Other Feral Animals

The camel (*Camelus dromedarius*) was originally imported to assist transport in the arid interior. It is now widespread in these regions and large mobs can be encountered both in the unsettled deserts and in pastoral districts. There has been no study of their ecology but camels are obviously very destructive to grasslands and the native shrublands. Some control is attempted from time to time by shooting.

Other feral animals include goats (*Capra hircus*) and several species of deer (Cervus). The goats are numerous in the inland and clearly very destructive but little is known of their distribution or ecology. The policies of the States with regard to deer are diverse. In some cases they are considered pests, in some game, and in others just ignored.

CONSERVATION

The herbivorous animals and, for that matter, many other native animals have declined greatly as a result of the impact of introduced predators and the competition provided by the introduced herbivores both domestic and wild. These effects far outweigh those of any deliberate persecution that has occurred. No habitat except perhaps the densest rainforest is free of introduced mammals or remains in anything like its original state.

There are not enough reserves in Australia to ensure conservation of the fauna and such reserves are particularly lacking in the grazing lands. At present efforts are being made by some States to increase the areas reserved, but the scale of effort needs to be greatly enlarged.

The idea that the acquisition of a reserve is enough to ensure the survival of an animal population persists in some quarters, but this is really only the beginning. Many animals cannot survive unless the introduced competitors are removed from the reserve or at least their numbers greatly reduced. Many species of native fauna are associated with a particular stage of botanical succession and if they are to be abundant the reserve needs to be managed so that this stage of succession is maintained. In many animals the populations need to be manipulated in various ways if, with close protection, they are not to increase in numbers to the point where they destroy their own habitat. In addition many wide-ranging animals including the large kangaroos are valuable resources and their conservation depends on the development and procedures of multiple landuse where they can be conserved not only in reserves but throughout the populations in pastoral areas.

The recognition of the need for management of populations of wild animals in Australia has unfortunately developed very late in man's history of the exploitation of the continent.

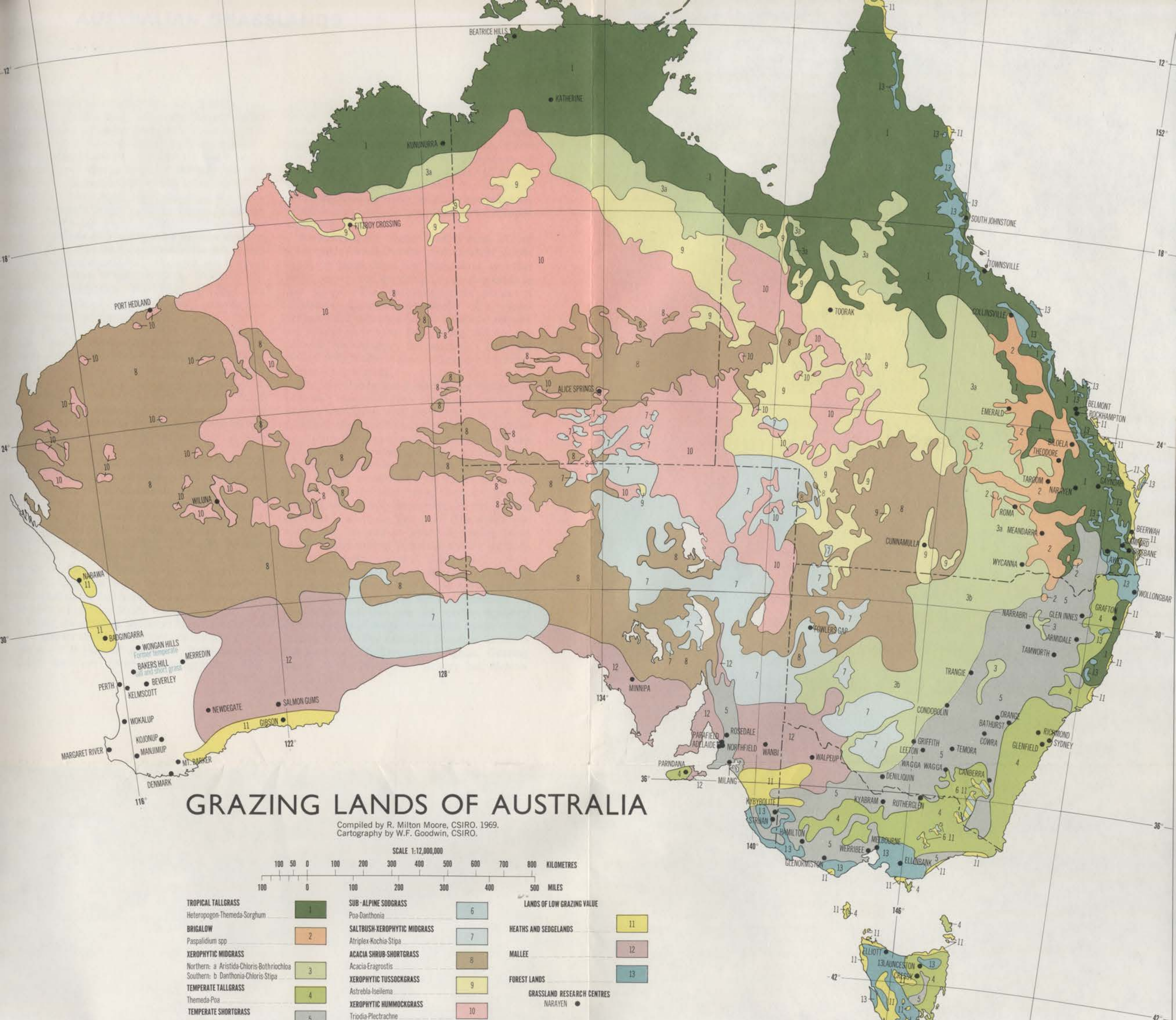
B

THE GRAZING LANDS AND PASTURES

AUSTRALIAN GRASSLANDS (MAPS 4 AND 5)
TROPICAL AND SUB-TROPICAL FORESTS AND HEATHS
  Grazing lands: Tropical Tallgrass
    Heaths and Forestlands of low grazing value
  Pastures: Tropical Perennial
TROPICAL AND SUB-TROPICAL WOODLANDS AND GRASSLANDS
  Grazing lands: Tropical Tallgrass
  Pastures: Tropical Annual
THE BRIGALOW
  Grazing lands: Brigalow
  Pastures: Xerophytic Perennial Grass
WET TEMPERATE FORESTS AND HEATHS
  Grazing lands: Temperate Tallgrass
    Heaths, Sedgelands, and Forestlands of low grazing value
  Pastures: Temperate Perennial
DRY TEMPERATE FORESTS AND HEATHS
  Grazing lands: Temperate Tallgrass
    Heathlands of low grazing value
  Pastures: Temperate Perennial Grass-Annual Legume
    Mediterranean Annual
SOUTH-EASTERN TEMPERATE WOODLANDS AND GRASSLANDS
  Grazing lands: Temperate Shortgrass
  Pastures: Temperate Perennial Grass-Annual Legume
    Mediterranean Annual
SUB-ALPINE AND ALPINE COMMUNITIES
  Grazing lands: Sub-alpine Sod-tussock grass
    Heathlands of low grazing value
  Pastures: Temperate Perennial (in part)
SOUTH-WESTERN TEMPERATE FORESTS, WOODLANDS, AND HEATHS
  Pastures: Temperate Perennial Grass-Annual Legume
    Mediterranean Annual
THE MALLEE AND MALLEE HEATHS
  Grazing lands: Mallee lands of low grazing value
    Xerophytic Midgrass
  Pastures: Mediterranean Annual (in part)
    Temperate Perennial Grass-Annual Legume (in part)
SEMI-ARID WOODLANDS
  Grazing lands: Xerophytic Midgrass
  Pastures: Mediterranean Annual (in part)
ARID SHRUBLANDS AND GRASSLANDS
  Grazing lands: Saltbush-Xerophytic Midgrass
    Acacia Shrub-Shortgrass
    Xerophytic Tussockgrass
    Xerophytic Hummockgrass
WATER AND IRRIGATED PASTURES

GRAZING LANDS OF AUSTRALIA

Compiled by R. Milton Moore, CSIRO. 1969.
Cartography by W.F. Goodwin, CSIRO.



6

AUSTRALIAN GRASSLANDS

R. MILTON MOORE

The grazing lands and pastures as defined in the preface to this book constitute the Australian grasslands. They are classified in Table 6 : 1 and their distributions are shown in Maps 4 and 5.

Grazing lands are classified on the bases of climate, the physiognomy of the communities, and the characteristics of the common edible species. For purposes of classification the boundary between tropical and temperate in eastern Australia is taken to be a line running north-west from latitude 32°S on the coast (high rainfall) to latitude 29°S at the inland limit of the sub-humid area (approximately the 20 in. (508 mm) annual rainfall isohyet at latitude 29°S). North of this line the temperate Danthonia and Stipa are largely replaced by the tropical genera Dichanthium and Bothriochloa.

Although grasses of the genera Stipa and Poa are important in temperate grazing lands their systematics are confused and uncertain. There are reputedly several distinct species within *Poa caespitosa* auctt. aust. but as yet no published descriptions, and in this book all forms from the tall coarse tussocky species of moist sites in temperate woodlands to the short fine-leaved snow grasses of the alps are included in *Poa caespitosa* sens. lat.

The short to mid-height forms of Stipa common in temperate woodlands are designated *Stipa falcata* and the more robust forms of shrub woodlands and arid communities are called *S. variabilis*. This is in conformity with published ecological studies of these woodlands (e.g. Biddiscombe 1953, 1963; C. W. E. Moore 1953 (a); R. M. Moore 1967a; O. B. Williams 1956) but Dr N. T. Burbidge (private communication) considers *Stipa falcata* is likely to be restricted to the fine-leaved form of the Southern Tablelands of New South Wales.

In the classification shown in Map 4 and Table 6 : 1 grasses above 3 ft (91 cm) are tall and those below 1·5 ft (45 cm) are short. Between these limits they are designated midgrasses. The grazing lands of temperate woodlands and grasslands are designated Temperate Shortgrass because the grasses common today are mostly less than 1·5 ft (45 cm) (Pls. 43, 45, 46). There are places, particularly in the grasslands of northern New South Wales, where tall species such as *Stipa aristiglumis* and *Poa caespitosa* sens. lat. have survived but these are relatively small in area and are not classified or mapped separately.

Rainforests, the higher rainfall areas of wet sclerophyll forests, heaths, and eucalypt shrublands (in part), have few herbaceous or other edible species and are classed as grazing lands of low value. The wet buttongrass plains of Tasmania, composed principally of a cyperaceous plant (*Gymnoschoenus sphaerocephalus*), are also of little value for grazing and are not suitable environments for pastures. They are classed with heaths as lands of low grazing value (Table 6 : 1, Map 4).

The woodlands and forests of the south-west originally resembled their counterparts in south-eastern Australia and herbaceous species in particular were similar or closely related to those in eastern temperate woodlands. For reasons not completely understood but almost certainly related to the hot dry summers and light sandy soils of the south-west, the native perennial grasses (like the later sown perennial pasture species) were rapidly eliminated by the grazing of confined domestic livestock. The south-west today may be said to have no grazing lands (Map 4) and animal production there depends entirely on sown species (Chapter 14).

The species shown as characteristic of particular grazing lands in Map 4 and Table 6 : 1 do not always occur in the same community; in some instances they are the species typifying different parts of the environmental ranges of the grazing lands. For example, *Sorghum intrans* is characteristic of Tropical Tallgrass Grazing Lands in the Northern Territory but *Hetero-*

pogon contortus typifies these grazing lands in eastern Queensland. The characteristic species are those of high constancy in present-day grazing lands and not necessarily those of the climax communities.

In tropical and temperate humid and subhumid areas, a feature of the herbaceous layers of the climax communities whether forest woodland or grassland, was the predominance of *Themeda australis* (kangaroo grass) on all but the heaviest-textured soils. Themeda, a warm season perennial, was present, if not a dominant, even in the woodlands and open forests of the south-west where the summers are hot and dry. It is also one of the more common species of present-day woodlands and sclerophyll forests in northern Queensland and the Northern Territory where the summers are wet and the winters dry (Pl. 26). Themeda is found at sea level and at altitudes of 5000 ft (1524 m).

According to Hayman (1960), *Themeda australis* is a polyploid complex based on n = 10 with diploid, triploid, tetraploid, pentaploid, and hexaploid individuals. Most individuals examined were either diploid or tetraploid. It is postulated that the diploid race was the original coloniser that migrated southwards along the east coast to temperate Tasmania. The diploid, unlike the tetraploid, was not able to migrate westwards to Western Australia. *Themeda australis* is closely related to *Themeda triandra*, a species that extends from South Africa to eastern Asia.

The dominance of warm season perennial species in the herbaceous communities of subhumid to dry temperate areas including those with a pronounced Mediterranean climate appears to be associated with the mineralisation of soil organic matter in summer. Species growing in the summer seemingly utilise nitrogen and other nutrient elements as they are mineralised because levels of nitrate nitrogen, for example, seldom exceed more than a few parts per million at any time of the year in the surface soils of un-

Plate 25 Tropical Tallgrass grazing land of *Themeda australis* (kangaroo grass) and *Sorghum plumosum* (perennial sorghum), Northern Territory (CSIRO photo)

TABLE 6 : 1 A classification of the grasslands, grazing lands, and pastures of Australia

Grasslands	Vegetation	Grazing lands		Pastures	
		Types	Characteristic species	Types	Characteristic species
Humid Tropical	Tropical heaths incl. wallum	Heathlands of low grazing value	Herbaceous species rare	Tropical perennial	*Panicum maximum* *Paspalum dilatatum* *Pennisetum clandestinum* *Digitaria decumbens* *Centrosema pubescens* *Pueraria javanica* *Glycine wightii* *Desmodium uncinatum* *Desmodium intortum*
	Tropical and sub-tropical forests	Forestlands of low grazing value (in part)	Herbaceous species rare	Tropical perennial	
		Tropical tallgrass (in part)	*Themeda australis* *Heteropogon contortus*		
Sub-humid Tropical	Tropical and sub-tropical woodlands	Tropical tallgrass	*Heteropogon contortus* *Themeda australis* *Sorghum plumosum* *Sorghum intrans*	Tropical annual	*Stylosanthes humilis*
	Tropical grasslands	Tropical tallgrass (bluegrass-browntop downs)	*Dichanthium fecundum* *Eulalia fulva*	Tropical annual	*Stylosanthes humilis*
Dry Tropical	Tropical grasslands	Tropical tallgrass (bluegrass downs)	*Dichanthium sericeum* *Bothriochloa erianthoides*	Xerophytic perennial grass	*Chloris gayana* *Panicum maximum* var. *trichoglume* *Cenchrus ciliaris*
	Brigalow forest	Brigalow	*Acacia harpophylla* (regrowth) *Paspalidium* spp.	Xerophytic perennial grass	*Chloris gayana* *Panicum maximum* var. *trichoglume* *Cenchrus ciliaris*
	Semi-arid shrub woodlands	Xerophytic midgrass (northern)	*Aristida jerichoensis* *Aristida contorta* *Aristida inaequiglumis* *Chloris acicularis* *Bothriochloa decipiens*	Xerophytic perennial grass (small area)	*Cenchrus ciliaris* *Sorghum almum*
				Mostly without pastures	
	Semi-arid low woodlands	Xerophytic midgrass (northern)	*Aristida pruinosa* *Aristida contorta* *Triodia pungens*	No pastures	
Arid	Arid tussock grasslands	Xerophytic tussock grass (Mitchell grass downs)	*Astrebla squarrosa* *Astrebla pectinata* *Astrebla lappacea* *Iseilema membranaceum*	Mostly without pastures	

TABLE 6 : 1 (continued)

Grasslands	Vegetation	Grazing lands		Pastures	
		Types	Characteristic species	Types	Characteristic species
Arid	Arid hummock grasslands	Xerophytic hummock grass (spinifex)	*Triodia basedowii* *Triodia pungens* *Plectrachne schinzii*	Mostly without pastures	
				Xerophytic perennial grass (small area)	*Cenchrus ciliaris* *Cenchrus biflorus*
	Acacia shrublands	Acacia shrub-shortgrass	*Acacia aneura* *Acacia cambagei* *Myoporum* spp. *Eragrostis eriopoda*	Xerophytic perennial grass (small area)	*Cenchrus ciliaris*
				Mostly without pastures	
	Shrub steppe	Saltbush-xerophytic midgrass	*Atriplex vesicaria* *Stipa variabilis*	Mostly without pastures	
Dry Temperate	Semi-arid low woodlands	Xerophytic midgrass (southern)	*Stipa variabilis* *Bassia* spp. *Kochia* spp.	Mostly without pastures	
	Semi-arid shrub woodlands	Xerophytic midgrass (southern)	*Stipa variabilis* *Danthonia caespitosa* *Aristida contorta* *Aristida jerichoensis*	Mostly without pastures	
				Mediterranean annual (small area)	*Hordeum leporinum* *Medicago minima* *Medicago polymorpha* *Medicago laciniata*
	Eucalypt shrublands (Mallee)	Xerophytic midgrass (southern) (in part)	*Bassia* spp. *Stipa* spp. *Triodia irritans*	Mostly without pastures	
		Mallee grazing lands of low value (in part)	Herbaceous species rare	Mediterranean annual	*Hordeum leporinum* *Lolium rigidum* *Medicago truncatula* *Medicago minima* *Medicago littoralis*
	Temperate grasslands	Temperate tallgrass[a] (in part)	*Stipa aristiglumis*	Mediterranean annual	*Hordeum leporinum* *Medicago polymorpha* *Medicago minima*
Sub-humid Temperate	Temperate grasslands	Temperate shortgrass (in part)	*Danthonia carphoides* *Danthonia auriculata* *Stipa falcata*	Temperate perennial grass—annual legume	*Lolium perenne* *Phalaris tuberosa* *Trifolium subterraneum*

TABLE 6 : 1 (continued)

Grasslands	Vegetation	Grazing lands		Pastures	
		Types	Characteristic species	Types	Characteristic species
Sub-humid Temperate	Temperate woodlands	Temperate shortgrass (except south-west; see Map 4)	*Danthonia carphoides* *Danthonia auriculata* *Stipa falcata*	Temperate perennial grass—annual legume	*Lolium perenne* *Phalaris tuberosa* *Trifolium subterraneum*
			Stipa falcata	Mediterranean annual	*Trifolium subterraneum* *Trifolium hirtum* *Bromus* spp. *Lolium rigidum*
			Herbaceous species now rare		
			Stipa falcata *Danthonia caespitosa*	Mediterranean annual	*Hordeum leporinum* *Medicago polymorpha* *Medicago minima*
	Mallee heaths	Heathlands of low grazing value	Herbaceous species rare	Temperate perennial grass—annual legume	*Phalaris tuberosa* *Trifolium subterraneum*
	Temperate dry sclerophyll forests	Temperate tallgrass	*Danthonia pallida* *Dichelachne* spp. *Poa caespitosa* sens. lat.	Temperate perennial grass—annual legume	*Phalaris tuberosa* *Trifolium subterraneum*
	Temperate heaths (dry)	Heathlands of low grazing value	Herbaceous species rare	Temperate perennial grass—annual legume	*Phalaris tuberosa* *Trifolium subterraneum*
				Mediterranean annual	*Bromus rigidus* *Trifolium subterraneum*
Humid Temperate	Temperate heaths (wet)	Heathlands of low grazing value	Herbaceous species rare	Temperate perennial	*Lolium perenne* *Trifolium repens*
		Sedgelands of low grazing value	*Gymnoschoenus sphaerocephalus*	No pastures	
	Temperate forests	Temperate tallgrass (in part)	*Poa caespitosa* sens. lat. *Themeda australis*	Temperate perennial	*Lolium perenne* *Trifolium repens*
		Forestlands of low grazing value (in part)	Herbaceous species rare		
Sub-alpine	Sub-alpine woodlands	Sub-alpine sod-tussock grass	*Poa caespitosa* sens. lat.	Mostly without pastures	*Lolium perenne* *Poa pratensis* *Trifolium repens* naturalised in places
	Sub-alpine grasslands	Sub-alpine sod-tussock grass	*Poa caespitosa* sens. lat. *Danthonia nudiflora*	Mostly without pastures	

[a] Areas small: included with Temperate Shortgrass Grazing Lands in Map 4.

grazed temperate woodlands in which Themeda is dominant (Moore 1967b). The taking-up of labile nutrients prevents the ingress of other species and gives stability to the community. Presumably it is when species are able to 'control' their environment in this way that succession is halted and the climax is attained.

However, Themeda makes most of its growth in summer and the equilibrium of a system controlled by a species growing out of phase with the rainfall regime is apparently easily upset, for when sedentary grazing is practised in temperate woodlands Themeda is rapidly replaced by cool season perennials. The community may then be invaded by introduced species (Moore 1959, 1962, 1966, 1967a and b). Themeda is a deep-rooted plant but there is evidence that defoliation during its growing period reduces its root growth. Reduction of the depth to which roots penetrate could result in the death of plants depending on stored soil water for growth and survival in dry summers.

Progressive changes in the herbaceous communities of temperate woodlands as a result of the introduction of domestic herbivores are shown in the following diagram.

Tall Warm Season Perennial Grasses
↓ — grazing
Cool Season Perennial Grasses
↓ — grazing
Short Cool Season Perennial Grasses
↓ — grazing
Short Cool Season Perennial Grasses
| Species from more
| ↙ arid communities
Short Warm Season Perennial Grasses
| — grazing
↓
Short Cool Season Perennial Species
|
Short Warm Season Perennial Species
Mediterranean |
annuals ↘ |
Introduced Cool Season Annuals
↓ — grazing and superphosphate
Introduced Cool Season Annuals
|
Native and Introduced Warm Season Annuals
↓
Introduced Nitrophilous Annuals and Biennials
(Moore and Biddiscombe 1964)

Species changes in the grazing lands of three temperate woodlands following the introduction of domestic livestock are shown in Tables 12 : 3, 12 : 4, and 12 : 5. There are fewer data from sub-tropical woodlands but there is some evidence of retrogression from *Themeda australis* to *Heteropogon contortus*, thence through Aristida or *Bothriochloa* spp. to *Chloris* spp.

The climax treeless grasslands of Australia are described briefly in Chapter 4. The only true grasslands able to be shown at the scale of the vegetation map are the Arid Tussock Grasslands, the so-called Mitchell grass downs, dominated by xerophytic tussock grasses of the genus Astrebla (Pl. 22); the Arid Hummock Grasslands (spinifex) of Triodia and Plectrachne (Pl. 26); the Sub-humid Tropical Grasslands of *Dichanthium tenuiculum* syn. *D. superciliatum*, *D. fecundum* (bluegrasses) and *Eulalia fulva* (browntop) (Perry and Lazarides 1964); and the coastal saline, fresh, and brackish water grasslands of the northern coastlines (Pl. 23).

The approximate locations but not the extent of sub-humid sub-tropical and temperate Grasslands are shown in Map 3. The Arid Hummock Grasslands are not entirely treeless but the communities in a structural and a physiognomic sense are closer to grasslands than to any other formation (see Chapter 17).

The drier equivalents of the northern bluegrass-browntop grasslands are the bluegrass downs of *Dichanthium sericeum* (Queensland bluegrass) and *Bothriochloa erianthoides* of central Queensland. The largest areas are in the vicinity of Springsure (lat. 24°S) and east of Clermont (lat. approx. 23°S) but scattered patches occur on black earths and grey clay soils as far west as longitude 145°E. Tropical grasslands are the humid equivalents of the Arid Tussock Grasslands, and following a succession of wet seasons *Dichanthium sericeum* is common in the more eastern of the Astrebla grasslands. This is the so-called 'fluctuating climax' of Blake (1938).

Dichanthium sericeum was almost certainly a dominant in the grasslands of the heavy-textured soils of the Darling Downs, Queensland. These grasslands may be regarded as ecotonal between the southern Temperate Grasslands, with which they are placed in Table 6 : 1, and the Tropical Grasslands further north (See Chapters 8 and 9). From the fragmentary evidence now available the other original species

Plate 26 Arid hummock grassland (spinifex): *Triodia basedowii* showing annular growth habit, Northern Territory (CSIRO photo)

of the Darling Downs grasslands appear to have been *Themeda avenacea* and *Stipa aristiglumis*. This appears to have been the most northern occurrence of the temperate Stipa as a frequent species.

In Map 3 all temperate grasslands are shown as sub-humid but there are two types, one on heavy-textured soils and the other on solodic or solodised solonetz soils. The drier of the temperate grasslands occurs intermittently on heavy-textured soils from southern Queensland (Darling Downs) to the Wimmera region of Victoria (lat. 37°S). Apart from these two areas, now largely cultivated for cereals, the most extensive of these grasslands are on heavy-textured basaltic soils on the Liverpool Plains and Monaro Plains of New South Wales. There are numerous small patches in the Macquarie region of New South Wales and in north-central New South Wales. In the north the fringing woodland species are principally *Eucalyptus populnea* or *Acacia pendula* and the annual rainfall is between 25 and 30 in. (635–762 mm). In the south the fringing trees are *E. moluccana* syn. *E. hemiphloia* or *Casuarina luehmannii* and the annual rainfall is only 16 in. (406 mm) but mainly incident in winter (see Table 12 : 2). These grasslands resemble the herbaceous communities of their adjacent woodlands and may be regarded as the southern equivalent of the dry tropical grasslands of central Queensland. The principal species in dry Temperate Grasslands are now *Stipa aristiglumis* syn. *S. bigeniculata* (plains grass) and *Danthonia* spp. Originally *Themeda avenacea* (native oatgrass) appears to have been at least co-dominant with Stipa but is now found only in areas totally protected from grazing (see Table 12 : 5). Just north of Clare (lat. approx. 34°S) in South Australia there is a small patch of treeless grassland in which the common species are now a grass-like liliaceous plant, *Lomandra dura*, and species of Danthonia. The community is associated with an *E. odorata* woodland and is analogous to the grasslands fringed by *E. moluccana* and *Casuarina luehmannii* in the Wimmera of Victoria. In Map 4 all temperate grasslands are included in the Temperate Shortgrass Grazing Lands.

The more mesophytic temperate grasslands are now composed mainly of the short cool season perennials, *Danthonia carphoides*, *D. auriculata*, and *Stipa falcata* (Chapter 12). They were formerly *Themeda australis*, *Stipa aristiglumis* and *Poa caespitosa* sens. lat. (Tables 12 : 3, 12 : 4). Small patches of these grasslands occur throughout the Southern Tablelands of New South Wales and the Western District of Victoria (Pl. 27).

There are small areas of sub-alpine sod-tussock grasslands in the south-eastern highlands (see Chapter 13). At levels of 4500 ft (1372 m) there are similar grasslands, treeless because of temperature inversions, fringed with woodlands of *Eucalyptus pauciflora*, *E. stellulata*, and *E. rubida* (Pl. 28). The principal grasses are a small fine-leaved form of *Poa caespitosa* sens. lat. (snowgrass) and *Danthonia nudiflora*.

All the true grasslands except the Arid Hummock appear to be part of a continuum extending from north to south on the mainland. Each grassland is linked to its geographically nearest neighbours by one or more species or

Plate 27 Temperate grassland: short species of Stipa and Danthonia on heavy-textured basaltic soils. *Eucalyptus camaldulensis* along watercourses, western Victoria (Soil Conservation Authority, Victoria, photo)

Plate 28 Sub-alpine sod-tussock grassland of *Poa caespitosa* sens. lat. (snowgrass) with fringing sub-alpine woodland of *Eucalyptus pauciflora* (snow gum) and *E. stellulata* (black sally), Currango, New South Wales (CSIRO photo)

genera in common. The tropical bluegrass-browntop grassland is linked to the bluegrass downs of central Queensland through species of *Bothriochloa*, for example *B. ewartiana*, and the genus Dichanthium. The bluegrass downs are linked to the Darling Downs grassland through *Dichanthium sericeum*, and this grassland in turn is linked to the drier of the temperate grasslands through *Stipa aristiglumis* and *Themeda avenacea*. The sub-humid tropical grasslands are related to the arid tussock grasslands through *Astrebla squarrosa*, *Iseleima* spp., and *Bothriochloa* spp. in the north and through *Dichanthium sericeum* further south. The temperate grasslands on heavy-textured soils are linked to those on solodic and solodised solonetz through *Stipa aristiglumis* and *Danthonia* spp. and these in turn are linked to sub-alpine grasslands through *Poa caespitosa* sens. lat.

The absence of trees on heavy-textured soils appears to be due to the failure of water to penetrate to a sufficient depth in the soil to enable trees to escape the intense root competition from grasses and other herbaceous species in the upper levels of soils. As clay soils swell when wet, poor aeration during rain periods may also be a factor limiting the growth of trees, particularly on the basalt plains of the Western District of Victoria. On lighter-textured soils of elevated valleys and plains low temperatures resulting from temperature inversions appear to account for the absence of trees.

Pastures are classified according to the provenances (tropical, Mediterranean, or temperate other than Mediterranean) of their most common species and according to whether the species are perennial or annual. Introduced grasses able to persist vegetatively in semi-arid areas are classed as xerophytic perennial. There is a narrow strip along the east coast in which

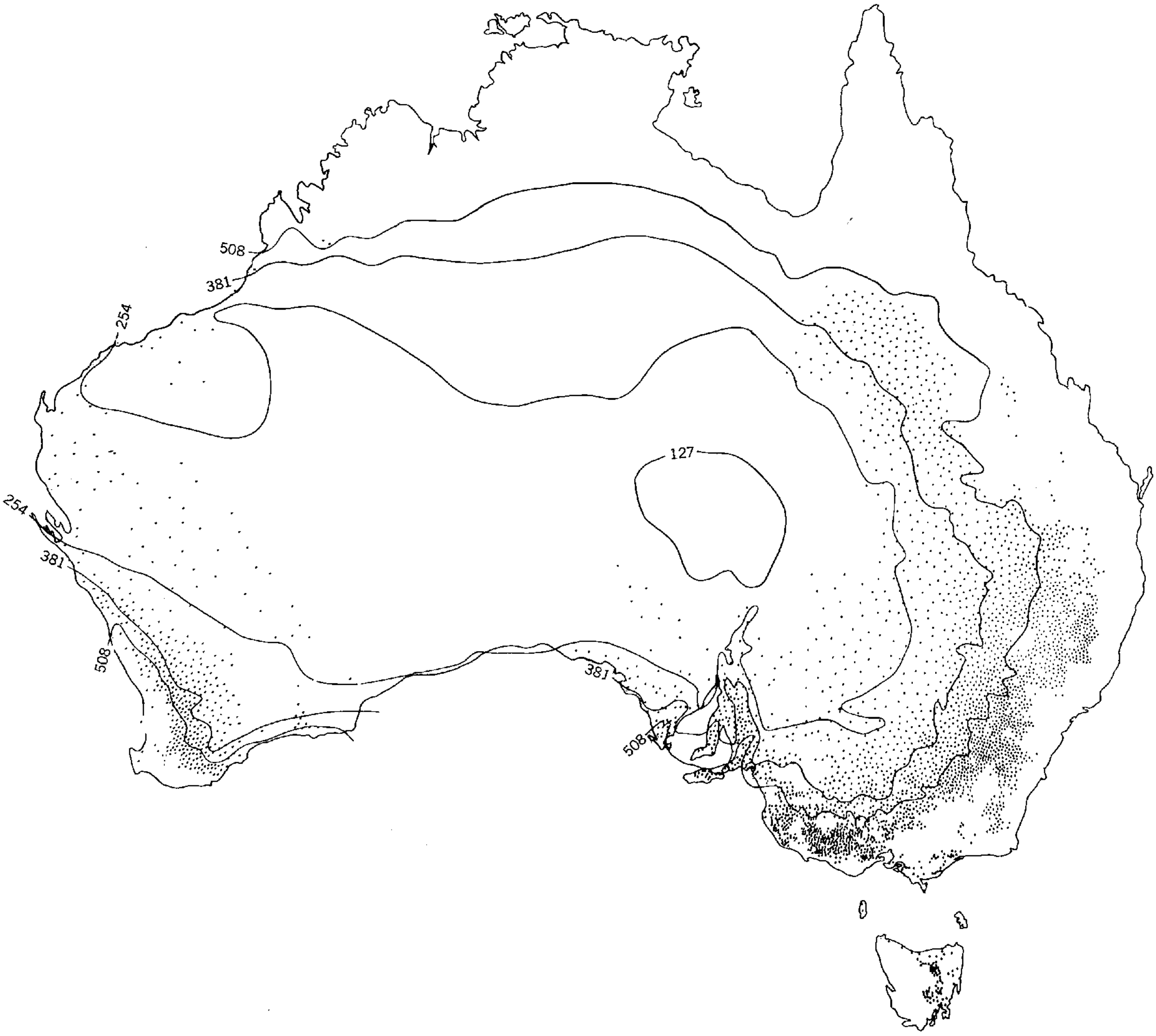


Fig. 6 : 1 Sheep in Australia, March 1965. Each dot represents 50,000 sheep (rainfall in mm)

both temperate and sub-tropical pasture species are sown. This is shown in Map 5 as an overlap of Tropical Perennial and Temperate Perennial Pastures (see also Figs. 1 : 11, 1 : 12, 1 : 15).

The Temperate Perennial Grass - Annual Legume Pastures are divided into two groups: (a) those of *Phalaris tuberosa* and *Trifolium subterraneum* (subterranean clover) and (b) those of *Lolium perenne* and *T. subterraneum*. The former are characteristic of the temperate woodlands of the south-eastern tablelands and slopes and the latter of the more humid woodland environments of Tasmania and the western districts of Victoria. The Mediterranean Annual Pastures are also in two groups: (a) those in which subterranean clover is the principal legume and (b) those in which the legume is one of the annual species of Medicago (see Map 5).

The total area sown to pasture grasses and legumes in Australia is less than 52 million acres (21 million ha). This is only about 10 per cent of the land area outside the arid zone. Map 5, therefore, shows potential rather than actual areas of pastures and where not delineated by pasture type the approximate present inland limits of important sown and volunteer species.

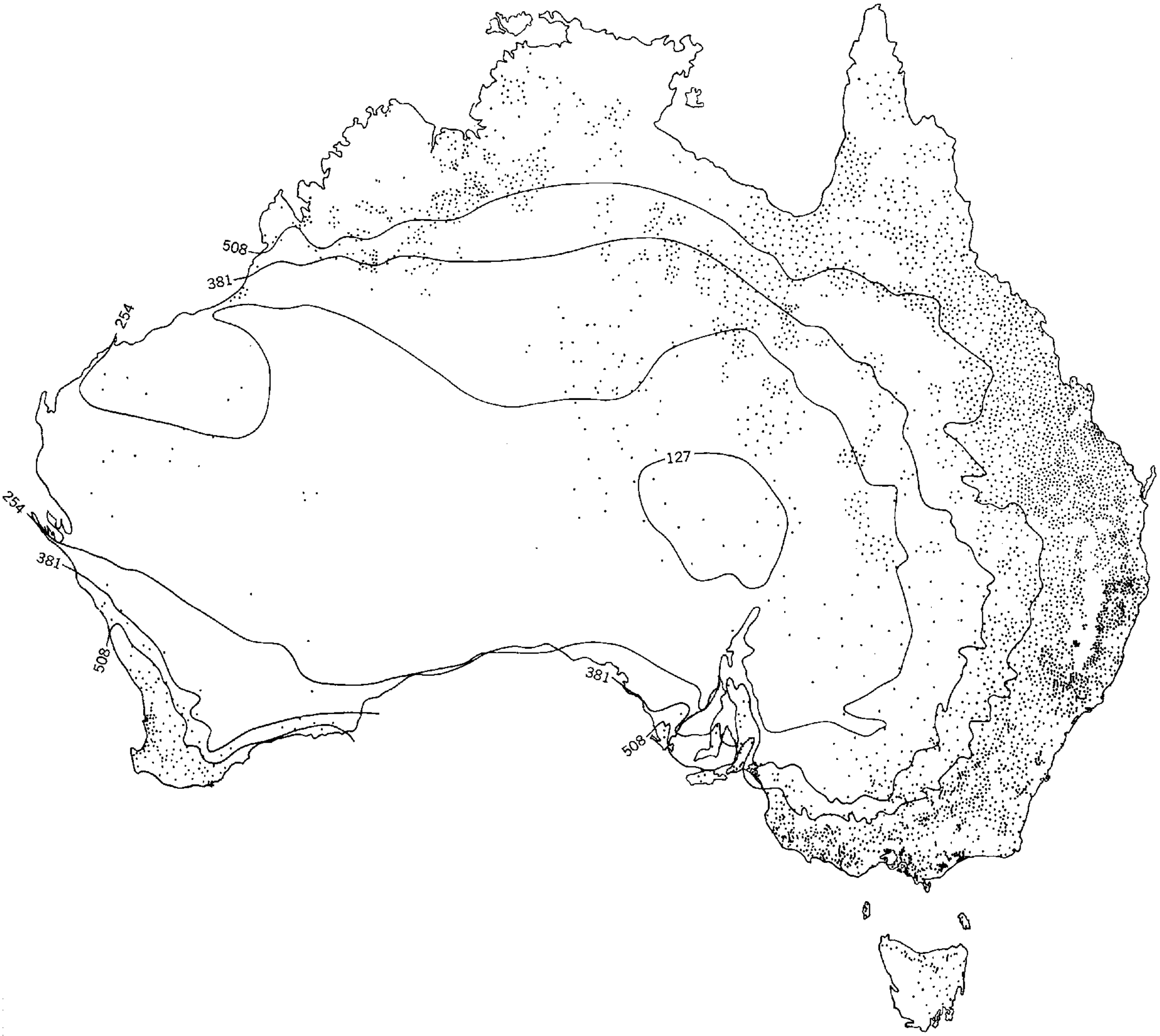


Fig. 6 : 2 Beef cattle in Australia, March 1963. Each dot represents 3000 beef cattle (rainfall in mm)

The distributions of sheep, beef and dairy cattle are shown in Figs. 6 : 1, 6 : 2, and 6 : 3. Comparisons of these with Maps 4 and 5 will show the relative importance of different grazing lands and pastures to the three livestock industries.

From Table 6 : 1 relationships can be seen of grazing lands and pastures to each other and to the original vegetation.

In the chapters immediately following, development of pastures and grazing lands from the original vegetation is described and productivities of pastures and grazing lands in terms of meat, wool, or milk are discussed.

Sources: Fig. 6 : 1 Geographic Section, Dept of National Development, Canberra, 1968.
Fig. 6 : 2 Commonwealth Bureau of Census and Statistics, Canberra, 1964.

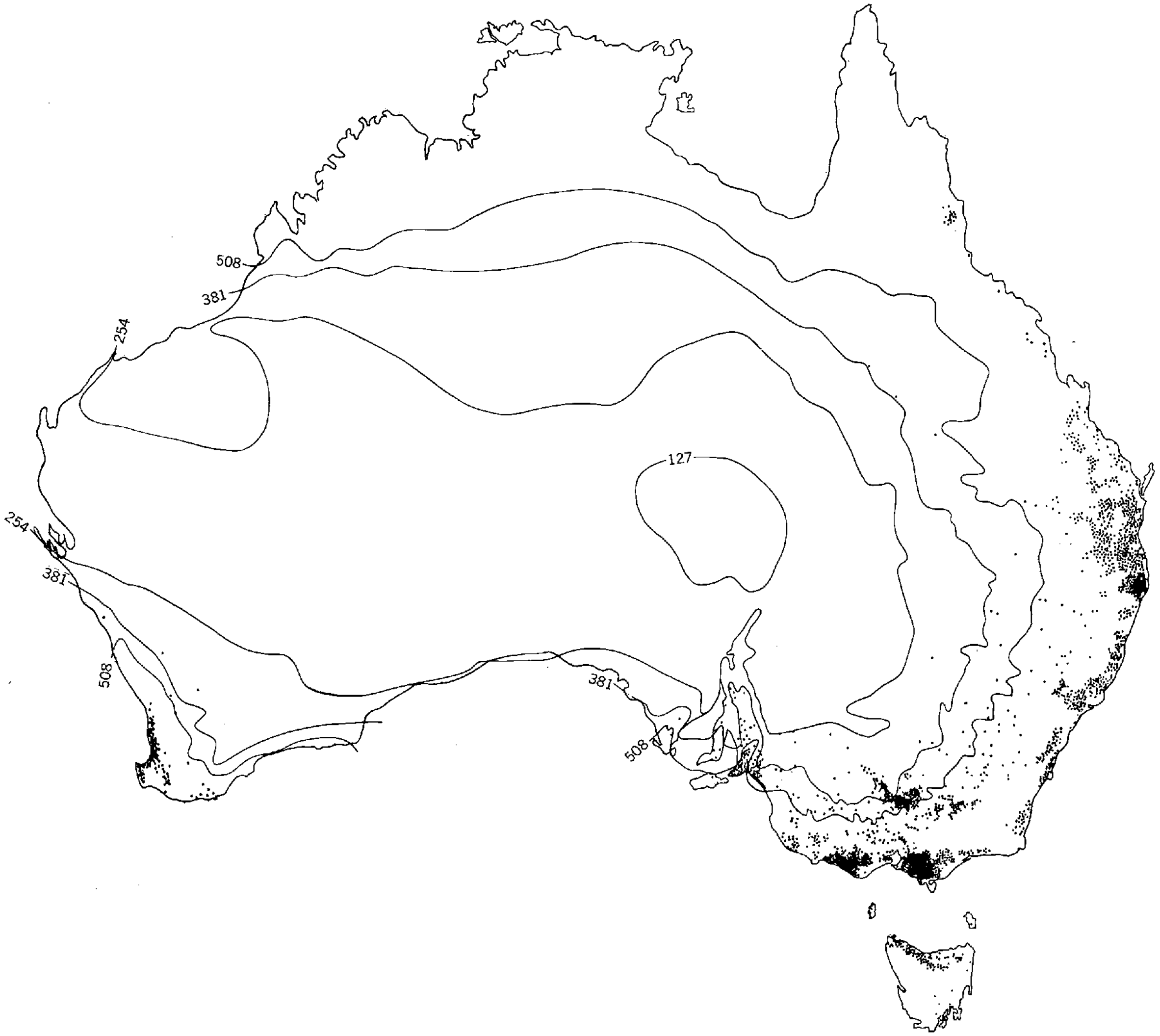


Fig. 6 : 3 Dairy cattle in Australia, March 1963. Each dot represents 2500 dairy cattle (rainfall in mm)
Source : Commonwealth Bureau of Census and Statistics, Canberra, 1964.

Plate 29 Xerophytic Midgrass grazing land (northern). *Aristida* spp. in semi-arid low woodland of *Eucalyptus argillacea* (western box), Northern Territory (CSIRO photo)

Plate 30 Tropical annual pasture of Townsville lucerne (*Stylosanthes humilus*), CSIRO Research Station Lansdown, near Townsville, Queensland (CSIRO photo)

Plate 31 Temperate perennial pasture on land formerly wet sclerophyll forest, north-western Tasmania (Department of Agriculture, Tasmania, photo)

Plate 32 Mediterranean annual pasture of *Trifolium subterraneum* and volunteer annual grasses on former *Eucalyptus albens* (white box) woodland, north-eastern Victoria (Department of Agriculture, Victoria, photo)

7

TROPICAL AND SUB-TROPICAL FORESTS AND HEATHS

W. W. BRYAN

DISTRIBUTION

Tropical and sub-tropical forests and heaths extend in a long narrow discontinuous strip along the north-east coast, from near Cooktown (lat. 15°S) in north Queensland to about Taree (lat. 32°S) in New South Wales (Fig. 7 : 1, Map 3). The range of communities includes tropical and sub-tropical rainforests, wet sclerophyll forests, and heaths in a mosaic resulting from the interaction of rainfall, topography, and soil. Narrow lowlands alternate with ranges, plateaux, and mountain peaks, and useful agricultural land has a patchy distribution. Of the total area of about 15 million acres (6 million ha) less than 50 per cent is suitable for animal production, but as it has a high and reasonably well distributed rainfall it is capable of supporting highly productive pastures and consequently high animal production. Because of the favourable rainfall, pastures can be sown with a minimum of economic risk.

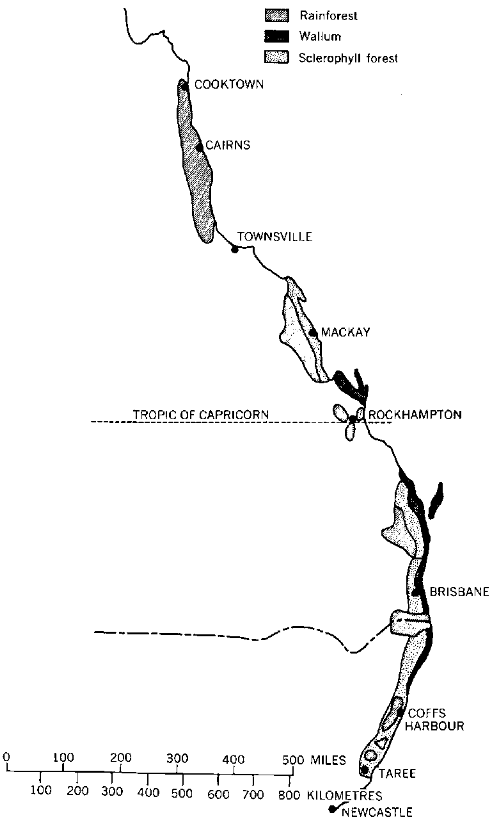


Fig. 7 : 1 Distribution of tropical rainforests, sclerophyll forests, and wallum

Two regions of high rainfall, namely, the strictly monsoonal areas of the 'Top End' of the Northern Territory and the northern half of Cape York Peninsula are discussed in Chapter 8, because although the rainfall is over 50 in. (1270 mm) it all falls in 3–5 months and the rest of the year is very dry and hot. Most of the pasture species used in these regions are the same as in the lower rainfall woodlands nearby and the sown pastures are quite different from those discussed in this chapter.

Tropical and sub-tropical forests and heaths may be divided into two main areas in terms of potentials for tropical pastures: a wet tropics zone north of lat. 21°S and a sub-tropics zone extending from lat. 21°S to lat. 32°S (see Map 5). Because of variation in elevation, soils, and rainfall, there is considerable diversity within zones. There is also a division between the flat ill-drained sandy areas of very low fertility adjacent to the coast and the better drained areas with mineral soils on the rolling to hilly country behind them.

The region of tropical and sub-tropical forests includes most of the cane sugar lands of Australia and competition among forms of landuse, both in agriculture and forestry, is high. Much of the land is rugged and the area available for animal production is relatively small. Thus in the wet tropics of north Queensland between Townsville and Cooktown the North

Queensland Land Classification Committee of 1960–1 (Sloan, Owens, and Johnston 1962) considered that only about 300 sq miles (77,760 ha) out of the total area of 9000 sq miles (2,332,800 ha) would be suitable for cattle grazing.

CLIMATE

Rainfall

The rainfall is predominantly of summer incidence, markedly so in the north and less so southwards, though the weather pattern is still one of wet summers and dry winters and springs. The amount of winter rain in the south is small but significant. The range of rainfall is from 35 in. (889 mm) in some of the southern dairying lands to 140 in. (3556 mm) or more between Ingham and Cairns (lat. 17°S). The variability of the mean annual rainfall is generally 20 to 25 per cent. Droughts are less frequent and less prolonged than in adjacent woodlands, but dry periods of two to seven months are nevertheless one of the major shortcomings of the climate.

Length of the growing season as determined by Miles (1947) is shown in Fig. 7 : 2. Temperature and rainfall patterns can be seen in Figs. 1 : 2 and 1 : 4.

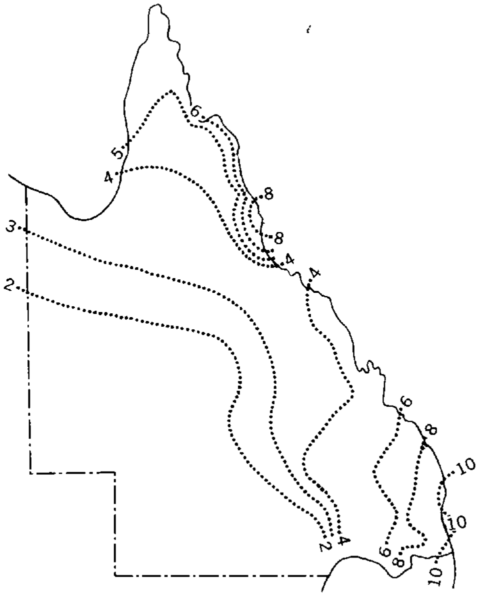


Fig. 7 : 2 Length of pastoral growing season in months (Miles 1947)

Temperature

Mean temperatures, summer 75–85°F (24–29° C) and winter 55–75°F (13–24°C), are generally favourable for plant growth. Searing heat waves are rare and of only a few days' duration. Radiation frosts are of major importance south of lat. 21°S (Coleman 1964) (see Fig. 1 : 3), and even though temperatures do not fall very low, plants which have not had an opportunity to harden are susceptible to injury. Frosts damage the foliage and tops of most of the legumes used in sown pastures but seldom affect their survival.

Other Climatic Factors

Convection storms are sometimes accompanied by damaging winds, and occasional cyclones cause heavy property loss; pastures are little affected, except by flooding.

Hail occurs with insufficient frequency or severity to affect pastures seriously.

SOILS

There is considerable variation in soils. The small plateaux near the coast are usually capped with basalt and the soils are acid kraznozems. On the coastal lowlands the soils are generally sandy with clay subsoils and may be gleys (low humic or humic), podzolics (lateritic, gleyed, groundwater) or solonchaks. The intervening soils are kraznozems, red earths, yellow earths, solodics, and alluvials (see Chapter 3 and Map 2).

The most general characteristic of the soils is that they are deficient in at least one nutrient, often more. The common deficiencies are in N, P, K, Ca, S, Mo and sometimes Cu and Zn (see Chapter 21).

VEGETATION

Rainforests

Rainforests occur in discontinuous belts along the coast and adjacent highlands and in a variety of forms. They reach their best development on fertile soils and where the rainfall is well distributed and 50 in. (1270 mm) or more annually. The largest areas are from the Daintree River to the Herbert River and west to the Atherton Tableland, from Mackay to Proserpine and west to the Eungella Range, in the district east of Gympie and south to the Blackall Range, from

PASTURES OF AUSTRALIA

Compiled by R. Milton Moore, CSIRO. 1969.
Cartography by W.F. Goodwin, CSIRO.

SCALE 1:12,000,000

100 50 0 100 200 300 400 500 600 700 800 KILOMETRES

100 0 100 200 300 400 500 MILES

TROPICAL PERENNIAL PASTURES Digitaria-Setaria-Panicum-Paspalum-Pennisetum-Desmodium-Phaseolus-Glycine	1
TROPICAL ANNUAL PASTURES Stylosanthes humilis	2
XEROPHYTIC PERENNIAL PASTURES Cenchrus ciliaris-Chloris gayana-Panicum maximum var. trichoglume-Sorghum almum	3
TEMPERATE PERENNIAL PASTURES Lolium perenne-Trifolium repens	4
TEMPERATE PERENNIAL GRASS-ANNUAL LEGUME PASTURES (a) Phalaris tuberosa-Trifolium subterraneum (b) Lolium perenne-Trifolium subterraneum	5
MEDITERRANEAN ANNUAL PASTURES	

BOUNDARY OF

Annual medicago

Subterranean clover

Perennial Ryegrass

GRASSLAND RESEARCH CENTRES

NARAYEN ●

ISOHYETS

Areas not coloured climatically suitable but otherwise unfavourable for sown pastures or their potentialities unknown.

the Macpherson Range to the Richmond River, and behind Coffs Harbour and Wauchope.

Tropical rainforest, which extends as far south as lat. 21°S, has a flora predominantly of Indo-Malaysian origin, and the forests are characterised by a great complexity of species and few dominants. Some of the trees are deciduous. The common genera are Agathis, Araucaria, Cedrela, Cinnamomum, Cryptocarya, Dysoxylum, Elaeocarpus, Eugenia, Endiandra, Flindersia, Ficus, Litsea, Tarrietia, and Weinmannia (Francis 1929) (Pl. 11).

Sub-tropical rainforest found as far south as lat. 35°S includes many of the species found further north and is characterised by small leaf sizes and dominance of *Araucaria* spp. (hoop and bunya pines) (Pl. 12). There are generally two tree layers compared with three in tropical rainforests. Much of the sub-tropical rainforest has been felled for agricultural use.

Sclerophyll Forests

Outside the rainforest, Eucalyptus is the dominant genus in most of the wet tropics. Generally several species of Eucalyptus occur together, often with species of Melaleuca, Tristania, Syncarpia, or Angophora. The forests are composed of Australian endemic species.

Wet sclerophyll forest, a closed community of evergreens, is found on the eastern slopes and caps of the north coast of New South Wales and on Fraser Island.

Lowland Forests and Heaths

Much of coastal Queensland and most of the sub-coastal region carries mixed eucalypt woodlands (see Chapter 8). These are very varied and include grassy forest, tall and low woodland, savannah woodland, and tropical savannah woodland. The heath (Wallum) areas near the coast are a mosaic of mixed coastal woodland, tree heaths, and heaths.

Rainforests and lowland heaths have few native grasses and support little if any animal production in their native state. They are classified as forest and heath grazing lands of low value (Chapter 6, Map 4). The eucalyptus forests with their understorey of grassy vegetation, in which kangaroo grass (*Themeda australis*) may be common, have grazing lands similar to those of tropical and sub-tropical woodlands (Chapter 8) and are classified similarly as tropical tallgrass (Chapter 6).

In the heath lowlands, the rises carry wet sclerophyll forest in which scribbly gum (*E. racemosa*), bloodwood (*E. gummifera*), and stringybark (*E. acmenioides*) are common. The main grasses are *Imperata cylindrica*, *Themeda australis*, and *Alloteropsis semi-alata*. The tree heaths, which are characteristically marshy, are dominated by tea trees (*Melaleuca* spp.), *Angophora* spp., swamp mahogany (*Tristania suaveolens*) and swamp oaks (*Casuarina* spp.). The Wallum proper is dominated by *Banksia aemula* and other dwarf Proteaceae, Epacridaceae, Leguminosae, and Myrtaceae. The grass tree (*Xanthorrhoea* spp.), is extremely common except in very wet situations.

Swamps

Scattered throughout the tropical forests and heaths are small areas of freshwater swamps. The grass vegetation, consisting of *Leersia hexandra, Paspalum distichum, Hemarthria compressa, Panicum obseptum*, and *Echinochloa crusgalli*, provides valuable stock feed, especially in dry times.

Saltwater meadows are found in places along the coast and in estuarine areas. They are largely vegetated by saltwater couch, *Sporobolus virginicus* var. *minor*, a harsh grass of limited feeding value. These freshwater and saline grasslands constitute the coastal grasslands (Chapter 6, Map 3, Pl. 23).

AGRICULTURAL INDUSTRIES

Half the dairying industry of Queensland and much of that of New South Wales is located in the wet tropics and sub-tropics. Farms are usually devoted wholly to dairying but sometimes dairy production is supplemented by pig raising and by growing fodder crops and cash crops such as green string beans. In the drier areas inland, dairying is part of mixed farming enterprises.

In northern New South Wales, where the industry is essentially for butter production, most of the dairy cattle are Jersey with some Guernsey and a few Friesian. In Queensland, where both butter and whole milk are produced, the main breeds are Jersey and Australian Illawarra Shorthorn, with a small but increasing number of Friesian.

Production per cow, per acre, and per farm is generally low, and as the Queensland Dairy Industry Advisory Committee (Anon. 1965a) pointed out, the basic reason is the poor nutrition of the dairy cow. This deficiency is gradually being overcome as the area of sown pastures increases. A viable industry is now emerging, through amalgamation of farms which in many cases are too small (average size about 260 acres (105 ha) around Gympie, Qld), the use of fertilisers, and the sowing of introduced tropical pasture species.

Sheep are unimportant, and the Queensland tropical forests and heaths carry only 0·05 per cent of the Australian flock. The few sheep run are for meat rather than wool.

The main grazing industry of the future will be beef production, mostly from beef herds but to some extent from dairy cows mated with beef bulls. Most of the beef will come from purely beef enterprises, but some will come from cattle run on the unassigned lands of sugar cane farmers. Sizes of holdings are likely to range from 300 to 5000 acres (122–2025 ha), with the mode about 1500 acres (608 ha).

Almost all the beef cattle in northern New South Wales are Hereford. In southern Queensland the breeds are Hereford and Hereford crosses with Santa Gertrudis or Zebu. In north Queensland the main breed is the Shorthorn but there are large and rapidly increasing numbers of cattle with some Asiatic blood.

The main agricultural industries of the wet tropics and sub-tropics at present are sugar cane production and forestry. The Atherton Tableland produces about one-quarter of Queensland's maize crop and the Northern Rivers about the same proportion of that of New South Wales. The Australian pineapple industry is located in the Queensland part of the region, and the banana industry is about equally divided between the sub-tropics of Queensland and New South Wales. The region also produces most of the tropical fruits such as papaw and mango. Salad vegetables and strawberries are also grown, mostly near Brisbane.

SOWN PASTURES

Because of the high rainfall the potential for animal production in the wet tropics and sub-tropics is high. However, high-yielding pastures are expensive to establish because of land clearing costs, seed costs, and the relatively high levels of fertiliser required.

In northern Australia, the objective in pasture improvement is to produce the maximum amount of dry matter and animal production in summer when moisture and radiant energy supplies, both light and heat, are highest. Attempts in the sub-tropics to produce more in winter and early spring by sowing temperate species have largely failed. Shallow-rooted plants like white clover are subject to water stress at that time, and grasses are likely to be short of nitrogen (Henzell and Stirk 1963).

A major deficiency in the nutrition of animals is the lack of quality, and sometimes of quantity, from April to September (or even later in northern New South Wales). These adverse effects are reduced as the legume content of the pastures increases or inputs of fertiliser nitrogen (Fig. 7 : 3) are increased.

Principles of pasture establishment and maintenance are similar throughout the wet tropics and sub-tropics, although species change with latitude, altitude, and with intensity of production. Nitrogen is almost universally deficient and its lack is generally overcome by legumes. For this reason legumes must be adapted to local conditions and be nodulated with effective strains of Rhizobium.

Acid soils and a summer rainfall regime limit the use of temperate legumes and grasses. White clover will grow at sea level as far north as latitude 25°S and on high plateaux in the tropics, but few other temperate species are successful. The early limitation to highly productive pastures in most of the region was lack of adapted species, especially legumes. As a result of Australian research during the last two decades, there is now a reasonable array of grasses and legumes for much of the wet tropics. Success is due mainly to plant introduction (see Chapter 19), the determination of plant nutrient deficiencies (Andrew and Henzell 1964) (see Chapter 21), and the isolation of suitable strains of Rhizobium (Norris 1964) (see Chapter 22). For the successful establishment of tropical grass and legume mixtures, every encouragement must be given to the legume, and furthermore it may be helpful to include more than one species of legume.

The area of sown pastures in the dairying regions has been greatly increased by dairy pasture subsidy schemes operating in Queensland and New South Wales. The schemes cover up to 100 acres (40 ha) per farm, and in the second year of the scheme in Queensland (1967–8) the sowing of 62,000 acres (25,110 ha) was approved.

Between 1958 and 1968 there was a ten-fold increase in the amount of fertiliser used on Queensland pastures (1600 to 16,000 tons approx.). Nearly half the area fertilised was in the wet tropics and sub-tropics and most of the fertiliser used was superphosphate.

The pastures are classified as Tropical Perennial (see Chapter 6, Map 5).

The Lowland Tropical Rainforest (Cooktown to Ingham)

This wet low-lying region is used mainly for growing sugar cane. When cleared, its pastoral use, on the approximately 200,000 acres (81,000 ha) available, is for beef cattle raising, primarily for fattening. A number of grasses are available, namely guinea grass (*Panicum maximum*), including cv. Hamil and cv. Colonial, molasses grass (*Melinis minutiflora*), para grass (*Brachiaria mutica*), *Brachiaria decumbens*, pangola (*Digitaria decumbens*), ruzi grass cv. Kennedy (*Brachiaria ruziziensis*), and elephant grass (*Pennisetum purpureum*). Suitable legumes include centro (*Centrosema pubescens*), stylo (*Stylosanthes guyanensis*), puero (*Pueraria phaseoloides*), glycine cv. Tinaroo (*Glycine wightii* syn. *G. javanica*) and siratro (*Phaseolus atropurpureus*), and the shrub *Leucaena leucocephala*. Of these, para is sown in wet situations, usually with centro. Siratro is restricted to drier sites. The commonest pasture mixture is guinea grass with centro and stylo, and the commonly recommended fertiliser application for establishment is 336 lb per acre (376 kg per ha) molybdenised superphosphate.

In rainforests it is usual to fell or push down the trees, burn *in situ* when dry, and sow into the ashes. Alternatively the material may be pushed into windrows, the intervening area cultivated and the windrows left to dry. On newly cleared rainforest it has been common practice to sow a pioneer species like molasses grass that will make rapid growth, and produce sufficient dry matter, generally in the second year, to carry a hot fire and complete the destruction of remaining logs. The permanent pasture species such as guinea grass and centro are then sown.

Many rainforest sites are steep and the usual method of sowing is to broadcast seed on the ground or in ashes. On flat country the traditional methods, which were basically adapted to the sowing of grass alone, are giving way to more sophisticated methods now that legumes and fertilisers are incorporated in the sowing mixture. In such cases seed and fertiliser are drilled into a prepared seed bed, using stump-jump equipment because of the many roots and stumps that remain. With the increasing availability of crawler tractors these methods are now also being used on hilly land, despite greater erosion hazards. If the country is too steep to be safely ploughed, methods of partial cultivation are adopted.

The Upland Rainforests

The tablelands, from Atherton in north Queensland to Lismore, N.S.W., have many common features. After clearing the rainforest they were usually sown to a mixture of *Paspalum dilatatum* and white clover (*Trifolium repens*), and their original fertility was sufficient to support highly productive pastures carrying approximately one dairy cow to the acre (0·4 ha). Under dairying and high annual rainfalls (50–100 in., 1270–2540 mm) fertility gradually declined to the point where the white clover lacked vigour and paspalum was replaced by weeds such as mat grass (*Axonopus affinis*). In this condition the pastures carry about one cow to 3 acres (1·2 ha).

With correction of nutrient deficiencies and some overseeding the pastures can be restored largely to their original productivity. In the past, deterrents to this have been lack of knowledge of nutrient deficiencies, unavailability of suitable species, and difficulty of obtaining credit for small heavily-mortgaged farms.

The Tropical Upland Rainforests

The Evelyn Tableland (Herberton to Ravenshoe) is the most recently developed, and the commonest pastures are paspalum or kikuyu and white clover. Greenleaf desmodium (*D. intortum*) is now being oversown at 1–2 lb per acre (1–2·2 kg per ha) to increase the legume content of pastures in summer and autumn.

The Atherton Tableland (Kairi to Millaa Millaa) was developed between 1900 and 1920, and in 50–70 years there has been a serious decline in soil fertility. Given fairly heavy initial dressings of approximately 448 lb per acre (502 kg per ha) of molybdenised superphosphate, more productive species are being introduced successfully. The grasses mostly used are *Panicum maximum*, cv. Petrie panic, in the drier northern part of the region and cv. common guinea or cv. Hamil in the wetter southern part. The main legume has been glycine, originally cv. Tinaroo (especially in the north), but this is now being replaced by cv. Clarence and other tetraploid strains. Greenleaf desmodium is also being sown to a greater extent.

The Eungella Tableland (west of Mackay) was first settled about 1900. At this latitude *Setaria sphacelata* (cv. Nandi and cv. Kazungula) can be used in pastures with greenleaf and silverleaf desmodium and glycine cv. Tinaroo. Soils are now somewhat deficient in phosphorus and molybdenum and applications of 224 lb per acre (251 kg per ha) molybdenised superphosphate are required. Green panic and molasses are other useful grasses.

The Sub-tropical Upland Rainforests of Southern Queensland and Northern New South Wales

The plateaux of Maleny, Beechmont, and Springbrook have been used for dairying for more than half a century and most soils are seriously depleted in fertility. To re-establish pastures, applications of molybdenised superphosphate of the order of 448–672 lb per acre (502–752 kg per ha) and potassium chloride 112 lb per acre (125 kg per ha) are required. Calcium at about 1120 lb $CaCO_3$ per acre (1254 kg per ha) is needed also to restore the productivity of white clover (White 1967). Annual fertiliser applications are 224 lb (251 kg per ha) superphosphate and 112 lb (126 kg per ha) of potassium salt (usually KCl).

The grasses sown are paspalum, kikuyu and setaria (both cv. Nandi and cv. Kazungula). Green panic is sown on the drier sites. White clover is the most commonly sown legume. Others sown are the desmodiums (greenleaf and silverleaf), siratro and glycine (cv. Cooper and cv. Clarence).

The 'Big Scrub' of northern New South Wales (the Richmond-Tweed Region) forms a triangle based on Lismore, Ballina, and Bangalow. This area was cleared between 1870 and 1900 and produces 40 per cent of the butter and cheese and 25–30 per cent of the pigs in New South Wales. Paspalum and white clover in the 1890s and kikuyu in 1920 were introduced and widely sown but there has been a steady decline in production per acre for many years (Kingsland 1950).

Feed year systems involving the incorporation of glycine pea cv. Clarence into depauperate kikuyu swards to give feed from December to May, the use of early cultivars of subterranean clover such as Clare for the winter, and vetch (*Vicia sativa*) as a supplement from June to September have improved animal nutrition (Colman, Holder, and Swain 1966; Holder 1967). October to December is still a difficult period because of unreliable rainfall. With such systems increases in total farm production of the order of 50–65 per cent have been obtained in two to five years. In addition to the species mentioned considerable use is being made of silverleaf and greenleaf desmodium, lotononis, white clover, siratro and *Dolichos lablab* (cv. Rongai), and of the grasses setaria, pangola, and *Panicum maximum.*

Two other methods of improving rundown pastures have been used in the big scrub where erosion and high soil temperatures are problems in conventional seed beds. One is sod sowing, mainly legumes, into existing depauperate pasture. This is successful with large seed but not with small seed legumes. The other method is to prepare a seed bed by spraying the old pasture with chemicals like paraquat. This method has not been widely tested or adopted.

The rainforest areas to the south of Lismore are similar to those of the Richmond-Tweed region.

The Sub-tropical Lowland Rainforests

Rainforests of this type are found in the Gympie-Cooroy area in south Queensland and along the river valleys of north-eastern New South Wales. Climate is similar throughout. The commonly used grasses are paspalum, kikuyu, setaria, and pangola. Legumes include silverleaf and greenleaf desmodiums, siratro, white clover, and glycine (cv. Clarence and Tinaroo). Green panic and Rhodes grass are also sown in Queensland and *Paspalum wetsteinii* and *Panicum coloratum* in New South Wales. Of other legumes, lotononis is sown on lighter soils and lucerne on well-drained ones.

The commonly applied fertilisers are molybdenised superphosphate at 300–900 lb per acre (336–1008 kg per ha) and potassium chloride at 112 lb per acre (125 kg per ha). Some soils also require lime at about 2000 lb per acre (2240 kg per ha).

The Sclerophyll Forests of Southern Queensland and Northern New South Wales

These areas are similar to, but slightly drier than, the sub-tropical lowland rainforests. The terrain is mostly rolling to hilly. Dairying and beef production are the main livestock industries. In general the same nutrient deficiencies occur, but fertiliser application is lighter because of the drier environment. The species used are the same but with more emphasis on those adapted to drier conditions.

Before sowing permanent pastures on run-down pastures, one or two annual crops of cowpeas or *Dolichos lablab* may be sown to control Axonopus and Cynodon (Cassidy 1968). In some cases it is possible to improve existing pastures simply by over-sowing; e.g. Roe (1963) has successfully established Lotononis in blady grass (*Imperata cylindrica*) in this way.

The Coastal Lowlands (Wallum)

Between Taree in New South Wales and Broad Sound in Queensland there is a narrow discontinuous strip of lowland country, flat to gently rolling, 2–30 miles (3–48 km) wide, lying between the shoreline and the coastal ranges (Coaldrake 1961). The total area is about 5 million acres (2 million ha). The annual rainfall is 40 to 70 in. (1016–1778 mm), well distributed throughout the year but with a distinct summer incidence. The soils are very high in silica (Hubble 1954) and deficient in N, P, K, Ca, S, Cu, Zn and Mo (Andrew and Bryan 1955, 1958). Fertiliser requirements in lb per acre (approx. kg per ha) for pasture establishment are superphosphate 560, calcium carbonate 560, potassium chloride 112, copper sulphate 7, zinc sulphate 7, and elemental Mo 0·125, and for maintenance the requirements are superphosphate approximately 224 and potassium chloride 112 annually.

Many of the soils are poorly drained and all are subject to high and widely fluctuating water tables. Except in the lowest situations this is not a serious impediment to pasture production. Droughts, usually of relatively short duration (2–3 months), are the most important cause of production losses in both pastures and animals.

As a result of research begun in 1950, several grasses and legumes are now known to be adapted to the Wallum environment. The main legumes are phasey bean (*Phaseolus lathyroides*), an annual that is rarely self-regenerating, and the perennials greenleaf desmodium, silverleaf desmodium, lotononis, siratro, white clover, and Kenya clover (*Trifolium semipilosum*). Of the grasses the most productive are the perennials paspalum (*Paspalum dilatatum*), plicatulum (*P. plicatulum*), scrobic (*P. commersonii*), bahia (*P. notatum*), pangola (*Digitaria decumbens*), setaria (*S. sphacelata*), *Panicum coloratum*, and Rhodes (*Chloris gayana*).

North of Maryborough rainfall in the Wallum is only 40–45 in. (1016–1143 mm), not as evenly distributed as further south, and the soils have lower infiltration rates, all of which contribute to greater aridity, especially in spring and early summer. Because of this the temperate and the more mesophytic species of the southern Wallum are replaced in the northern Wallum by more drought-hardy species. Thus *Panicum* spp. tend to be more successful than *Paspalum* spp., siratro replaces the desmodiums and Kenya clover replaces white clover (Evans 1967a). Some of the soils of the northern area are saline (Evans 1967b).

On the Wallum, methods of pasture establishment vary. At one extreme is wet heath with a low shrub cover and a great mass of fibrous root material in the top foot of soil. Heath is fired, slashed, and cultivated once or twice with a tractor-operated rotary hoe. This makes an excellent seedbed. Surface drainage is required on wet heaths.

In lowland forests and woodlands trees are pulled and windrowed and the soil is cultivated with multiple disc implements. Heavy tandem discs are required on surfaces with strong micro-relief to permit later use of wheeled equipment. A good seedbed is automatically produced in the process of removing native vegetation from these sandy soils. If clearing is not complete, ringbarking the trees and cultivating between them offers a cheap alternative but dead trees constitute a hazard to grazing stock, especially in high winds.

On light soils which dry quickly at the surface, it is usual to roll with a cambridge or a tyre roller after sowing to compact the soil and provide better moisture conditions for the germinating seed and the seedling.

ANIMAL PRODUCTION

Although the wet tropics is small in proportion to the size of Australia, it contains over 1 million of the 9 million beef cattle of Queensland and New South Wales, and 830,000 of a combined total of 1,860,000 dairy cattle (see Figs. 6 : 2, 6 : 3). The north-east of New South Wales has 160,000 of the State total of 500,000 pigs.

Animal production varies enormously from district to district and from farm to farm. Stocking rates are a beast to 1 to 2 acres (0·4–0·8 ha) on sown pastures and a beast to 8 to 30 acres (3·25–12 ha) on grazing lands. Accordingly, liveweight gains in beef cattle are from 10 to 30 lb an acre (11–34 kg per ha) a year on grazing lands, and from 150 to 400 lb per acre (168–448 kg per ha) on sown mixed pastures. Age at marketing is commonly 2 to 3·5 years, dressed weights being in the range of 400 to 600 lb (181–272 kg).

Dairy production ranges from 70 to 300 lb (32–136 kg) butter fat per cow per year. Calving percentages are higher in dairy cattle (75 to 95 per cent) than in beef cows (65 to 85 per cent). Losses in young animals are low.

Poor and legume rich pastures differ not only in liveweight gain per acre but also in the seasonal patterns of liveweight changes (Fig. 7 : 3). Among the causes of the reduction or removal of liveweight loss in winter and spring on sown pastures are better quality and quantity of feed throughout summer and especially in autumn, leaving better aftermath for animals, which in turn are in better condition for the nutritional stress of winter. Where quality and quantity remain adequate through winter, as in some grass-legume pastures of the wet tropics or in some pastures given nitrogen, animals continue to gain weight at a fairly constant rate throughout the year.

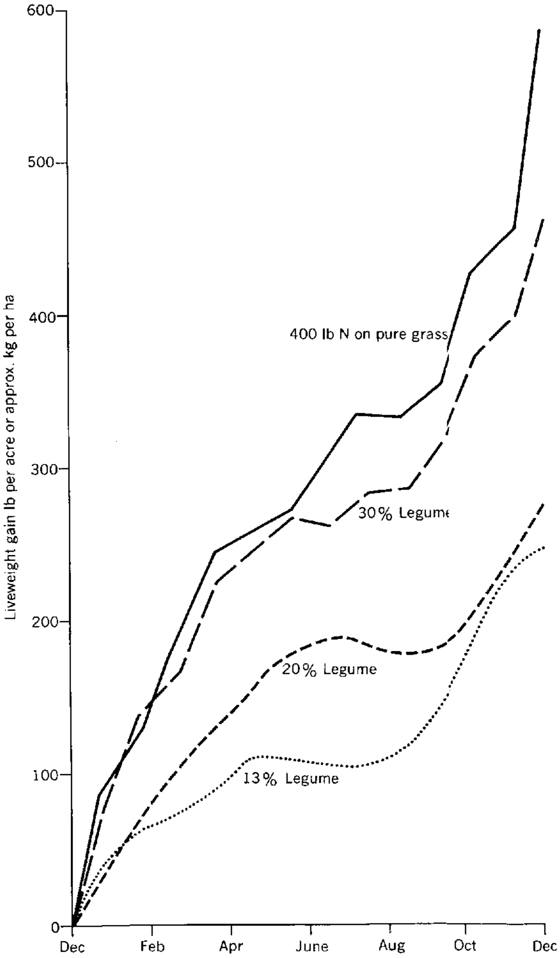


Fig. 7 : 3 Effect of legume content of tropical pastures on cumulative liveweight gains of beef cattle at Beerwah, south-east Queensland. Means of two to seven years.

As native grazing lands do not exist in a true sense in former rainforests the comparisons are between depauperate pastures of low-producing introduced species and good ones. On the coastal tablelands the rundown pastures are dominated by *Axonopus* spp. (especially *A. affinis*) with remnants of paspalum and kikuyu and a little white clover. Such pastures support a low-producing cow to 3 acres (1·2 ha) in comparison with a high-producing cow to one or one and a half acres (0·4–0·6 ha) on improved pastures. On coastal rolling country where many pastures are overrun by blady grass and bracken, no reliable figures are available but production per acre is very low, and production per farm on average well below the figure of 8000 lb (3629 kg) butter fat set as a minimum by the Commonwealth Committee of Inquiry in 1960. Luck and Douglas (1966) showed that on one farm on steep country in the Gympie region production per cow rose from 72 lb (33 kg) butter fat to 146 lb (66 kg) butter fat when 80 acres (32 ha) of improved pastures were provided for approximately 70 cows; total production on the farm rose from a mean of 3350 lb (1520 kg) butter fat to over 11,000 lb (4990 kg) in five years. Similar figures are quoted by Holder (1967) for the Lismore region, where on eight farms adopting a pasture development program, production of butter fat per farm increased from a mean of 7200 lb to 11,400 lb (3266 to 5171 kg) in from two to four years.

On the Wallum, commercial development is too recent for reliable figures, but in experimental work at Beerwah and Coolum beef cattle grazed at approximately a beast per acre (0·4 ha) have averaged 250–300 lb per acre (280–336 kg per ha) liveweight gain per annum in 5-year periods (Bryan 1968a; Anon. 1965b). In more recent studies at Beerwah liveweight gain per annum has averaged between 300 and 400 lb per acre (336–448 kg per ha) (Bryan and Evans 1968) for two years.

With a longer growing season, pastures on former rainforest near Innisfail, Queensland, have produced much greater gains. At South Johnstone annual liveweight gains have been as high as 650 lb per acre (728 kg per ha) per annum on a *Brachiaria decumbens-Desmodium heterophyllum* pasture and about 600 lb per acre (672 kg per ha) on pangola-*D. heterophyllum*.

In the Wide Bay (Gympie) region of south Queensland, Cassidy and Burns (1965), after making a number of case studies of dairy farms, concluded that the use of dryland tropical pastures was the most profitable single practice applicable on a large scale for the improvement of dairy production. They estimated that the minimum area for worthwhile improvement was one acre (0·4 ha) for each cow, and showed that for the first five years of a pasture improvement program an annual expenditure of $14 per acre ($34.50 per ha) resulted in an annual increase of $16 in net income per acre ($39.50 per ha) per year.

On sown pastures it is usual to rely completely or almost completely on pasture for feed throughout the year. When the sown pastures are of limited extent as in the initial stages of improving a farm, they may be used in a system similar to deferred grazing. At later stages most farmers graze their paddocks in rotation, although there is little evidence to indicate that this system is more productive than continuous grazing (see Chapter 27). Where pasture quality is of major importance, as with cows in milk, the subdivision of the herd and rotation of milkers on to the first pick of feed is normal and desirable, and in dairying areas pastures are grazed in rotation so that the milkers get fresh feed every day. Rotation of night paddocks helps to prevent concentration of fertility but unavoidably there is some concentration on camping sites. Thus on hilly country kikuyu grass, a high fertility demander, is found mostly where cattle camp or where the wash from dairy buildings and yards extends. Rotational grazing may be more effective in disease and parasite control, for example for worms in calves and young cattle, but the use of modern drugs is reducing the need for this.

Cattle ticks are present throughout the wet tropics, but control by pasture spelling is too long (4–5 months) to be practical.

Paddocks are generally small, 10 to 150 acres (4–61 ha). Numerous watering points are therefore required, and these are provided either by reticulation from a single source (bore or earth tank or stream) or by a series of small earth tanks.

Fodder conservation is little practised despite the advantages to be gained in some cases of maintaining production in the dry season. Pasture saving, hay and silage making, irrigation and the storage of home grown maize or sorghum are all done to a limited extent. Factors that militate against conservation on the property are the amount of capital tied up, shortage of labour and equipment, summer rain, and the chemical composition of many of the species which makes them unsuitable for silage.

As a substitute for conservation, winter cereal crops, especially oats for grazing, are grown in some areas of dairying districts. The practice is probably of economic advantage only where whole milk is the end-product and where a subsidy is paid on milk produced in winter.

In the past small areas of varieties of sugar cane with a soft rind were stood over as a form of drought insurance, but this practice has largely disappeared; in any case, the quality of the material as feed was low. One promising approach is the search for plants that might respond to applications of nitrogen in winter, such as one of the frost tolerant species of *Setaria*.

Use of Nitrogen on Grass

In the higher rainfall regions shortage of nitrogen is likely to be a major limitation to production even in good grass-legume pastures. Tropical grasses given an adequate supply of nitrogen are capable of high yields of dry matter and of protein (Shaw *et al.* 1965; Henzell 1963; Bryan and Sharpe 1965; Colman 1966). These yields are rarely, if ever, achieved in legume-based pastures and there is therefore a trend towards the use of nitrogen on grass for intensive grassland production. Among the advantages of having more protein in beef fattening pastures are that the effects of short droughts are minimised and winter weight losses reduced or avoided, thus permitting a substantial increase in stocking rates and earlier turn-off of finished animals.

Few data are available in north-eastern Australia on the effect of nitrogen fertilised grass on animal production and fewer still on the relative profitability of fertiliser and legume nitrogen. In many experiments the use of nitrogen fertiliser has been confounded with other factors. However, Colman and Holder (Holder 1967) at Wollongbar, N.S.W., obtained 240–290 lb per acre (269–325 kg per ha) of butter fat from kikuyu grass given 300 lb per acre (336 kg per ha) of nitrogen as sulphate of ammonia as compared with about 80 lb per acre (90 kg per ha) from unfertilised grass. Thus taking butter fat at 50c per lb (110c per kg), an extra return of $80 was obtained for an outlay of $50 per acre ($124 per ha).

With beef cattle at Beerwah, Qld, Evans (1969) obtained liveweight increases of 1100 lb per acre (1232 kg per ha) from 400 lb per acre (448 kg per ha) of nitrogen as ammonium nitrate. Taking the cost of nitrogen at 15c per lb (33c per kg) and of beef at 25c per lb (55c per kg) this represents an output of $165 for an input of $66 per acre ($408 for $163 per ha). Against this must be set an average liveweight gain of 300 lb per acre (336 kg per ha) on legume-based pastures, which reduces the net extra output of liveweight gain from nitrogen to about 800 lb per acre (896 kg per ha) and the beef value to about $125 per acre ($309 per ha).

At Samford, Qld, Jones (1967) obtained an average liveweight gain of 480 lb per acre (538 kg per ha) from 300 lb per acre (336 kg per ha) of nitrogen as urea on Nandi setaria and Rhodes grass. No comparable figures are available from grass-legume mixtures.

To be profitable fertiliser nitrogen must enable stocking rates to be increased substantially. Thus Holder (1967) increased the rate at Wollongbar from 2·4 acres (1 ha) per cow on unfertilised pasture to 1·0 and 0·75 acres (0·4 and 0·3 ha) per cow by using nitrogen; Evans (1969) increased stocking rate from 1 beast per acre (2·5 per ha) to 3 beasts per acre (7·4 per ha), while Jones (1967) carried 1·5 to 2 beasts per acre (3·7 to 5 per ha) as compared with about a beast to 2 acres (0·8 ha) on unfertilised grassland.

It is still not known whether the returns from nitrogen are economic. The use of nitrogenous fertiliser greatly increases cash inputs, both for fertiliser and for extra cattle. Henzell (1968) came to the conclusion that, on the evidence available, legumes seem a better economic proposition than nitrogen fertiliser.

IMPEDIMENTS TO ANIMAL PRODUCTION

Weeds can present major problems, especially to establishment on old cultivations but also at later stages in sown pastures. They compete strongly with seedlings of pasture species, with poorly adapted sown species, and when soil fertility has declined or pastures have been mismanaged. Control usually lies in correcting such basic causes, rather than in direct attack on the weeds (see Chapter 23). If a direct attack has to be made, the usual means of control are pre- and post-emergent weedicides or mechanical methods.

In some cases the weeds are species originally present, for example native trees and shrubs which have regenerated, blady grass (*Imperata cylindrica*) or bracken (*Pteridium aquilinum*), but most pasture weeds are not native. The more important weeds are lantana (mostly *L. camara*), wild tobacco (*Solanum* spp. and *Nicotiana* spp.), carpet grasses (*Axonopus* spp.), couch grass (*Cynodon dactylon*), *Sida* spp., many thistles, docks (*Rumex* spp.), sedges, rushes (*Juncus* spp.), stinking Roger (*Tagetes minuta*), summer grasses (*Digitaria* spp.), groundsel (*Baccharis halimifolia*), crofton weed (*Eupatorium* spp.), *Paspalum urvillei*, and *Urena lobata*.

Pests and Diseases of Sown Pastures (see Chapter 18)

Nematodes are prevalent in the drier soils of the Wallum.

Probably the most serious insect pest of pastures in the region is the Amnemus weevil (*Amnemus* spp.) (see Chapter 24). This species occurs from Moruya, N.S.W., to Rockhampton, Qld, but the worst affected area is the Northern Rivers of New South Wales. The insect attacks only legumes. White clover, phasey bean, and *Desmodium* spp. are highly susceptible; siratro and lotononis are largely undamaged (Braithwaite, Jane, and Swain 1958). Effective control is possible with DDT or deildrin, but both these chemicals are proscribed because of the limits set for chlorinated hydrocarbons in export meat.

Larvae of the pasture soldier fly (*Altermetroponia rubriceps*) eat the roots of grasses especially on the uplands, as do also army worms (*Cirphis* spp.) and white grubs (*Lepidiota caudata*). Funnel ants (*Aphaenogaster* spp.) are the major insect pest on the Atherton Tablelands; the only effective control measure is to maintain a high sward density. Seed harvesting ants may affect the establishment of pastures in north Queensland. The bean fly (*Agromyza phaseoli*) attacks *Phaseolus* spp. in south Queensland and some grasses are susceptible to damage by the felted grass coccid (*Antonina graminis*). Weevils, jassids, cutworms (*Euxoa* spp.), leafrollers, and mites are minor pests of pastures.

Of the diseases, the most important are viruses, which affect many sown legumes and some grasses (Hutton and Grylls 1956). Among the affected legumes are *Desmodium uncinatum*, *D. intortum*, *Lotononis bainesii*, centro, and white clover. Fungal diseases are also fairly common. No disease has yet proved to be devastating.

Diseases and Pests of Animals

Probably the main impediments to animal production are ecto- and endo-parasites of cattle. Of these the cattle tick (*Boophilus microplus*) is by far the most important, involving costs of mustering and dipping and of inoculation against tick fever caused by the protozoan, *Babesia argentina*. Control is made more difficult by the development of resistance by ticks to chemicals used in dips. The Northern Rivers region of New South Wales is largely free of ticks.

Buffalo fly (*Siphona exigua*) is troublesome in the coastal and sub-coastal areas of northern Queensland.

In young stock the occurrence of worms, scours, blackleg, and leptospirosis is fairly general. In adult cattle the main problems are worms, tuberculosis, blackleg, leptospirosis, brucellosis, vibriosis, and mastitis. Liver fluke (*Fasciola hepatica*) is mainly temperate in distribution but it occurs just south of Gympie, Queensland.

March or gad flies (*Tabanus* spp.) can cause considerable irritation to cattle in summer. On the other hand mosquitoes and midges do not appear to cause much worry except to horses.

Dingoes are present in much of the region but cause only small losses, and except in the most southern part of the region, rabbits are of no consequence.

LAND TENURE

In established areas, especially in the dairying regions, most of the land is freehold. On the drier margins and in areas being used for beef, particularly new areas such as the Wallum, more of the land is held under Crown leases. Most of the leases make provision for freeholding when reasonable improvements have been made and it can be anticipated that freeholding will be more general in time to come.

Land values range widely from $20 to $500 an acre ($49–$1235 per ha) depending on rainfall, soil type, slope, and whether developed or not. Dairy farms are seldom more than 400 acres (162 ha) but beef properties are generally in excess of 2000 acres (810 ha).

8

TROPICAL AND SUB-TROPICAL WOODLANDS AND GRASSLANDS

N. H. SHAW AND M. J. T. NORMAN

DISTRIBUTION

Tropical and sub-tropical woodlands and grasslands extend in an arc from northern Australia down the east coast into south-east Queensland (see Map 3). In some instances boundaries with other vegetation formations, for example Brigalow and Mitchell grass, are quite sharp and usually coincide with geological changes. Elsewhere the woodlands merge into adjacent vegetation and the transition is largely associated with climate. Thus on the eastern boundary the woodlands merge into the wet sclerophyll forests (see Chapter 7). Again, in the Northern Territory and Western Australia there is a gradual change to semi-arid woodland (see Chapter 16); the boundary here has been taken as lying between the 20 and 30 in. (508–762 mm) isohyets, as on present information this probably represents the southern limit for large-scale commercial establishment of introduced pasture legumes.

The woodland region is almost bisected by the broad belt of grasslands which stretch south from the Gulf of Carpentaria (see Map 3), and it will be convenient to deal with these two sections separately. They will be referred to as the Northern Territory-Western Australia (N.T.-W.A.) and the Queensland sections.

Accounts of geomorphology, soils, vegetation, climate, and landuse for much of the area under discussion are given in the survey reports of the CSIRO Division of Land Research (Christian and Stewart 1953; Christian *et al.* 1953; Christian *et al.* 1954; Perry *et al.* 1964; Gunn *et al.* 1967; Story *et al.* 1967; Speck *et al.* 1960; Speck *et al.* 1965; Speck *et al.* 1968; Galloway, Gunn and Story, in press).

CLIMATE

The region as a whole has a summer rainfall climate with annual means ranging from 30 to 60 in. (762–1524 mm) in N.T.-W.A. and from

TABLE 8 : 1 Temperature and rainfall data for some coastal (c) and inland (i) stations

Station	Temperatures (°C)[a]						Rainfall			
	Hottest month			Coolest month			Summer	Winter	Total	
	Month	Max.	Min.	Month	Max.	Min.	Oct.–Apr. (mm)	Mar.–Sept. (mm)	(mm)	(in.)
Kununurra (c)	Nov.	39	24	July	31	14	732	14	746	29
Darwin (c)	Nov.	34	26	July	31	20	1515	34	1549	61
Katherine (i)	Oct.	38	23	June	30	13	944	15	959	38
Townsville (c)	Jan.	31	25	July	24	15	985	109	1094	43
Georgetown (i)	Nov.	36	22	July	28	12	678	44	722	28
Rockhampton (c)	Jan.	32	22	July	23	11	756	193	949	37
Emerald (i)	Dec.	35	21	July	23	7	450	141	591	23
Maryborough (c)	Jan.	31	20	July	22	9	882	272	1154	45
Gayndah (i)	Jan.	33	19	July	22	5	582	175	757	30

[a] Figures rounded to nearest °C.

Sources: Kununurra—Kimberley Research Station records. Darwin, Katherine—*Climatological Survey Region* 1—*Darwin—Katherine Northern Territory.* Commonw. Meteor. Bur. Aust., Melbourne, 1961. Others—*Climatic Averages Australia.* Commonw. Meteor. Bur. Aust., Melbourne, 1956.

20 to 60 in. (508–1524 mm) in Queensland. Isohyets are roughly parallel to the coast. The summer incidence is marked in N.T.-W.A. with about 95 per cent of the rainfall in the summer months of October to April, and similar conditions exist in the north-western part of the region in Queensland. The winter rain component gradually increases towards the southern part of the Queensland section, but, even there, two-thirds of the annual rainfall is in summer (see Table 8 : 1). The length of the summer rainfall season is shorter in the northern parts of the region than in southern Queensland, but the amount of rain is more reliable.

Temperature regimes cover a wide range with hottest conditions in N.T.-W.A. and coolest in south-eastern Queensland. Temperatures show two distinct trends. Both maximum and minimum temperatures in summer and winter decrease southwards, but within this overall trend, maximum temperatures in summer increase and minimum temperatures in winter decrease from the coast inland (see Table 8 : 1). Frosts do not occur in N.T.-W.A. or in the northern part of the region in Queensland, but they increase in frequency and severity south of about latitude 18°S, particularly away from the coast, and are a most important component of the climatic environment of pastures and grazing lands in these parts (Coleman 1964). For example, at Gayndah, Queensland, there are about sixteen frosts a year with screen temperatures of 36°F (2°C) or less, spread over an average of 11 weeks, and of these about five a year have screen temperatures of 32°F (0°C) or less (Foley 1945).

SOILS

Accounts of the soils of much of the region are contained in the reports of the CSIRO Division of Land Research already referred to, and reference to *A Handbook of Australian Soils* (Stace *et al.* 1968) will give further information. Only a few general comments are made here, and the terminology follows the *Handbook.*

Lithosols predominate in the N.T.-W.A. section and occupy over half the area. Other important soil groups are red earths, yellow earths, and ironstone gravels either in a sand or yellow duplex soil matrix.

In Cape York Peninsula lithosols, yellow earths, red earths, and acid grey earths (mainly unconsolidated sands) are the major soil groups. The first three are also common further south, but by far the largest areas are covered by texture-contrast soils, either solodised solonetz, solodic, non-calcic brown soils, or soloths. Grey or brown clays and black earths occur in the areas of grassland associated with the woodlands.

From the pasture point of view the most important characteristics of the soils of the woodlands are that water-holding capacity and fertility tend to be moderate to low. The grassland soils are very much better in these respects.

VEGETATION

Northern Territory-Western Australia

Except in areas liable to periodic flooding or under the direct influence of the ocean, the major vegetation formations of this section are open eucalypt woodlands.

The most widespread community is a tall open woodland of *Eucalyptus tetrodonta* and *E. miniata* (50–70 ft, 15–21 m), with a very variable and often discontinuous low tree and shrub layer. The ground flora consists almost wholly of grasses, which on medium-textured soils are bunch-type perennials and on coarse-textured soils are annuals.

In drier situations, that is towards the southern boundary of the section, on shallow soils or in hilly country, the tall open woodland gives way to a range of open eucalypt woodlands of lower stature (20–50 ft, 6–15 m). The main species are *E. tetrodonta*, *E. miniata*, *E. bleeseri*, *E. confertiflora*, *E. foelscheana*, *E. tectifica*, *E. grandifolia*, *E. polycarpa*, *E. dichromophloia*, *E. phoenicea*, and *E. ferruginea.*

The important perennial grasses of the ground storey under eucalypt woodlands are *Themeda australis*, *Sorghum plumosum*, *Chrysopogon fallax*, *Sehima nervosum*, *Aristida pruinosa*, *Heteropogon triticeus*, *H. contortus*, and *Plectrachne pungens.* All are bunch grasses and all but Plectrachne are tall (4–6 ft, 1·2–1·8 m). The important annual grasses are *Sorghum intrans*, *S. stipoideum*, *S. australiense* (all very tall, up to 12 ft, or 3·6 m), *Aristida hygrometrica*, *A. browniana*, *Brachyachne convergens*, *Rottboellia formosa*, and *Brachiaria* spp. (all mid to short, up to 2 ft, or 0·6 m).

Queensland

The vegetation of this section is quite diverse, as might be expected from the range of latitude involved. The pattern is complex and this complexity increases southwards. The major formation is eucalypt woodland merging to forest in areas of higher rainfall along the eastern margin, and to semi-arid woodland along the drier western margin. Within the woodland region there are areas of Dichanthium grassland and of Acacia forests (locally known as scrubs) dominated by *Acacia rhodoxylon* or *A. shirleyi.*

The most common woodland communities have one of the narrow-leaf or silver-leaf ironbarks as the dominant tree (Pl. 16). These are widespread throughout the whole of the area shown on the map but do not occur in northern Australia west of the Great Artesian Basin (Perry and Lazarides, in Perry *et al.* 1964).

Narrow-leaf ironbark woodlands are commonly characterised by *E. crebra* and *E. drepanophylla*, together with *E. cullenii* or *E. whitei* in the north, and *E. siderophloia* or *E. sideroxylon* in the south. Sometimes they occur as almost pure stands but more commonly other eucalypts are also present. These include *E. dichromophloia*, *E. polycarpa*, *E. intermedia*, *E. tessellaris*, *E. alba*, and *E. papuana*.

Silver-leaf ironbark woodlands are mostly characterised by *E. melanophloia* which often occurs alone in the tree layer, but *E. shirleyi* also occurs in the north, particularly in drier habitats. Associated eucalypts include those mentioned above, together with *E. orgadophila*, *E. populnea*, and narrow-leaf ironbarks.

There are very many other eucalypt communities which occupy considerable areas. Box woodlands occur commonly with *E. brownii* as a dominant in the north and *E. populnea* in the south (see Chapter 16). Woodlands of *E. tetrodonta* and *E. polycarpa*, similar to those in the Northern Territory, are found in north Queensland. Communities of *E. papuana* and *E. alba* occur in coastal areas in the tropics. In central Queensland *E. orgadophila* is common on black earths and cracking clays, and in southern Queensland *E. tereticornis* is the dominant tree species in sub-coastal woodlands adjacent to streams.

Woodlands characterised by species of Melaleuca occur in many coastal areas, the most extensive occurrence in this region being in Cape York Peninsula and the Gulf country (Chapters 7 and 16). Much of this may be flooded shallowly for at least part of the rainy season.

Dichanthium grasslands occur on fine-textured soils, mostly dark cracking clays (Chapters 4 and 6). They are commonly treeless or with trees widely scattered or in isolated patches, but are often transitional to woodlands of *E. orgadophila* and *E. leptophleba* in north Queensland, or of *E. orgadophila*, *E. melanophloia*, or *E. populnea* in central and south Queensland. These grasslands are often adjacent to brigalow scrubs (see under Central Downlands in Chapter 9).

THE LIVESTOCK INDUSTRIES

The major livestock industry throughout the region is beef cattle raising and fattening. There are no sheep in the N.T.-W.A. section and few in Queensland, and most of those within the Queensland woodland region are confined to the Dichanthium grasslands. Dairy cattle are relatively few and are mostly confined to the southern half of the Queensland woodlands, either in the higher rainfall parts or in areas with fertile soils. There are some 150,000 feral water buffaloes in the sub-coastal plains of the Northern Territory which are being exploited for manufacturing and pet meat.

It is difficult to obtain the numbers of beef cattle in the region because boundaries of statistical divisions do not coincide with ecological boundaries, but it is estimated that the average number over the past decade is about 3 million in the Queensland section and 230,000 in the N.T.-W.A. section. This is about one-quarter of the Australian beef cattle population.

Until recent years beef enterprises in the region have been entirely based on low input-low output use of native grazing lands. In the N.T.-W.A. section properties are large, averaging about 1500 square miles (390,000 ha), capital investment on fences and water is low, and herd control is minimal. Until recently killing facilities for marketing fat cattle were restricted to a small meatworks at Wyndham, W.A., and the only other outlets were for store cattle walked overland to Queensland or for small shipments of live cattle from Darwin to South-East Asia. The opening in 1962 of export meatworks at Katherine and Darwin, together with the rapid displacement of droving by road transport and the development of a 'beef roads' network, has changed the situation dramatically. Most cattle can now be killed locally. However, because nearly all cattle still come from large properties and graze on unimproved grazing lands, meat quality is low and is mostly sold as manufacturing beef to the U.S.A. Concurrently, a steady rise in the price of beef and technical advances in pasture agronomy and cattle breeding have initiated what is likely to become a major transformation of the industry. Capital for development is flowing in rapidly.

In the Queensland section beef production is on a more intensive scale but there is an enormous range in size of holdings and in carrying capacity. Generally speaking, properties are smaller and carrying capacity is higher in the southern than in the northern part where holdings may be as large as several thousand square miles (1000 sq miles = 259,200 ha). Carrying capacity ranges from one beast to 5 acres (2 ha) in the south to about 4 per square mile (1 beast to 65 ha) in parts of the Cape York Peninsula (Sutherland 1961).

Until about ten years ago most improvements in beef production in the Queensland section were the result of investment in better water facilities, more subdivision, ringbarking, and better stock, all of which helped to increase the efficiency of use of unimproved grazing lands. Since then, there has been a considerable increase in the use of both summer and winter cereal crops for grazing, mainly sorghum and oats, and more recently an increase in sown pastures. At the same time a change in market preferences towards smaller carcases with less fat coverage has made it possible to market animals at a younger age from unimproved grazing lands. Other factors such as better transport and higher prices for beef have contributed to an overall increase in beef production. As an indication of the extent of this increase, beef production in Queensland has risen from an average of 150,000 tons a year in the ten years to 1937, to 297,000 tons a year in the ten years to 1967 (Bureau of Agricultural Economics 1968).

Beef herds throughout the region were based originally on British breeds, mainly Hereford and Shorthorn. Over the last twenty to thirty years, however, there has been a pronounced change towards an infusion of breeds of tropical origin. These stem mainly from the American Brahman or the Santa Gertrudis, and the aim has been to improve performance due to better adaptation and tick resistance.

There are several important pests and diseases of cattle in northern Australia although many of the major infectious diseases of the world do not occur. The most important is the cattle tick (*Boophilus microplus*), with associated tick fevers, which has been estimated to cost the industry $20,000,000 annually (Anon. 1959b).

More information on the beef industry in northern Australia can be found in publications such as Kelly (1952), Beattie (1956), and Franklin (1961), and from the bibliographies prepared by Culey (1961 and 1965).

Agricultural crop production in the Queensland section is mainly confined to the southern half where it is mostly on alluvial soils, cracking clays, and kraznozems, soils which are more fertile and have good water-holding capacity (see also Chapter 9). The major crops are summer and winter cereals both associated with beef production and for cash cropping. Crop production is slowly extending.

Until 1963, agricultural crop production in the N.T.-W.A. section was negligible. In 1963–4 the first crops of cotton were grown on the Ord River Irrigation Project and in 1967–8 12,000 acres (5000 ha) were sown plus some grain sorghum; the irrigation area is planned to expand to some 170,000 acres (69,000 ha) by 1979. In the Northern Territory a dryland crop project has started between Katherine and Darwin with an initial sowing of 12,000 acres (5000 ha) of sorghum in 1967–8. The stated intention is to expand to nearly 200,000 acres (81,000 ha), diversifying to other annual cash crops.

THE GRAZING LANDS

The grazing lands of the region comprise the grassy understorey of the woodlands which have been modified to a greater or lesser extent by the influence of man and his grazing animals. They are classified as Tropical Tallgrass (Chapter 6, Map 4).

Northern Territory-Western Australia

The herbaceous communities of the eucalypt woodlands in the Northern Territory portion of this section are classified by Perry (1960) as:

1. *Kangaroo grass-perennial sorghum (Themeda australis* and *Sorghum plumosum).* On medium-textured soils of low relief.
2. *Kangaroo grass on lowlands mixed with hilly country.* Grazing lands dominated by kangaroo grass, with a range of other species, on more variable topography. The communities are interspersed with small areas of treeless grassland on grey-brown fine-textured soils, with *Astrebla* spp., *Eulalia fulva* and *Iseilema* spp.
3. *Annual sorghums and other tall grasses.* On coarse-textured soils of low relief. The most common species are *Sorghum intrans* and *S. stipoideum.* On skeletal soils in areas of rugged relief, which cover at least half of the region, the ground storey of the eucalypt woodlands is dominated by annual Sorghum species and *Plectrachne pungens.*

In estuarine areas of high rainfall (> 50 in., 1270 mm), where the land is periodically flooded, the eucalypt woodland is replaced by treeless grassland and reed-sedge communities. Perry (1960) has divided these into:

- (i) *Kangaroo grass-Eriachne grasslands.* On meadow podzols dominated by the perennials *Themeda australis* and *Eriachne burkittii* in areas flooded for 3–4 months of the year.
- (ii) *Reed-wild rice communities.* On clay soils of the sub-coastal plains flooded for 6 months of the year; dominated by *Oryza rufipogon* (wild rice) and *Eleocharis* spp. (reeds).

In addition, there is a strip of land with salt flats, samphire flats, and dunes on the south edge of the Gulf of Carpentaria.

In the North Kimberley area of Western Australia, the grazing lands are generally poor, the main dominating grasses being *Plectrachne pungens*, *Chrysopogon fallax*, *Sehima nervosum*, *Sorghum* spp., and *Aristida hygrometrica* (Lazarides, in Speck *et al.* 1960).

The woodland region is bounded to the north by the sea. To the south, the communities transitional to the semi-arid region (Chapter 16) are low open eucalypt woodlands with a grass understorey dominated by *Aristida pruinosa* on coarse to medium-textured soils of low relief (E of the 132nd meridian), and a complex of open eucalypt woodlands on variable soils and topography, including areas of treeless Astrebla grassland (W of the 132nd meridian).

Queensland

The characteristic herbaceous community of the eucalypt woodlands in the Queensland section is the 'eastern mid-height grass' of Perry and Lazarides (in Perry *et al.* 1964). Such communities are widespread (Christian *et al.* 1953; Gunn *et al.* 1967; Story *et al.* 1967; Speck *et al.* 1968; Galloway, Gunn, and Story in press). They are composed of perennial tussock grasses growing to about 3 ft (0·9 m) high in the southern part of the section and to 4 ft (1·2 m) in the north; forbs and legumes are consistent but minor constituents. In this book they are classified as Tropical Tallgrass (see Chapter 6). The species most commonly dominant is *Heteropogon contortus* (bunch spear grass) and this has given rise to the descriptive term 'spear grass region' (Shaw and Bisset 1955). Other species which are commonly prominent are *Themeda australis*, *Bothriochloa bladhii* syn. *B. intermedia*, *B. ewartiana*, *B. decipiens*, and *Aristida* spp. Originally *T. australis* was probably dominant more widely than it is today, while *H. contortus* is thought to have increased. Species of the genera Chrysopogon, Cymbopogon, Chloris, Dichanthium, Eriachne, Shizachyrium, Sorghum, and Eragrostis are also common and are prominent at times. Botanical composition varies considerably, even over short distances, but several broad generalisations can be made. On soils of fine texture, and where fertility is reasonably good, the dominant grass is commonly *B. bladhii* (southern and higher rainfall parts of the region) or *B. ewartiana* (western and drier parts). The latter sometimes occurs as almost pure stands. *Dichanthium* spp. are often prominent as well. On soils of medium texture *H. contortus* and either *B. bladhii* or *B. decipiens* are generally dominant, together with *T. australis.* The presence of the latter probably depends on the intensity of grazing in the area, the species being more prominent under light grazing. On soils of coarse texture species of Aristida and Chrysopogon become more prominent, although *H. contortus* and *T. australis* may still be present. Somewhat similar species are found in the Melaleuca woodlands to the south and east of the Gulf of Carpentaria.

Similar herbaceous communities occur in Cape York Peninsula where *T. australis* and *Heteropogon triticeus* are very common.

The Dichanthium (bluegrass) grasslands occur mostly in the drier western half of the woodland region. There are two main subdivisions commonly known as the bluegrass-browntop downs of the Gulf country, and the bluegrass downs further south (see Chapter 6). In the former the dominant species are *Dichanthium fecundum*, *D. tenuiculum* syn. *D. superciliatum*, and *Eulalia fulva*, whilst in the latter *D. sericeum* is the common species, sometimes with *D. affine* syn. *D. humilius*. There are many associated grasses mostly in the genera Aristida, Bothriochloa, Enneapogon, Panicum, and Thellungia. Native legumes are common and contribute to the grazing value of these communities, the main genera being Rhynchosia, Glycine, Neptunia, Alysicarpus, and Crotalaria. Towards the northern end of the Central Downlands (Fig. 9 : 1) Heteropogon sometimes occurs as the dominant grass over extensive areas (Story *et al.* 1967). The Dichanthium grasslands generally provide much better grazing than spear grass areas and have always been much sought after. However, because the soils are fertile and have good water-holding capacity, large areas in central and southern Queensland are being converted to cropping (see under Central Downlands in Chapter 9).

Animal Production on Grazing Lands

The pronounced summer incidence of rainfall throughout the region and the low natural fertility of the soils impose a sharply-defined pattern of yield and quality of native grasses which severely limits productivity of beef cattle. There is a general pattern of rapid grass growth in summer, a period of maturation in autumn with an associated decline in quality, and a further decline in quality in winter. The effects of climate, soil, and management practices on these changes in quality have been discussed by Christian and Shaw (1951). While the pattern is common to the whole region there are differences of degree within it.

Studies of native grazing lands in central coastal Queensland by Miles (1949) and Shaw and Bisset (1955) showed that dry matter yields ranged from 1 to 3 tons per acre (2500–7500 kg/ha). The latter authors found that about 60 per cent of the total yield was produced between January and April and that there was almost complete absence of growth in winter even when rain occurred. Miles showed a close relation between grass growth and mean maximum temperature and found little growth below 70°F (21°C). Both studies indicated that crude protein levels in the forage on offer seldom exceeded 7 per cent and declined to 2–3 per cent in winter; phosphorus content was also low. The decline in quality in winter is associated with maturation, leaf-fall, leaching by rain and dew, and frost damage.

At Katherine, N.T., grass growth is rapid in mid-summer, reaching a maximum yield of about 0·5 ton per acre (1250 kg/ha) by late March. Within a month of the end of the rains in April, the grasses have dried off and remain as 'standing hay' until the following wet season. Maximum values for crude protein (about 10 per cent) and phosphorus (about 0·12 per cent) occur at the start of the season, but by mid-winter these values have declined to about 2 and 0·02 per cent respectively. Because of the dry climate, the grasses retain a moderate energy value (though highly deficient in protein) throughout the winter until the leaching rains of early spring (Arndt and Norman 1959; Norman 1963b).

Thus while climate has a profound influence on the quantity and quality of feed available in both the northern and southern tropical woodlands, the particular controlling elements are not always the same. In northern areas grass growth ceases when moisture becomes limiting at the end of summer; temperature limitations on growth are seldom operative because of the absence of winter rain. In southern Queensland, on the other hand, where winter soil moisture may provide the opportunity for grass growth, there is an operative temperature limitation for the native grasses. These differing climatic controls have important implications in relation to pasture improvement based on introduced species.

The liveweight performance of beef cattle on these grazing lands has been documented by various authors (Chester 1952; Alexander and Chester 1956; Sutherland 1959; Norman and Arndt 1959; Norman 1965b).

In southern Queensland beef steers gain weight over about 8 months and lose over about 4 months. The net gain varies considerably from year to year, ranging from about 120 to 300 lb (54–136 kg) and as a result steers are usually 3 to 4 years old at slaughter. In north Queensland the adverse seasonal effects are stronger so that net yearly gain is usually not greater than 200 lb (91 kg) (Shelton 1956).

At Katherine steers on native grass gain for only 6–7 months of the year. Losses start about a month after the wet season has ended, and by late dry season amount to about 20 per cent of the peak liveweight. The net annual gain of growing steers may be as low as 100 lb (45 kg) and marketing is commonly not until 5–7 years of age (Norman 1965b).

An additional major drawback to beef production in the less favoured parts of the woodland region is that the reproductive rate of cows is low. Thus, in a study of six herds in north Queensland, Donaldson, Ritson, and Copeman (1967) found mean pregnancy levels of only 36·4 per cent in lactating and 77·5 per cent in non-lactating cows, and concluded that under-nutrition was one of the factors involved.

Subdivision of beef properties into paddocks in this region is designed for herd management (i.e. segregation of sexes and age groups) rather than for pasture management. Paddocks are generally stocked with a fairly constant number of animals throughout the year and there is little fluctuation from year to year except in severe drought. Limited local research suggests that such continuous grazing at conservative stocking rates is better than rotational or deferred grazing systems (see Chapter 27).

A general management practice in much of the region is annual burning. In the northern areas, where the dry season is long and severe, grazing lands are often burnt in the dry season to encourage the dormant perennial grasses to utilise residual soil moisture and produce new shoots. This is the so-called 'green-pick'. In southern parts of the region the burn is more commonly delayed until after the danger of frost is past and after a fall of rain; the purpose is to remove the standing dry grass from the previous growing season which restricts accessibility to new season's growth.

Such burns have important effects on the botanical composition of the pastures (Shaw 1957; Norman 1963a); the burns of themselves do not appear to result in instability of the vegetation, but burning in combination with heavy grazing may bring about marked vegetation changes.

SOWN PASTURES

Pasture improvement in the tropical and subtropical woodlands is a very recent development. Research on which it is based dates only from 1944, and in fact most results of practical significance have emerged within the last ten years. At the time of writing the total area of improved pasture in the region is probably no more than 200,000 acres (81,000 ha), but most of this has been achieved within the last five years and the acreage is increasing.

The general thesis on which all the research has been based has been described by Davies and Shaw (1964). The essential point is that while climate, plant species, and inherently low soil fertility all contribute to the difficulties of feeding animals on the native grasses, nevertheless the climate, despite its drawbacks, should permit higher pasture production. Thus improvement is based on a change of species together with use of appropriate fertilisers to raise soil fertility.

Sown pastures in the region are based almost entirely on legumes as the source of nitrogen. It is known that fertiliser nitrogen can give high grass yields but the effect on animal production has not been measured, and on prices at the time of writing the economics of fertiliser nitrogen for beef is doubtful. The legume of most importance is *Stylosanthes humilis* (Townsville lucerne) (see footnote, p. 16) but other legumes are sown to a limited extent.

Pastures Based on Townsville Lucerne

These pastures are classified and mapped as Tropical Annual Pastures (see Chapter 6, Map 5, Pl. 30). The history of this species in Australia has been reviewed by Humphreys (1967a). A native of Central and South America, it was accidentally introduced in the early 1900s, probably through the port of Townsville, and it slowly spread from that centre. It received attention from a number of agricultural advisers and land holders in north Queensland over the years, but interest in it was sporadic. Concerted research into the use of this legume dates from the start of work by CSIRO at Rodd's Bay in

Queensland in 1944 and at Katherine in the Northern Territory in 1946. Humphreys concludes that the main impetus to the current active commercial use was the demonstration of increased animal production on Townsville lucerne pastures at these two centres (Norman and Arndt 1959; Shaw 1961; Norman 1966). This stimulated a considerable increase in research by CSIRO, the Queensland Department of Primary Industries, and the Northern Territory Administration (see reviews by Norman 1966 and Humphreys 1967a).

Townsville lucerne is an herbaceous legume, either erect in habit up to 2 ft (0·6 m) high, or semi-prostrate, with thin stems and elongated, pointed, trifoliate leaves. It is free-seeding and usually behaves as an annual, although in southern Queensland a proportion of plants may persist for more than one year.

The attributes of Townsville lucerne which make it so valuable are that it is easy to establish, that it withstands heavy grazing and regenerates annually, that it will grow on poor soils, and that it effects big increases in animal production.

The adaptation of Townsville lucerne to the range of soils and climates in the region is still being actively explored. On present information it appears that, given moderate amounts of fertiliser (commonly superphosphate), the species will grow on a wide range of soils, being restricted only by extreme shallowness of soil or waterlogging in the early part of its growth phase. In the N.T.-W.A. section and north Queensland, the climatic limitation to growth is principally rainfall, and the species is at present confined to areas with more than 25 in. (635 mm) of annual rainfall. In central and south Queensland the species is restricted to near-coastal areas and it is thought that low night temperatures in late summer and autumn may be a factor limiting spread further inland.

The present range of adaptation is likely to be extended by selection of cultivars since Cameron (1965) has found significant variation in flowering time and in some growth characteristics in collections from the naturalised population in Australia. New introductions from other countries may also extend the range.

In most instances Townsville lucerne is sown alone to produce a mixture with the existing native grasses. Best establishment is obtained when seed is sown on the surface of a well-prepared seedbed. However, the seed germinates rapidly and there is an extensive development of roots in the seedling stage (Torssell *et al.* 1968), so that good establishment is possible on roughly prepared seedbeds and even on uncultivated land. The two most common practices are surface broadcasting on a rough seedbed, and aerial sowing on uncultivated land. Establishment is more reliable on well-prepared seedbeds, but even a poor initial establishment can ultimately produce a dense stand from self-sown seed. Aerial sowing is of special value because large areas can be covered in a short sowing season, and because land need not be completely cleared of trees. Where land is partially cleared, or where the trees are widely spaced, a modification to suit large areas is to sow in strips and rely on subsequent spread from self-sown seed to cover the intervening spaces. The fact that Townsville lucerne always has a proportion of hard seed gives an added safety factor when using these 'rougher' sowing methods.

Seed rates commonly range from about 1 to 4 lb of the single-seeded pods per acre (1·1 to 4·5 kg/ha). Low rates produce a low-density stand in the first year and prolong the time taken to achieve maximum production. Hence it is preferable to sow 4 to 5 lb per acre (4·5 to 5·6 kg/ha) and even more if seed prices permit.

Apart from sowing techniques and seed rates, the other important factor in establishment of Townsville lucerne is to achieve a degree of control over competition from grasses for light (Sillar 1967) and sometimes for moisture. This can be achieved by burning or heavy grazing before sowing and then maintaining grazing pressure after sowing. With strip sowing and aerial sowing it is a mistake to remove stock in order 'to give the legume a chance to establish'.

A unique establishment technique has been developed for areas in the Northern Territory where the dominant native grasses are tall annual sorghums (Stocker and Sturtz 1966). These grasses have very little hard seed so that they can be almost eliminated by burning the dead grass of the previous season when the new season grass is in the seedling stage. The ash makes a good seedbed for Townsville lucerne, and the practice lends itself readily to aerial seeding.

Different results have been obtained at Katherine and in Queensland in connection with competition between grasses and Townsville lucerne. Experience in Queensland has generally been that Townsville lucerne is compatible with *Heteropogon contortus* and other native grasses and comparative stability has been observed over many years. Grass-legume balance seems to be governed mainly by stocking rate, legume dominance resulting from heavy grazing, and grass dominance from light grazing. However, in an experiment under lenient intermittent grazing (L. 't Mannetje and N. H. Shaw, unpublished) Townsville lucerne became dominant in association with Rhodes grass (*Chloris gayana*). In contrast, experiments at Katherine show that Biloela buffel grass (*Cenchrus ciliaris*) competes with Townsville lucerne, and that Gayndah buffel grass and Birdwood grass (*C. setigerus*), although less aggressive, still tend to dominate (Norman 1962). An important consequence of this is to reduce the amount of Townsville lucerne available for dry season grazing, and Norman (1962) has questioned the desirability of including any sown grass with Townsville lucerne in that environment. The question of competition between Townsville lucerne and annual and perennial grasses is complex and is receiving close attention from research workers.

Townsville lucerne has always had a reputation in Australia for being able to grow on poor soils without fertiliser. In this connection Andrew (1966b) showed that excised roots of Townsville lucerne had a much higher rate of phosphorus absorption than several other species tested, while Gates, Wilson, and Shaw (1966) drew attention to the capacity of the species to grow and synthesise protein while adapting to big changes in cation balance. Nevertheless Townsville lucerne responds well to improved nutrition, both in terms of dry matter (e.g. Norman 1959 and 1965a) and nitrogen content (Shaw, Gates, and Wilson 1966). Results such as these have effectively disposed of the idea, once commonly held, that Townsville lucerne is a 'low quality' legume.

From fertiliser studies conducted on soils in the region it can be expected that most of the soils of tropical and sub-tropical woodlands will be deficient in nitrogen and phosphorus. Deficiencies of sulphur and molybdenum also seem to be common and sometimes also of potassium, at least in Queensland. Common fertiliser usage is about 1 cwt per acre (125 kg/ha) of superphosphate or molybdenised superphosphate annually, but it is certain that some of the poorer soils would benefit from higher initial applications.

Animal Production on Townsville Lucerne Pastures

Big increases in animal production from Townsville lucerne pastures have been recorded in experiments at Katherine, N.T., and in Queensland. At Katherine the average liveweight gain of steers on stand-over Townsville lucerne during the dry season is 150 lb/head (68 kg) at a stocking rate of 1 beast/acre (2·5/ha), whereas on unimproved grazing lands they lose about 20 per cent of their initial liveweight even when stocked at 100 acres/head (40 ha/head). Steers maintained continuously on Townsville lucerne from weaning at 3 acres (1·2 ha)/beast equivalent/year reach slaughter weight at less than 3 years of age (Norman 1968) compared with 5–7 years on native grasses. At Rodd's Bay, on the Queensland coast, weaner steers grazed on Townsville lucerne pastures also reach slaughter weight at less than 3 years at a stocking rate of 2 to 3 acres (0·8 to 1·2 ha) per beast, compared with 4½ years on native grasses at about 9 acres (3·6 ha) per beast.

These results are from Townsville lucerne pastures fertilised with superphosphate and at Rodd's Bay with molybdenum as well. The difference in animal production between fertilised and unfertilised Townsville lucerne pastures at Rodd's Bay over 7 years to 1965–6 has amounted to an average of 60 lb (27 kg) liveweight gain per head or 50 lb per acre (56 kg/ha) (Shaw, unpublished data). Humphreys (1967a) states that for seven responsive sites in Queensland the increase from superphosphate varied according to year and to site from 8 to 131 lb liveweight gain per acre per year (9–147 kg/ha). Another most important effect of fertiliser on animal production from Townsville lucerne pastures has emerged from an experiment by Ritson, Edye, and Davies at Townsville (CSIRO 1966) in which both breeder performance and calving rate were much improved. The significance of these findings in relation to the generally low reproductive rate of cattle on unimproved grazing lands (Donaldson, Ritson, and Copeman 1967) is obvious.

There is a striking and important difference between the results from Katherine and Rodd's Bay with respect to performance of animals in the dry season. At Katherine with almost complete absence of rain and dew in the dry season, Townsville lucerne 'hays off' after seeding and remains as standing hay at about 12 per cent crude protein until the first rains of the following wet season. Cattle gain weight on this feed. On the other hand, at Rodd's Bay the matured Townsville lucerne gradually deteriorates under the influence of dew and light falls of rain, and cattle lose weight, although the amount of loss and the duration of loss are both less than on native grasses. These results, due to differences in rainfall, probably represent the two extremes that can be expected in the region.

The importance of stocking rate in establishing Townsville lucerne has already been mentioned. It is equally a factor in maintenance of the pasture. Stocking rates suited to unimproved grazing lands are too low for Townsville lucerne because they will lead to excessive competition from grasses. Stocking rate is, of course, a significant factor in determining animal production from these improved pastures.

Pastures Based on Other Legumes and Grasses

Other legumes which are suitable for sown pastures in the region are siratro (*Phaseolus atropurpureus*) and Hunter River lucerne (*Medicago sativa*), but at present their use is mostly confined to the southern half of Queensland. The role of perennial legumes in the north Queensland and N.T.-W.A. parts of the region is still in doubt; promising results have been obtained with siratro in areas of more than 40 in. (1016 mm) of rainfall, but generally the long dry season imposes great stress on perennials and an annual such as Townsville lucerne has decided advantages.

Hunter River lucerne grows well on many of the alluvial and more fertile clay soils in southern Queensland, and because of its cold tolerance is able to continue to grow in winter when soil moisture is available. Good animal production on mixed grass-lucerne pastures has been recorded by Christian and Shaw (1952) and Young, Fox, and Burns (1959), and the advantages have been confirmed under commercial use. A well-prepared seedbed is required for establishment and, as lucerne usually does not persist for more than four or five years, these pastures are probably best adapted to a rotation with cropping. Recent work by 't Mannetje (1967a) shows that the use of Hunter River lucerne can be extended to many of the poorer and moderately acid soils of the woodland region if the seed is lime-pelleted to achieve successful nodulation.

Siratro has performed well in recent years in experiments at several centres in the woodland areas of southern Queensland (e.g. 't Mannetje 1967a; Shaw 1967b). It has given high yields of pasture, has combined well with a number of different grasses, and has persisted well under grazing. Commercial experience indicates high carrying capacity and good animal performance but experimental measurements of animal production are limited. Its area of adaptation overlaps that of Townsville lucerne in central Queensland and extends beyond Townsville lucerne in southern Queensland.

Most of the south Queensland woodlands where siratro can be grown are subject to frosts which are sufficient to kill all top growth of the legume. In contrast, lucerne is unaffected by such frosts. 't Mannetje (1967a) showed that siratro and lucerne could be grown together, producing a pasture in which the two legumes exhibited complementary seasonal growth.

Of the other legumes tested in the woodland region *Leucaena leucocephala*, *Glycine wightii* syn. *G. javanica*, and *Lotononis bainesii* show promise. *Desmodium intortum* may also be useful in the higher rainfall parts of south-east Queensland, where this region overlaps with areas described in Chapter 7, but generally conditions are too dry for this species.

Many perennial introduced grasses can be grown in the region, and the more important species are Rhodes grass (*Chloris gayana*), green panic (*Panicum maximum* var. *trichoglume*), buffel grass (*Cenchrus ciliaris*), Birdwood grass (*C. setigerus*), and *Urochloa mosambicensis*. The choice of grass depends largely on rainfall, but the major factor determining persistence is a continuing supply of nitrogen from a legume or as fertiliser. The chief advantages expected from use of one of these introduced grasses rather than the native grasses are higher yield and higher digestibility, especially in late summer and autumn, but much more research is needed on these aspects.

The Future of Sown Pastures

The beef industry in the woodland region is in a stage of transition. Most of the industry is still on an extensive grazing basis and the advent of sown pastures offers the first real opportunity for the industry to intensify. There is no doubt that present knowledge is sufficient to permit commercial development of sown pastures over a very large proportion of the region. Increased research into extending the geographical and climatic range of sown pastures, improving pasture production, improving pasture use, and integrating pastures, crops, and grazing lands into efficient and economical production units will provide a sounder basis of development.

9

THE BRIGALOW

J. E. COALDRAKE

The brigalow is characterised by vegetation in which the leguminous tree *Acacia harpophylla* is conspicuous (Pl. 33). There are scattered outliers but the region occupied by brigalow forests lies mainly between latitudes 20°S and 29°S (some 700 miles, 1127 km) and terminates more or less on the border between Queensland and New South Wales. To the east and west, the region is bounded approximately by the 30 and 20 in. (762 and 508 mm) isohyets of mean annual rainfall. Within this general area of about 26 million acres (10·5 million ha) there is a mosaic of soils differing sharply in fertility, with brigalow occupying clay soils of moderate to high fertility on some 12 million acres (4·9 million ha). The remainder is largely occupied by Eucalypt forests and woodlands on infertile solodic soils where plant growth is limited by physical conditions as well as by nutrient deficiencies. The third important unit of landscape is an area of about 3 million acres (1·2 million ha) of rolling grasslands on deep cracking clay soils ('black earths') of high fertility towards the northern end of the brigalow region. These contrasting landscapes will be referred to as the 'brigalow' and 'solodic' lands and as the 'Central Downlands' (see Fig. 9 : 1).

Both the brigalow and solodic lands in their original state have a carrying capacity of about 1 steer to 50 acres (20 ha), the higher fertility of the brigalow lands being offset by the poor growth of herbs under the very dense tree layer (Pl. 33). Both have the same climate, both require total replacement of the original vegetation for effective animal production from pastures, and both present problems of woody regrowth following tree felling and burning. But the brigalow lands will support pastures without the use of fertiliser for at least ten years, whereas the solodic lands require fertilisers from the outset and there are some complex interactions between elements; this is the main reason why the brigalow lands have been developed first. The combination of fertile soils with the need for total replacement of vegetation has led to the situation where the brigalow region contained 1·7 million acres (0·7 million ha) out of the total area of 3·6 million acres (1·4 million ha) of sown pasture in Queensland in 1968 (Queensland Department of Primary Industries).

The Central Downlands are mainly grassland with a much higher carrying capacity (about 1 steer to 10 acres or 4 ha), and are more or less free of timber so that there are no problems of regrowth. The soils, while being at least as fertile as those of the brigalow lands, are more prone to erosion, and this factor in land development is accentuated by the high intensity of much of the rainfall. This chapter concentrates mainly on brigalow forests; grasslands and

Plate 33 Brigalow forest: *Acacia harpophylla* (brigalow) on heavy clay soil with gilgai micro-relief, southern brigalow region, Queensland (CSIRO photo)

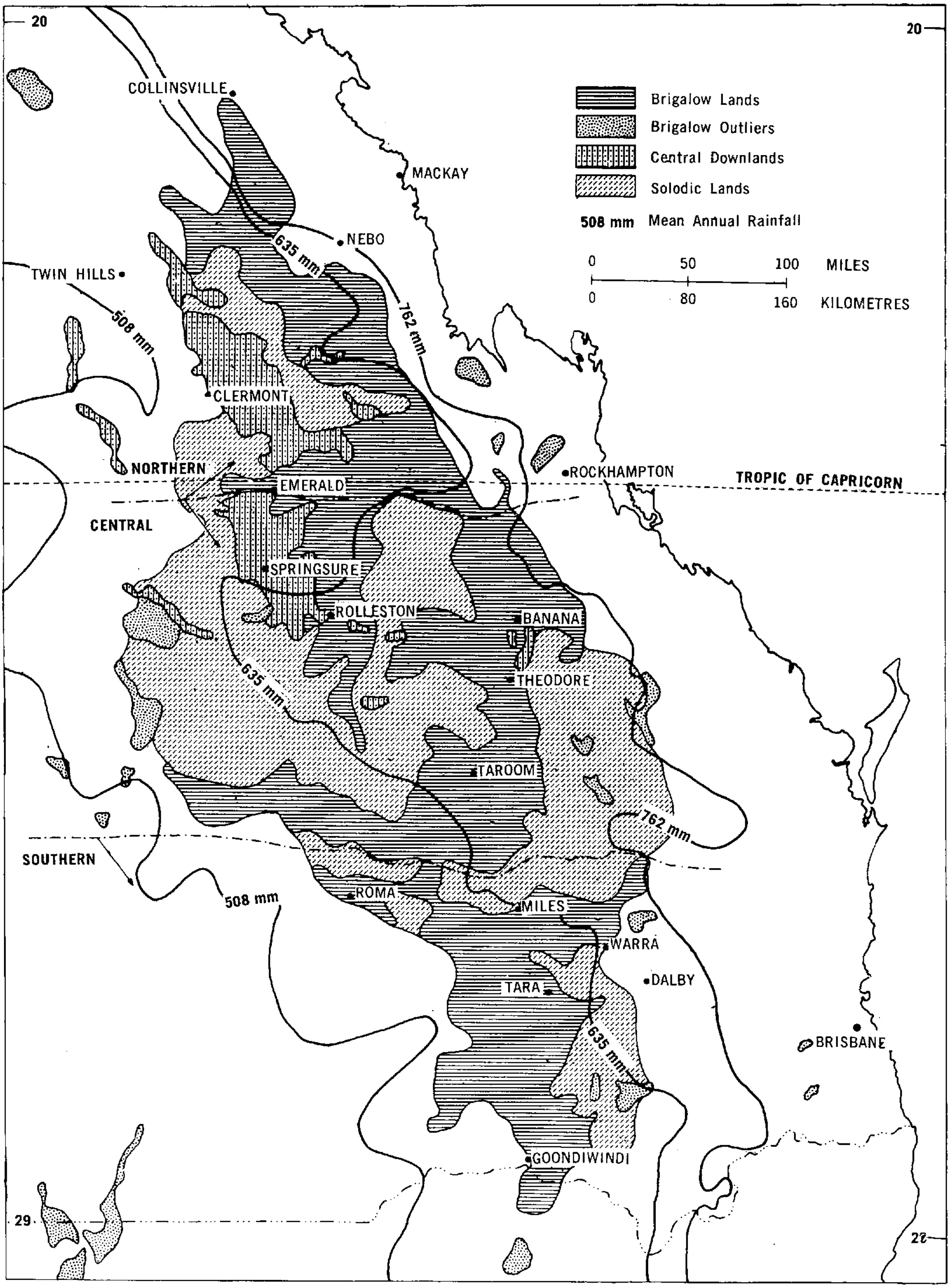


Fig. 9 : 1 The distribution of the major units of landscape in the brigalow region

eucalypt woodlands are discussed in other chapters.

For convenience the region is divided geographically into three units called respectively the southern, central, and northern brigalow (see Fig. 9 : 1).

The first comprehensive studies on the soils and the regional ecology of the brigalow lands were carried out by Isbell and co-ordinated in the final paper of his series (Isbell 1962). The vegetation of brigalow communities was described by Johnson (1964) in conjunction with his studies on control of brigalow regrowth. Recently comprehensive studies of the central and northern parts of the brigalow have been published by Speck *et al.* (1968), Story *et al.* (1967), and Gunn *et al.* (1967). These key papers have been drawn on freely in the following account of the environment.

CLIMATE

The outstanding characteristics of the climate of this region are:

(1) The variability of rainfall throughout the year and between years.
(2) Over much of this region of predominantly summer rainfall the winter rainfall is equally reliable and highly effective due to lower evapo-transpiration.
(3) The coupling of frosts with a wide diurnal range of temperature in winter.
(4) The incidence of heat waves.

Rainfall

Mean monthly and annual rainfall for a range of stations throughout the brigalow region are given in Table 9 : 1. Roughly two-thirds of the annual total falls in the summer months of October-March inclusive, but the effectiveness of this is lowered by the combination of high intensities and high temperatures. Some indication of intensities is given in Table 9 : 2 which shows that a daily total of over 4 in. (102 mm) is not exceptional, so that as much as 20 per cent of the total rainfall for one year may fall in one day. At Theodore (lat. 25°S) the following are the highest intensities recorded over short periods: 0·25 in. (6·2 mm) in 5 minutes, 0·85 in. (22 mm) in 20 minutes, 1·70 in. (43 mm) in 1 hour (Anon. 1960).

Apart from year to year variation in the frequency and intensity of major weather systems the main source of variation is rainfall from thunderstorms. While these tend to follow mean pathways in any part of the region, individual storms always wander erratically so that places only a few miles apart may get 2 in. (51 mm) of rain, and none, on the same day. Since thunderstorms are the chief source of opening rains in early summer, that is the months of acute demand for water for new pasture growth and for the preparation of land for sowing of summer growing species, serious delays are frequent in these two vital phases of pasture production.

Winter rains, by contrast, are mainly from the passage of major frontal systems and tend to widespread uniformity. They are an important component of the total annual rainfall about as far north as the tropic, beyond which their influence declines rapidly. South of the tropic,

TABLE 9 : 1 Mean monthly and annual rainfall at selected centres in the brigalow region (mm)

Centre	Years of record	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual total mm	Annual total in.	Annual range mm
Goondiwindi lat. 28° 33′S	78	77	72	59	35	41	45	43	31	37	48	58	70	616	24	264–1034
Miles lat. 26° 40′S	72	96	79	75	37	39	41	42	28	34	56	66	82	675	27	246–1176
Taroom lat. 25° 39′S	81	104	91	66	38	42	40	36	27	35	50	77	83	689	27	241–1201
Banana lat. 24° 28′S	85	107	101	75	36	36	44	34	23	31	53	64	91	695	27	272–1217
Twin Hills lat. 21° 50′S	35	100	134	72	44	29	31	27	10	17	34	57	70	625	25	135–1471

Source: Partly Anon. 1960 and 1961a.

TABLE 9 : 2 Highest monthly and 24-hour total of rainfall for selected stations in the brigalow region (mm)

		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Goondiwindi	M	231	374	297	165	185	177	159	110	140	172	236	263
lat. 28° 33′S	D	123	113	94	64	78	77	83	75	50	56	86	109
Taroom	M	273	421	403	164	224	229	241	98	186	204	292	296
lat. 25° 39′S	D	119	138	119	109	142	97	109	53	81	73	102	159
Clermont	M	516	428	403	171	176	307	192	125	107	114	264	671
lat. 22° 50′S	D	171	119	123	81	82	99	97	68	98	78	111	419

M = Highest monthly total. D = Highest daily total.
Source: Coaldrake 1964.

the expectancy of sufficient rainfall to support effective growth throughout a winter season is at least as great as the expectancy of an equivalent rainfall over a summer season.

Short droughts of 3 to 4 months' duration occur almost every year somewhere in the brigalow region. Rainfall records are still too short to allow accurate estimation of the probability of droughts of differing duration, but the figures available suggest an expectancy of a major drought, that is a period of a full year with less than two-thirds of the mean annual rainfall about once in every ten years. About once in every fifty years there is an expectancy of two such years in succession.

Temperature

The temperature and other atmospheric data shown in Table 9 : 3 may be regarded as typical for most of the brigalow region. The data for relative humidity, when taken in conjunction with those for temperature and radiation, point to high rates of potential evapotranspiration; this is supported by limited data for evaporation from a free water-surface in standard evaporimeter tanks which is approximately 65 in. (1651 mm) per year over most of the region.

While frosts occur throughout the whole region there is a general trend to fewer and milder frosts in the northern brigalow region. Frosts may be expected at any time between late April

TABLE 9 : 3 Mean monthly temperatures (°C) and total radiation (cal. cm^{-2} day^{-1}) at Miles and relative humidity at Goondiwindi (lat. 28° 33′S)

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year
Mean max.	33·4	32·7	30·9	27·6	23·6	19·8	19·4	21·7	25·4	29·1	31·8	33·1	27·4
Mean min.	19·2	18·9	16·7	12·1	7·3	4·9	3·6	4·7	8·5	13·0	16·4	18·4	12·0
No. days ≥32°	19·1	12·3	9·9	0·6	—	—	—	—	0·9	3·8	13·1	16·7	76·4
No. days ≥38°	2·7	0·5	0·1	—	—	—	—	—	—	—	1·4	2·9	7·6
Average no. days screen temp. ≤2°				0·3	2·1	—	—	—	2·4	0·4			5·2
Average no. days screen temp. ≤0°					0·3	6·0	6·6	6·1	1·3				20·3
Mean daily radiation	600	560	500	420	340	290	320	400	480	560	620	650	480
Rel. humidity 15.00 hrs[a]	35	36	39	41	44	51	48	41	35	32	32	32	39

[a] Figures given are for Goondiwindi since there are no records for Miles.
Sources: Temperature and humidity data are from Anon. 1961a, and radiation data are interpreted from Hounam 1963.

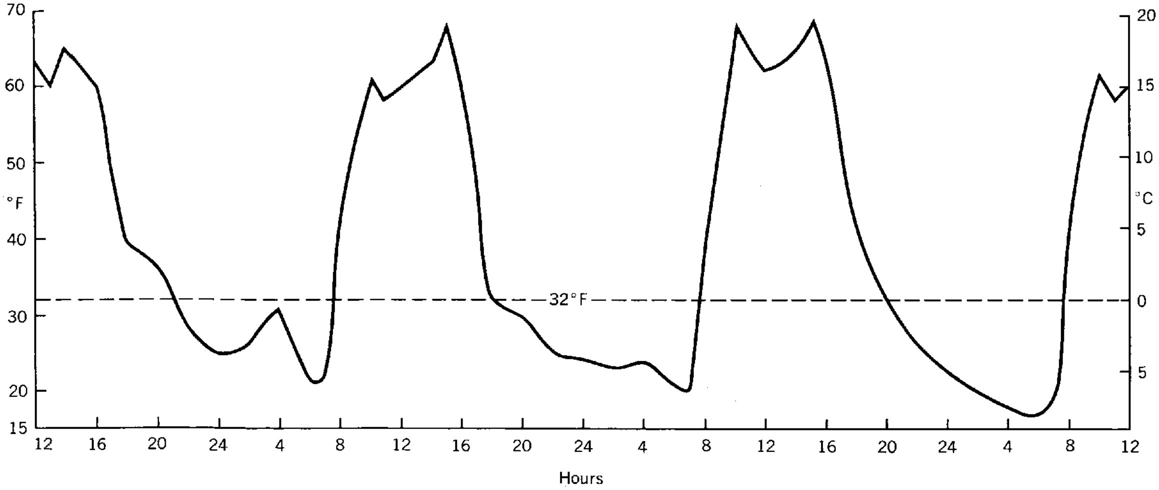


Fig. 9 : 2 Daily temperature curve during frosty weather at 3 in. (76 mm) above ground level on open grassland at Meandarra in the southern part of the brigalow region. The curve is plotted from hourly readings. The sensor was in a depression in gilgaid land where minima are usually 5°F (3°C) lower than on the adjoining bank. Similar diurnal curves could be recorded over most of the brigalow region.

and early October. Terrestrial minimum ('grass') temperatures may drop to 15°F (−9°C) and it is not uncommon to experience ten mornings in a year with grass temperatures below 20°F (−7°C). Neither the number nor the severity of frosts is great by comparison with colder regions, but problems arise from their drastic effects on summer-growing perennials that have had no chance to harden, even those that are reasonably frost tolerant (e.g. lucerne). Figure 9 : 2 illustrates other problems associated with frost—the wide diurnal range of temperature that is commonly associated with frosty periods in the brigalow region, and the fact that there may be over 8 hours per night of frost.

Skerman's (1958) stress on the importance of heat waves in killing young plants soon after germination or in reducing growth of established plants is germane to the whole of the brigalow region. Table 9 : 4 shows the occurrence of heat waves at centres on the eastern (Dalby) and western (Roma) sides of the brigalow region. In an extended hot spell at Roma (December 1946–January 1947) there were 30 consecutive days with temperatures over 95°F (35°C); this included a 6-day and a 7-day period of over 100°F (38°C) and one of 5 days over 105°F (40°C).

TABLE 9 : 4 The occurrence of heat waves at two centres during the months of October to March inclusive for a 30-year period

Number of consecutive days >100°F (38°C)	Dalby, Qld lat. 27° 32′S	Roma, Qld lat. 26° 32′S
2	19	49
3	9	39
4	6	25
5	3	11
6–7	1	11
>7	—	16

Climate and Plant Growth

The variability of rainfall and the high intensity of much of it, the incidence of high and low temperatures, and the high rates of evaporation, all combine to make this often a difficult environment for summer-growing species (Chapter 1). Fitzpatrick's (1965b, 1967b, 1968) studies of plant-soil-water relations using models show that over much of the brigalow region monthly potential evapotranspiration exceeds rainfall throughout the year. But he comments (1968) that 'it cannot be assumed that growth is precluded when rainfall fails to satisfy potential evapotranspiration. Much useful growth normally continues over some considerable range of available soil moisture.' Fitzpatrick (1965b) calculated the probable duration of periods of 'active' growth of native grazing lands in the central brigalow region from a water-use model and weekly rainfalls over a standard 35-year period. His estimates show that over 10 weeks of 'active' growth per year may be expected in only 12 to 24 per cent of years depending on location in respect of rainfall. He also comments on the favourable moisture regime during the winter period of mid-May to mid-September in many years.

Until more extensive climatic data can be combined with more refined models, studies such as those of Fitzpatrick can only be taken as broad confirmation of the fact that water stress is a normal condition of pastures in the brigalow region for much of the time. On the fertile brigalow lands, nutrients and energy are in adequate supply and it is usually water that sets the limits on growth (see Chapter 1). On the infertile solodic lands after fertility is adjusted water again becomes the limiting factor.

In most years the total production of summer-growing species comes from a few short outbursts of active growth over periods of from about 5 to 20 days. That production can still be quite high under this system is suggested by Russell's (1968) figure of 103 lb/dm/acre/day (115 kg/ha) by Rhodes grass during a 28-day period at a site in the southern brigalow region when it had adequate soil moisture and fertility. The extent and comparative reliability of winter rainfall over the southern and central parts of the brigalow region offer much scope for the use of winter-growing annual pasture species and forage crops such as oats.

SOILS AND TOPOGRAPHY

Brigalow Soils

Isbell (1962) divided soils characterised by a brigalow-dominant vegetation into five broad groups on the basis of differences in parent material, depth of solum, degree of gilgai micro-relief and reaction profile. One of these groups occurs only in outlying areas about 100 miles west of the main brigalow region and is not considered here. The remaining four groups may be broadly classified as follows:

*Gilgaid deep clay soils (*5·6 *million acres or* 2·3 *million ha).* These occur on nearly flat to very gently undulating landscapes (Pl. 6). They are coarsely structured, heavy cracking clays of great depth (10–15 ft, 3–4·5 m) normally having an alkaline surface on a strongly acid subsoil (pH 4·0 at 24 in., 61 cm), or acid throughout. Their most striking feature is a moderate to strong development of gilgai micro-relief (see Pl. 5) commonly of the order of 2 to 3 ft (0·6–0·9 m), with differences in texture, fertility, and water-relations in the three positions in the micro-relief: top, slope, and depression. Among the brigalow soils these have the lowest content of phosphorus (2 to 100 ppm of available P) and the highest salinity in the upper part of the profile (0·01–0·60 per cent total soluble salts at 0–6 in. (15 cm) and 0·06–0·68 per cent at 6–12 in. (15–30 cm)) with total soluble salts often exceeding 1 per cent at depths of 100 in. (254 cm).

These are the most difficult soils to develop, not only because of mechanical problems associated with micro-relief but also because of fertility characteristics such as those mentioned above.

*Sedentary clay soils (*5·06 *million acres or* 2·05 *million ha).* These are commonly found on moderately undulating landscapes with slopes of up to 15 per cent. They are medium to heavy clays of moderate depth (3–4 ft, 90–122 cm) formed mainly from sedimentary rocks of Permian and Jurassic age. Reaction is alkaline (pH 8·0–8·5) throughout the profile, in about half of them with the remainder becoming acid (pH 4·5 to 5·5) below about 40 in. (102 cm). Gilgai micro-relief is normally absent. These soils are more fertile than the gilgaid clays and the only real problem with them is the risk of soil erosion. They occur chiefly in the central and northern two-thirds of the region.

*Alluvial clay soils (*0·8 *million acres or* 0·32 *million ha).* These are fairly deep (to 5 ft, 152 cm) heavy clays derived from unconsolidated fine-textured stream alluvia. They are alkaline throughout and gilgai is absent or only moderately developed. They have the highest phosphorus (19–680 ppm) content and lowest salinity of the brigalow soils. They occur mainly on the floodplains of major streams and annual flooding to a depth of several feet for 4 to 5 days is the chief problem in their use.

*Miscellaneous deep clay soils (*0·4 *million acres or* 0·16 *million ha).* These occur sporadically throughout the brigalow region on flat to gently undulating landscapes. They are heavy clays of considerable depth formed from various unconsolidated clay materials. The profiles are alkaline in the upper levels but may be strongly acid at depth. Gilgai micro-relief is normally absent. Salinity and phosphorus contents are both low by comparison with other brigalow soils. They present no special problems in development.

The working definition of brigalow lands used by Isbell in the broad subdivision given above excluded some fertile soils on which brigalow is present though not dominant. In the southern brigalow region the important group is Isbell's (1957) weakly solonised brown clay loam association covering 0·9 million acres (0·36 million ha). In the central brigalow region Sweeney's (1968) mapping units suggest an additional 1·0 million acres (0·40 million ha) of grey-brown to black cracking clays. In the northern brigalow region Gunn's (1967) mapping units suggest an additional 0·7 million acres (0·28 million ha) of similar soils.

Solodic Soils

These are shown in Map 2. They have been mapped and described in detail for part of the southern region by Isbell (1957) and at a broader level for the central and northern parts by Sweeney (1968) and Gunn (1967). They have also been discussed briefly by Hubble (1964) and Leslie, Mackenzie, and Glasby (1967). The estimated areas in the brigalow region are: Southern 4·0 million acres (1·6 million ha) (Leslie, Mackenzie, and Glasby 1967), Central 5·7 million acres (2·3 million ha) (derived from Sweeney 1968 and Gunn 1967), Northern 2·0 million acres (0·81 million ha) (derived from Gunn 1967 and Sweeney 1968).

'Solodic' is used here to imply the past influence of salinisation with subsequent solodisation and partial removal of sodium, especially from the surface soil. Hubble (1961) states that most of the soils in this group in southern Queensland were either 'solodised solonetz' or 'solodic' with the latter retaining less soluble salts. Thus the soils of these solodic lands may be described as salt affected soils with sharp texture contrasts between the sandy to clay loam A horizons and the clay B horizons. Hubble (1964) states that 'dense clay subsoils of coarse prismatic of columnar structure, low permeability and moderate salt content are characteristic'. The predominant metal cation in the exchange complex is either sodium or magnesium. Gunn (1967) states that they occur mainly on gently undulating country with slopes of less than 5 per cent. Pastures or crops grown on them show gross deficiency of nitrogen and phosphorus and sporadic deficiency of other elements such as calcium, copper, zinc, and boron (Russell 1967). They also have physical properties which restrict penetration of water and plant roots. However, soils of this group with sandy A horizons from about 3 to 30 in. (7·6–76 cm) deep possess one advantage over the heavy clay soils of the adjoining brigalow lands. They have much lower permanent wilting points than the heavy brigalow soils so that a much greater percentage of the water is available for growth from small falls of rain; this difference can be important to winter-growing temperate legumes and summer-growing pastures during drought. In the southern and central brigalow regions these infertile soils are likely to be developed rapidly because they are already served with the public facilities necessary to development (e.g. roads) by virtue of the fact that they are intermingled with the brigalow lands that are being developed. The achievements in research on, and development of, solodic lands discussed later in this chapter show that they can now be regarded as a major source of land for development to pasture throughout the region.

Central Downlands

These are restricted to the central and northern parts of the brigalow region where they occur on gently undulating country with slopes generally of the order of 2 to 3 per cent. Broad-scale descriptions of them have been given by Gunn *et al.* (1967) and Story *et al.* (1967). The estimated areas are: central Brigalow 1·3 million acres (0·5 million ha) and northern Brigalow 1·9 million acres (0·8 million ha).

The majority of the soils have formed *in situ* from basaltic or other basic volcanic rocks and there is commonly a sequence from dark brown clay loams on the broad crests of rises grading downslope to darker clay soils. The depth varies from 1 to 6 ft (0·3–1·8 m) with the majority being 2 to 3 ft (0·6–0·9 m) deep. These are all cracking clay soils with the water relations characteristic of such soils. Skerman's (1953) figures show that they are well supplied with phosphorus (90–200 ppm available P) and potassium, but nitrogen levels (0·07 to 0·1 per cent total N) are generally lower than in virgin brigalow lands. Linear gilgais are common on these soils.

The gentle topography, the absence of trees, and the fertility of these downlands make them ideal for conversion from natural grasslands to crops or sown pastures. However, the erosion hazard is very high and there are strong climatic risks associated with heat waves, frost, and rains of high intensity and high variability. These all operated at different times to the detriment of early attempts to farm these soils—notably the large-scale operations attempted by the British Food Corporation in 1948–54. Since then the understanding of these soils has improved to the point where about half a million acres are now farmed successfully with crops such as grain sorghum, wheat, and safflower. Their use for sown pastures has been limited by problems of establishing small-seeded species on self-mulching surface soils, but large-seeded species (especially perennial sorghums) are being used with success.

VEGETATION

The brigalow, with the eucalypt shrub woodlands, is a zone of transition from the wetter coastal forests and woodlands to the arid Acacia shrublands dominated by Acacia and Chenopodiaceae (see Map 3). While climate determines this broad trend, the pattern within the region results from an intermingling of communities from both sources determined by soils and topography. There is no single climatic climax formation but many ecosystems, each with its own stable community. The commonest change is an oscillation in species composition of the lower layers within communities according to the vagaries of rainfall and fire. In some communities this natural fluctuation has been dampened by the introduction of domestic livestock and the associated alteration of the frequency of burning. Notable changes of this type are the widespread decrease of *Themeda australis* and the increase of *Heteropogon contortus* in many forest and woodland communities, and the increase of *Aristida leptopoda* and *Panicum queenslandicum* at the expense of *Dichanthium* spp. (Bisset 1960) in the grasslands of the Central Downlands (see Chapter 8).

In terms of area covered and suitability for development to grassland there are five important plant formations in the region:

1. Acacia forests ('scrubs')
2. Microphyll vine woodland } 'softwood
   Semi-evergreen vine thicket } scrubs'
3. Eucalypt woodlands
4. Grassland.

Where specific references are not given below details of the vegetation may be obtained from one or more of the following: Isbell 1957, 1962; Pedley 1967; Story 1967; Speck 1968.

1. *Acacia Forests ('Scrubs')*

While the brigalow forests are the most extensive type within the group, and the most important for development, there are other types centred on other species of Acacia especially in the central and northern parts of the region. Many of these forests are characterised by the great density and comparative lowness of the tree layer (Pl. 33). It is these characteristics which lead to the use of the popular term 'scrub' rather than the technically correct terms such as 'forest' or 'woodland'.

The brigalow forests were divided by Johnson (1964) into eleven different communities based on presence or absence of various trees or shrubs in association with the brigalow. The tree layer is normally 30–50 ft (9–15 m) in height, but brigalow itself attains a height of 80 ft (24 m) in some areas of higher rainfall. The most widespread of the communities named by Johnson (1964) are set out below together with their soil affinities as interpreted from Isbell (1962).

Brigalow—wilga. This is a layered forest 30–50 ft (9–15 m) high in which the tall rutaceous shrub wilga (*Geijera parviflora*) and sandalwood (*Eremophila mitchellii*) are prominent below the canopy of brigalow. This community is common on the gilgaid soils. In the southern and central brigalow regions belah (*Casuarina cristata*) and in the central brigalow bottle tree (*Brachychiton rupestre*) and *Bauhinia carronii* may become locally prominent in the tree layer. There is a scattering of other shrubs from such families as Myoporaceae and Myrtaceae. The grass layer is sparse and ephemeral, being prominent only in years when rainfall equals or exceeds the mean; Paspalidium, Chloris, Leptochloa and Sporobolus are the common genera.

Brigalow—belah. In this community, which is extensive in the southern brigalow, belah is co-dominant with brigalow or may assume dominance. The shrub and grass layers resemble those of the brigalow-wilga community. They occur on the gilgaid clays and weakly solonised brown clay loams. Prominence of belah generally indicates land that is more easily developed to grassland or crops than that carrying brigalow-wilga.

Brigalow—yellowwood. Yellowwood (*Terminalia oblongata*) is associated with brigalow chiefly in the northern brigalow where it becomes the most prominent member of the understorey. At the fringes of these communities it often forms an ecotone leading into grassland and here there is also an intermingling of grasses more characteristic of the adjoining open downlands. These communities occur on a wide range of soils including the alluvial floodplains.

Brigalow—Eucalyptus. Eight species of Eucalyptus are known to occur with brigalow; the majority of them occur in relatively small patches, but some are widespread. In the central and northern brigalow *E. cambageana* (Dawson gum), *E. populnea* (poplar box), and *E. thozetiana* (yapunyah) are all common associates of brigalow on gilgaid clay soils and may cover large acreages. Dawson gum does not extend into the southern brigalow but the other two are common. On the extensive flood plains of the central and northern brigalow *E. microtheca* (coolibah) is commonly associated with brigalow.

Brigalow—gidgee. Just to the west of the main brigalow region as mapped in Fig. 9 : 1 there are extensive communities in which brigalow combines with gidgee (*Acacia cambagei*) on all of the brigalow soil groups discussed above. These communities are low forests or woodlands in which Isbell (1962) states that brigalow often 'forms a fringe around a pure stand of gidgee, changing abruptly to surrounding grassland'.

Other Acacia forests. Two species of Acacia occur in dense forests in which one or the other forms an almost monospecific layer with sparse understoreys. They occur mainly on shallow or stony soils in the central and northern brigalow. With these two species (rosewood, *A. rhodoxylon* and lancewood, *A. shirleyi*) there is usually no admixture with brigalow. Three other Acacias, yarran (*A. homalophylla*), bendee (*A. catenulata*), and blackwood (*Acacia* sp.), appear as the dominants in communities where scattered brigalow is present.

2. *Microphyll Vine Woodland and Semi-evergreen Vine Thicket*

These two communities, popularly known as softwood scrubs, are associated with brigalow communities chiefly in the central brigalow region. Floristically they are mixtures of Indo-Malayan rainforest species with the typical semi-arid flora of the main brigalow communities. The nomenclature for this formation is from Webb's (1959) physiognomic classification of rainforests.

There is a gradation from brigalow-softwood forests through to softwood forests without brigalow. The most striking members of the tree layer are the sterculiaceous bottle trees with their bulbous trunks (*Brachychiton rupestre* and *B. acerifolia*); other trees common in some areas of these communities are bonewood (*Macropteranthes leichhardtii*), *Geijera salicifolia*, and *Flindersia collina.* Robust lianes are common and the shrub layer is generally dense, but the ground layer is very sparse and litter is plentiful. Eucalypts such as *E. cambageana* and *E. orgadophila* may be present as emergents above the main canopy. These communities occur mainly on the sedentary clay soils and on some of the miscellaneous deep clay soils.

3. *Eucalypt Woodlands*

These are the principal communities of the solodic lands. In all of them the tree canopy gives 30 to 70 per cent cover. A compilation from various authors shows that, in this formation, there are twenty-eight species of Eucalyptus in differing combinations in different parts of the region (Isbell 1957; Johnson 1964; Story 1967; Speck 1968); only a few typical and important communities will be considered here. Reference to related communities is to be found in Chapters 4, 8, and 16.

E. crebra—E. populnea—Casuarina luehmannii—Callitris columellaris. Varying combinations of these species are found chiefly in the southern brigalow region. The trees are normally 30 to 50 ft (9–15 m) in height and the frequency of the four species changes according to the soil. *E. crebra* is prominent on stony ridges, *E. populnea* on lower slopes with shallow A horizons and heavy subsoils, *C. luehmannii* (buloke) on shallow soils with dense more saline B horizons, while *Callitris columellaris* (cypress pine) is very prominent on soils with more than about 1 ft (30 cm) of sand over the clay. The understorey may contain *Acacia* spp. and other sclerophyllous shrubs. Aristida, Eragrostis, Chloris, and Bothriochloa are the common genera of grasses.

E. crebra—E. maculata—E. drepanophylla. These are the widespread trees in tall forests (often 80–100 ft, 24–30 m high) scattered through the central region on solodic and other soils of low fertility. They occur in varying combination with other eucalypts such as *E. citriodora*, *E. fibrosa*, *E. polycarpa.* The understorey again consists of *Acacia* spp. and other sclerophyllous shrubs and there is a wide range of grasses, the commonest being: *Aristida* spp., *Themeda australis*, *Heteropogon contortus*, *Dichanthium sericeum*, *Cymbopogon refractus.*

E. tereticornis—E. tessellaris—E. microtheca—E. polycarpa. These are the common trees, either singly or in combination, along valley bottoms or fringing streams throughout the whole region, with *E. polycarpa* increasing towards the northern end. The community is generally a grassy forest or woodland in which the common genera are Dichanthium, Chloris, and Bothriochloa; they often provide very significant amounts of grazing despite their comparatively limited area.

Other eucalypts common throughout the brigalow are *Eucalyptus melanophloia* (silver-leaved ironbark) and *E. crebra* (narrow-leaved ironbark); Speck (1968) lists each of them as occurring in nine different woodland communities in the central brigalow. Common tree associates are *E. polycarpa*, *E. moluccana*, and *E. populnea.* Shrubs tend to be common on the poorer soils. The commonest grasses are *Bothriochloa bladhii* syn. *B. intermedia*, *B. decipiens*, *Heteropogon contortus*, and *Aristida* spp. These woodland communities grade into the forests or grassland or Acacia forests through ecotones which can be distinctive and extensive. These are discussed in Chapters 8 and 16.

4. *Grassland*

The major communities within this formation are described in Chapters 4, 6, and 8.

THE GRAZING LANDS

The grazing lands of the brigalow are of low value and are classified as Brigalow Grazing Lands (Chapter 6).

The features of animal production and the limitations thereto of these and other native grazing lands in this region are the same as those already discussed in Chapter 8 by Shaw and Norman. The problem of decline in feeding value in winter is heightened by the fact that frosts may occur as early as the latter part of April. These problems of feed quality are exacerbated throughout the brigalow region by the high variability of the rainfall, especially the frequent failure of rainfall in the early months of summer when animals are still living off the low quality feed of the previous winter. Stocking rates under present management are set at levels that afford reasonable safety in dry years. Hence the low carrying capacities of 1 steer to 10 to 50 acres (4 to 20 ha) on the grazing lands of the different communities described in this chapter.

Of the grasses listed grazing comes chiefly from species of Chloris and Paspalidium on the brigalow lands, from Heteropogon, Dichanthium, Bothriochloa, and Chloris in eucalypt woodlands, and from Dichanthium and Bothriochloa on the central downlands. *Themeda australis* is eaten out rapidly by domestic livestock and is now reduced to relatively small areas where extraneous factors such as distance from stock water limit grazing pressures. Brigalow grazing lands have low carrying capacities in their natural state—about 1 steer to 50 acres (20 ha) or 1 sheep to 10 acres (4 ha).

In parts of the southern brigalow region (especially on the weakly solonised brown clay loams) in winters of suitable rainfall, there can be a very important contribution to grazing from the growth of annual herbs. The burr medics (*Medicago polymorpha* and *M. minima*) which are now naturalised in the area can be especially important in this regard in the communities that follow clearing (Coaldrake *et al.* 1969).

On the fertile soils of the brigalow lands and central downlands there is now a well-established system of feeding animals on native grazing lands in summer and on forage crops in winter; this allows higher stocking rates in summer. There is evidence from outside the brigalow region to suggest that another system would also allow much higher stocking rates on grazing lands; this involves the use of small areas of lucerne as supplementary grazing (especially during winter and spring) with the animals given free choice between native grasses and adjoining lucerne. Such a system has been used successfully in 30 in. (762 mm) rainfalls at 'Brian Pastures' research station, Gayndah (Anon. 1963), on grazing lands with a normal carrying capacity of 1 beast to 10 acres (4 ha). Over a 5-year period animals on grazing lands only (1 beast to 6 acres (2·4 ha)) gained an average of 187 lb/head/year (84 kg/head/year), whereas those at an equal overall stocking rate but with access to lucerne on 1 acre (0·4 ha) of the 6 gained an average of 345 lb/head/year (155 kg/head/year); the advantage from lucerne was greater in dry years. It is now known that lucerne grows well on a wide range of soils in the southern and central brigalow so that this system would appear to be widely applicable in areas awaiting development to sown pastures.

SOWN PASTURES

Species

Of the species discussed in Chapter 19 there is a fairly wide range of introduced grasses that are suited to the brigalow region, but the range of legumes is still limited. The grasses currently in use come from the following genera: Chloris, Panicum, Sorghum, Cenchrus, and the pastures are classified as Xerophytic Perennial Grass (Chapter 6). The first sown grass to be used extensively in the brigalow was *Chloris gayana* (Rhodes grass) and it is still used extensively since it establishes well on newly cleared land on a wide range of brigalow and solodic soils. It is not so drought-resistant as some of the other grasses. Petrie panic (*Panicum maximum* var. *trichoglume*) is the other grass now in wide use. It is difficult to establish on heavy clay soils, but it is very drought-resistant. The perennial sorghum, *Sorghum almum*, is a most valuable pioneer grass on newly cleared brigalow land where it is able to make rapid use of the stored reserves of nitrogen and water; in this situation it may require stocking at 6–8 weeks after planting at up to 1 steer per acre (0·4 ha) (Davies and Edye 1959). The wide range of cultivars of buffel grass (*Cenchrus ciliaris*) mentioned in Chapter 19 are now being used throughout the brigalow region, being prized especially for their drought resistance. In good seasons buffel grass tends to give lower animal production than the other grasses mentioned above and on the clay soils it competes strongly with legumes. Finally, work by R. W. Strickland and R. J. Williams (unpublished data) indicates that some species of Digitaria may be very useful in the brigalow region, especially on the gilgaid soils where many other sown grasses fail to persist. Of the cultivars currently under test pangola grass (*Digitaria decumbens*) is showing high drought resistance and good frost tolerance and may become an important pasture grass on the gilgaid soils.

The range of pasture legumes currently available for the brigalow region is still limited. Lucerne (*Medicago sativa*) is still the outstanding perennial legume, being adapted to most soil types except those subject to flooding. It has the high drought resistance and good frost tolerance lacking in so many of the tropical legumes. Establishment is most successful when combined with a winter forage crop such as oats which serves as a nurse crop. There is much scope for the use of annual temperate legumes in the southern and central brigalow regions. Several cultivars of barrel medic (*Medicago truncatula*) and other annual medics such as *Medicago littoralis* (harbinger medic) and snail medic (*Medicago scutellata*) (Russell 1967) are also successful. Leslie, Mackenzie, and Glasby (1967) have suggested that the serradellas (*Ornithopus sativus* and *O. compressus*) may be useful on some of the solodic lands.

Of the many tropical legumes tested only the annual species such as *Dolichos lablab* and *Phaseolus lathyroides* are currently successful on brigalow soils. The scope for summer-growing annual legumes may equal that for the winter annuals but much more work is needed here. Among the perennials siratro (*Phaseolus atropurpureus*) and some cultivars of *Glycine wightii* syn. *G. javanica* show adequate drought resistance, but further selection or breeding is necessary to gain the necessary frost tolerance and adaptability to a wide range of soils; the twining habit common in tropical legumes is also a doubtful character in this region of lower rainfall. The original strain of siratro is useful on solodic soils with more than about 12 in. (30 cm) of sandy soil in the A horizons (Mackenzie 1966).

Fertilisers

In brigalow soils there are no initial deficiencies of mineral nutrients that seriously limit growth of pastures. Indeed, on most of the soils concerned the problem in the first year under sown pasture is to achieve the stocking rate necessary to use all of the feed produced. Production is high because of the soil nitrogen available after removal of the nodulating legume, brigalow, and the soil water stored under virtual bare fallow between clearing and burning. However, as Isbell (1962) points out, conversion of brigalow land from forest to pasture or crop will lead to a depletion of nitrogen. While there is no critical evidence available field experience suggests that soil nitrogen declines rapidly under pasture for 2 to 3 years and then at a slower but steady rate. The phosphorus status is marginal on some of the brigalow soils and Fergus (1962) obtained significant responses ($P < 0{\cdot}05$) to phosphorus on 9 out of 10 brigalow soils tested in pots with *Phaseolus lathyroides*. Phosphorus fertiliser will unquestionably come to be used on pastures on brigalow land, especially when a wider range of legumes is available.

In contrast to the brigalow lands the solodic lands require substantial correction of nutrient deficiencies at the outset of conversion from forest to sown pasture. Leslie (1963) and Russell (1967) working on different solodic soils have now shown deficiencies of nitrogen, phosphorus, calcium, potassium, molybdenum, copper, zinc, manganese, and boron. Nitrogen and phosphorus are the primary limiting deficiencies and are universal on these soils. At the time of writing this chapter Russell (1967) and Leslie, Mackenzie, and Glasby (1967) indicate that a basal dressing of 2 to 4 cwt/acre (251 to 502 kg/ha) of superphosphate is needed by all sown species on solodic soils, while requirements for other elements vary with species and with soil type. Responses to lime and to trace elements are marginal in the field and there are inconsistencies between experiments in the field and in the glasshouse (Russell 1966). The marked anisotropy of these soils in relation to exchangeable sodium may also be of importance.

Apart from nutrient deficiencies many of the

Plate 34 Brigalow forest pulled for pasture development, southern brigalow region, Queensland (CSIRO photo)

Plate 35 Brigalow forest burnt after pulling, southern brigalow region, Queensland. Pasture seeds are commonly sown on fine white ash shown (CSIRO photo)

soils of the solodic lands present physical problems associated with salinity, and Isbell (1962) pointed out that the high salinity on the gilgaid brigalow soils may also cause problems as they are brought into more intensive use.

On the fertile clay soils of the Central Downlands there are no indications yet of any nutrient deficiencies.

Land Preparation and Pasture Establishment

Plates 34 and 35 show the two main stages in the conversion from brigalow forest to pasture. The forest is first flattened by a heavy chain or cable pulled between two crawler tractors; this uproots, or breaks at ground level, all except the smaller trees. In this process one clearing team of two tractors covers about 100 acres (40 ha) per day at a cost of $2.00 to $4.00 per acre ($4.90 to $9.80 per ha) depending on density of the forest and location. The fallen scrub is allowed to lie for up to one year and then burned to produce the ash-bed shown in Pl. 35; burning during hot dry weather leads to the almost total destruction of timber. During the interval between felling and burning the soils accumulate stored water in the manner of a bare fallow—the author has measured 5 acre-inches of available water in the top 42 in. (107 cm) of soil 5 months after clearing of virgin forest when the soil under adjoining forest was at permanent wilting point. This stored water is often important to the growth of the first pasture when drought follows a germinating rain.

Grass seed is sown from aircraft on to the loose ash as soon as it has cooled so that the ash provides both seed cover and nutrients. A typical seeds mixture is 2 lb per acre (2·2 kg per ha) each of Rhodes grass and *Sorghum almum*, and 1 lb per acre (1 kg per ha) of green panic. At current prices this costs about $2.50 per acre ($6.20 per ha), and the aerial sowing about $0.50 per acre ($1.24 per ha). At present the only legume which can be successfully used in air-seeding burnt brigalow land is siratro (Coaldrake and Russell 1965), and this species is not used much because of the limitations discussed earlier.

Given suitable rains for germination, pastures established by this system are ready for stocking at 1 steer to 2 acres (0·8 ha), or higher, six to eight weeks after sowing. Success, however, depends largely on good rains within two to three weeks of sowing because much of the seed may be redistributed by the whirlwinds that develop over newly burned land; this may result in patchy establishment of the pasture. There is also a great risk of seedling mortality through drought following light germinating rain. The seed is also liable to destruction by ants in the period between sowing and germination (Russell, Coaldrake, and Sanders 1967). Finally, the treatment of brigalow suckers with hormone weedicide may be retarded by the shield of grass which often develops before all the suckers have emerged.

On the solodic lands the original vegetation is felled by the method described above. But the different nature of the vegetation normally requires that it be heaped into windrows before burning at a cost upwards of $8.00 per acre ($19.80 per ha). Ploughing with preparation of a proper seedbed follows.

On the heavy clay soils of the Central Downlands forage crops with large seeds such as annual sorghums have been used in preference to perennial pastures because it is difficult to establish species such as Rhodes grass and green panic which have small seeds.

Annual Production on Sown Pastures

The high pasture production possible on brigalow land is rarely maintained for very long because of lack of soil water. Figures 9 : 3 and 9 : 4 show the pattern and level of production common under the variable rainfall regime of the brigalow region. The data in Fig. 9 : 3 were collected at the Cooper Laboratory to the east of the brigalow region but where the climate is similar. Those in Fig. 9 : 4 are from Banana on brigalow land in the central brigalow. Again, in the southern brigalow region Coaldrake *et al.* (1969) found that 'during 16 months of continuous grazing all of the pastures (green panic, Rhodes grass, buffel grass) carried less than 1000 lb per acre (1120 kg per ha) of standing dry matter'. For 15 of these 16 months steers on these pastures averaged total weight gains of up to 390 lb (175 kg) per head; during the 16th month the animals began to lose weight when severe drought stopped pasture growth. Figure 9 : 5 shows the liveweight gains of animals on these pastures during the first 11 months of this period.

While these figures suggest that, in the briga-

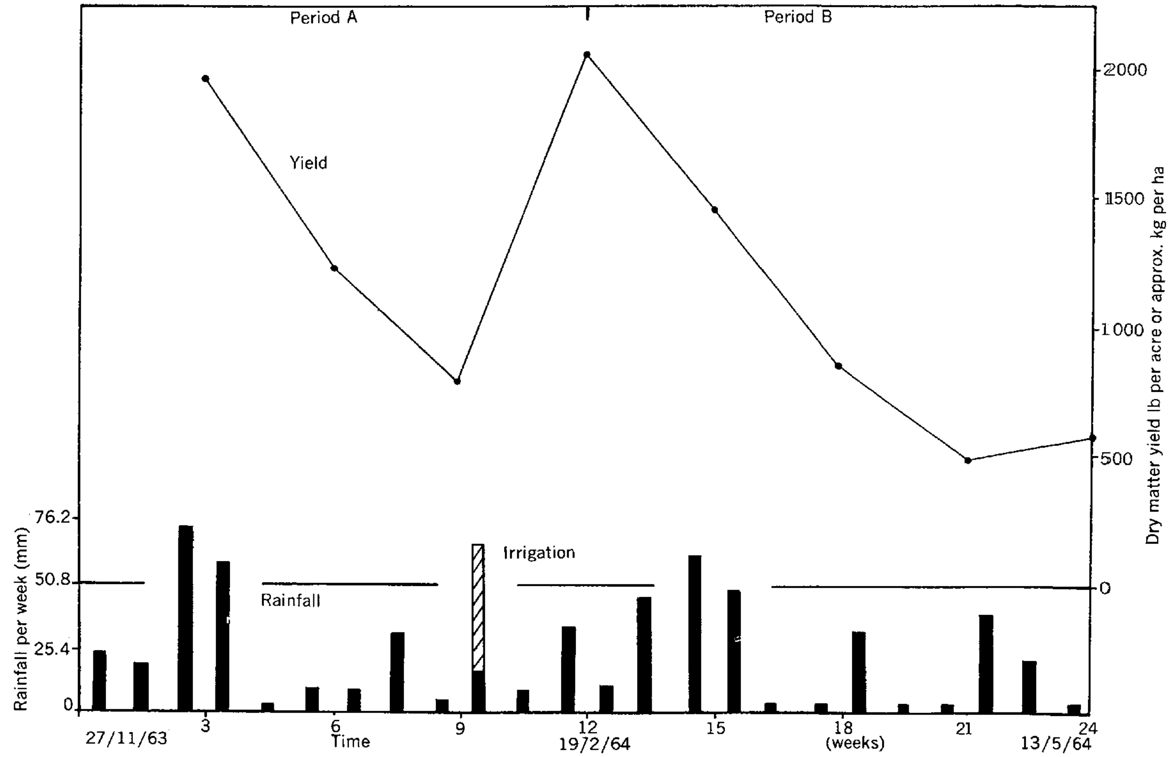


Fig 9 : 3 Production of total dry matter and water recorded in a mixed pasture at 3-weekly intervals at the Cooper Laboratory, Lawes, under conditions closely resembling those of the southern brigalow region (from Santhirasegaram, Coaldrake, and Salih 1966)

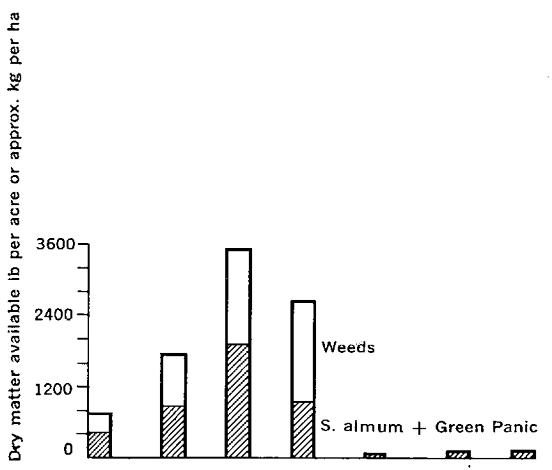


Fig. 9 : 4 Standing dry matter at monthly intervals in a mixed pasture of *Sorghum almum* and green panic on brigalow land at Banana in the central brigalow region. Animals grazing these pastures at a stocking rate of 1 steer to 2 acres (1 steer to 0·81 ha) gained an average of 1·4 lb/head/day (0·63 kg/head/day) over this period (from Coaldrake and Smith 1967).

low region, it is more or less normal for pastures to be growing at much less than their maximum rate due to shortage of water, animal production can, nevertheless, be sustained at satisfactory levels for long periods. Coaldrake and Smith (1967) obtained an average liveweight gain for 24 yearling steers of 392 ± 8 lb per head (178 ± 4 kg per head) over a 52-week period on a sown pasture of *Sorghum almum* and green panic in the central brigalow region. Rainfall during this period was 21 in. (533 mm) and the stocking rate was 1 beast to 2·3 acres (1 to 0·9 ha). During the winter months (May to October inclusive) these animals maintained an average liveweight gain of 1·4 lb/head (0·6 kg/head) at a time when cattle on adjoining grazing lands barely maintained weight.

In the southern brigalow region steers on a number of different sown pastures gained up to 2·2 lb/head/day (1 kg/head/day) over the 7-month period December–June at a stocking rate of 1 beast to 2·3 acres (1 to 0·9 ha) (Coaldrake

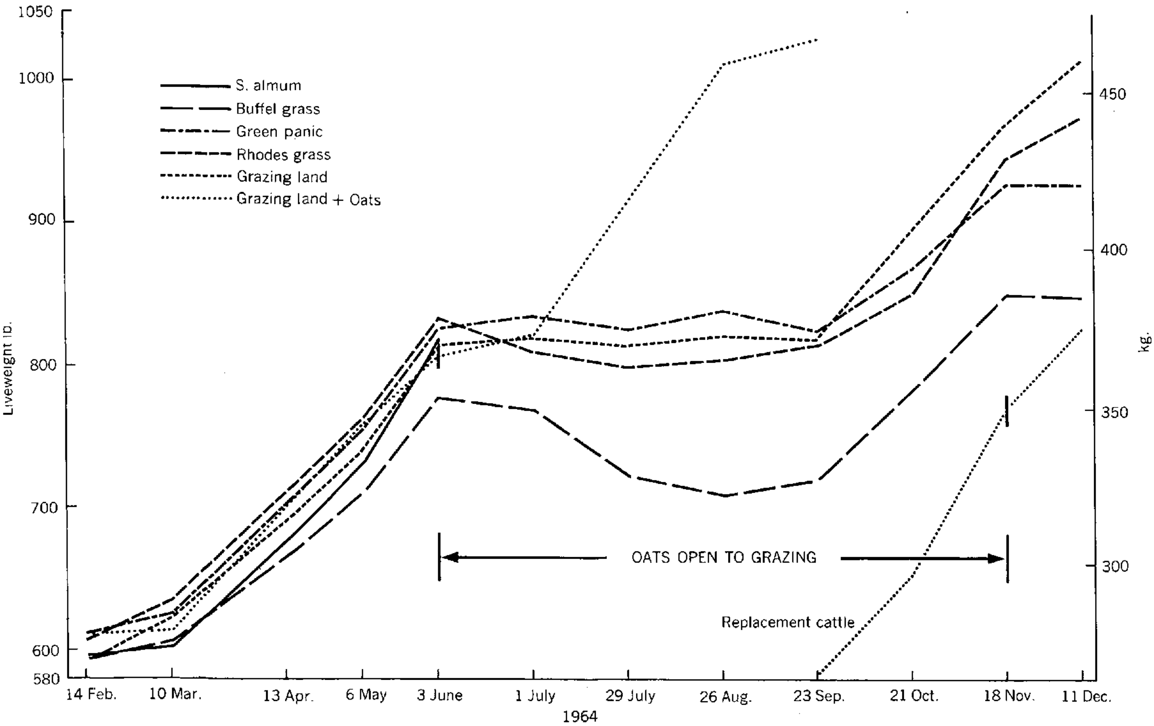


Fig. 9 : 5 Liveweight gains of steers on a series of grasslands in the southern brigalow area. The sown pastures were stocked at 1 steer to 2·3 acres (0·9 ha), the grazing land at 1 steer to 4·3 acres (1·7 ha), and the grazing land plus oats 1 steer to 4·3 acres (1·7 ha) with 0·3 of the area used for oats. Total rainfall for this period was 11·9 in. (302 mm) compared with a long-term mean of 21·1 in. (536 mm) (from Coaldrake *et al.* 1969). The pastures carried less than 1000 lb/acre (1120 kg/ha) dm throughout.

et al. 1969). Rainfall for this period was 6·9 in. (175 mm). These and other unpublished data (C. A. Smith and J. E. Coaldrake) suggest that sown pastures in the southern and central brigalow regions under ordinary station management should produce average liveweight gains of over 400 lb per head (181 kg per head) per year at a stocking rate of 1 steer to 2 acres (0·8 ha). Such a target figure cannot be stated yet for the northern brigalow region.

These figures for animal production are all from pastures grown on brigalow lands or soils of equivalent fertility. There are no data yet for animal production from solodic lands but farm experience such as that quoted by Hayward and Russell (1967) suggests that, with adequate fertilising, these soils will give similar levels of production.

The erratic rainfall of the brigalow region makes some form of conservation an essential feature of farm management. The form of conservation chosen—grain, hay, silage, understocking, or money is a matter for individual decision, and at present the decision is made more difficult by lack of critical information. Studies such as those reviewed by Morris (1968) provide reliable information on the use of supplements such as grain and urea in conjunction with drought-affected pastures but much more information is needed on other forms of conservation. Conservation of excess pasture growth as hay following periods of high rainfall is useful for providing reserve feed for drought periods, but C. A. Smith (1968) finds that cutting of hay for feeding back in winter to even out production in normal years introduces various side-effects so that there is no net annual gain in animal production. Silage from summer growing annuals such as the sorghums and *Dolichos lablab* is not used extensively yet.

Diminution of property size will inevitably force stocking rates up towards those quoted in the experimental results above. Conservation will then become absolutely vital—at present it is often avoided since property size and economic factors permit understocking in years of average rainfall or better.

Weeds and Woody Regrowth

It was in the brigalow region that widespread infestation of the forests and scrubs with prickly pear (*Opuntia* spp.) reached its zenith in the 1920s, and was controlled in a spectacular example of biological control by the introduction of *Cactoblastis cactorum* (Dodd 1927). Scattered plants of prickly pear still occur but are destroyed by Cactoblastis within a few years, the species apparently maintaining a nice ecological balance. Two other species of cactus (*O. aruntiaca* and *O. tomentosa*) that are not susceptible to attack by Cactoblastis still cause difficulties on scattered small areas of land. In the last twenty years yet another cactus (*Harrisia martinii*), originally introduced much earlier, has emerged as a serious pest. This species now occupies some 250,000 acres (101,250 ha) chiefly at the northern end of the brigalow region. So far the only known methods of control are clearing followed by cultivation on arable land, or repeated sprayings with chemicals elsewhere.

At present the chief problems of 'weed' control in the brigalow are those of controlling regrowth from numerous woody species which follows the initial clearing operations.

The brigalow tree itself is currently the biggest problem in terms of acreage affected by regrowth, the total area on which pasture growth is seriously retarded or virtually eliminated being over 1 million acres (405,000 ha). The sprouts ('suckers') develop freely on woody roots more than about 5 mm in diameter and the main crop of suckers normally develops within a few months of the clearing burn; by this process an original forest of 1500 trees per acre (3700 trees per ha) may be replaced by over 10,000 clumps of suckers per acre (24,700 clumps per ha) with counts in excess of 4000 per acre (9880 clumps per ha) being common. Isbell (1962) pointed out that suckering is more likely to be a problem on gilgaid land than on the other soils supporting brigalow. By the third or fourth year a stand of 4000• clumps per acre (9880 clumps per ha) seriously reduces pasture production (see Pl. 36).

Johnson (1962) lists four methods for controlling brigalow suckers:

Plate 36 Regrowth of brigalow (*Acacia harpophylla*) four years after felling the original forest (see Pl. 34), southern brigalow region, Queensland (CSIRO photo)

1. Competition from sown pastures. This retards rather than eliminates suckers and, even at best, enough suckers survive to require treatment later. The method has the economic advantage of allowing affected land to produce enough income in the early years to cover the cost of later treatment. It depends heavily on good rainfall in the first season to promote establishment of a dense pasture.

2. High stocking with sheep. This is essentially a matter of intermittently stocking land so heavily that the sheep are forced to keep emerging suckers cropped to ground level. This method calls for some skill in animal husbandry to prevent losses by starvation, and leads to reduced yield of wool. It is also costly in terms of the time the land is held out of production (usually about a year) and of the lost opportunity for cheap establishment of pasture by ash-seeding.

3. Chemical control by spraying with 2,4,5–T. The extensive work of Johnson (1964) shows that 2,4,5–T is effective when aerially sprayed on young suckers in their first season of growth, but that there are problems of technique in gaining an effective kill of older suckers with 2,4,5–T. Studies by Coaldrake (1967a) with 2,4,5–T C^{14} suggest that timing within the day,

form of carrier, excessive dryness or wetness of soil, and presence or absence of root nodules at time of spraying are all factors which have to be considered.

4. Ploughing (especially in association with cropping) is another method of control that has been used for some time on older suckers up to about 6 ft (1·8 m) high. Since about 90 per cent of all brigalow suckers come from within 4 in. (102 mm) of the surface, shallow ploughing is quite effective (Coaldrake 1967b). Ploughing with cropping allows net profits of over $10 per acre ($24.70 per ha) per year during the three years necessary for reduction of suckers to a harmless level, but the area that can be handled at any one time on most properties is restricted to about 1000 acres (405 ha). An alternative method is to wait until brigalow suckers are emerging freely and then plough the land once or twice. This method has the advantages of reducing suckers to a frequency at which they are not a subsequent problem, and also of permitting sowing of pastures into a prepared seedbed. The costs compare favourably with the combined costs of air-seeding and aerial spraying with 2,4,5-T.

While it is quite feasible to develop brigalow land without suckers ever gaining the ascendancy the relative ease of clearing large areas of brigalow land with heavy equipment has often resulted in single properties having several thousand acres of land with dense suckers. This legacy of over-hasty development is one of the major problems affecting much of the brigalow region.

While brigalow suckers are a problem throughout the whole of the brigalow region there are six other woody species which cause problems of regrowth in various parts of the region. Limebush (*Eremocitrus glauca*) a comparatively minor component of the original vegetation, has the capacity to sucker from roots up to 2 ft (61 cm) below the soil surface. On cleared land it can develop into dense thickets which are still difficult to control because of this deep-seated suckering. It is especially troublesome in parts of the southern brigalow region. Tea tree (*Melaleuca* spp.), sandalwood (*Eremophila mitchellii*), and poplar box (*Eucalyptus populnea*) also cause trouble in the southern brigalow region. All three of these can be controlled by ploughing while Moore and Robertson (1967) state that sandalwood and poplar box can both be controlled chemically.

In the central brigalow region another eucalypt, Dawson gum (*E. cambageana*), produces very rapid regrowth after the clearing burn and is difficult to control except by ploughing. In the northern brigalow region yellowwood (*Terminalia oblongata*) persists unless the individual trees are subjected to prolonged heat during the clearing burn.

Finally, these problems of woody regrowth during land development in the brigalow region are offset in some degree by the fact that serious invasion of pasture land by annual or perennial herbaceous weeds has been slow to develop. Even in the case of brigalow suckers there is some compensating effect from the presence of a nodulated legume until such time as the land can be brought back into full production from pastures.

Forage Crops

In the southern and central brigalow region the effectiveness and comparative reliability of the winter rainfall and the fertility of the soils have resulted in widespread use of forage crops. In the older settled areas most properties with cultivated land use some part of this for forage crops every year. The tabulation below shows the acreages sown to oats (winter) and sorghum (summer) for use as forage crops in the period 1966–7 (Anon. 1967d). The figures for total areas reflect the historical pattern of development from south to north while the figures for oats and sorghum reflect the decreasing reliability of winter rainfall going northwards. While oats is the major winter fodder crop there is also some use of barley and wheat. The commonly used sorghums are sudan grass (*Sorghum*

	Oats	Sorghum	Total
Southern brigalow	153,000 (61,965 ha)	27,000 (10,935 ha)	180,000 (72,900 ha)
Central brigalow	73,000 (29,565 ha)	60,000 (24,300 ha)	133,000 (53,865 ha)
Northern brigalow	1,000 (405 ha)	14,000 (5,670 ha)	15,000 (6,075 ha)
	227,000 (91,935 ha)	101,000 (40,905 ha)	328,000 (132,840 ha)

sudanense), sweet sorghum (*S. vulgare*), and various hybrids, especially Sudax.

The stocking rate on these fodder crops varies from about 0·6 to 1·5 bullocks per acre (1·5–3·7 per ha), or the equivalent in sheep; cattle weight gains of 2 to 3 lb (0·9–1·4 kg) of liveweight per head per day are common (see Fig. 9 : 5). Net profit per acre varies from about $5.00 to $15.00 per acre ($12.35–$37.00 per ha) depending on the location and the season.

While fodder crops are obviously important in the brigalow region, they do pose some major problems in farm management in this region of variable rainfall. At the beginning of a season production cannot be anticipated with much certainty and alternative sources of feed must be found in a dry season when pasture growth may already be limited, or extra stock have to be obtained at short notice to use the heavy production of a good season. In spite of these problems the acreage sown to fodder crops in the region is expanding steadily and they seem certain to continue as an important source of animal feed in the brigalow region. The efficient integration of fodder crops into schemes of year-round grassland production and into systems of crop-pasture rotation requires further study in the brigalow region.

Finally, there is another form of crop-grazing which is of varying importance throughout the region and from season to season; this is the grazing of sorghum stubble after harvesting of grain. This is a very important source of feed in the Central Downlands where grazing is often obtained for some months in winter, partly from ratoon growth.

FARM MANAGEMENT

The average size of property in the brigalow region is decreasing steadily, a process that will continue for some time yet. In the southern brigalow region farm size varies from about 1000 acres (405 ha) on the eastern side to over 5000 acres (2020 ha) on the western side with most properties lying in the range 2000–4000 acres (810–1620 ha). In the central brigalow region farm size varies widely as the region passes through a stage of rapid development but seems likely to settle in the range 4000 to 8000 acres (1620–3240 ha) for perhaps one generation after which many properties will again be divided. In the northern brigalow region properties are likely to exceed 10,000 acres (4050 ha) for some time yet. The increasing spread of grain production and fodder cropping in association with crop-pasture rotations seems likely to maintain a steady reduction of average farm size for some time yet in both the southern and central regions. This process has been accelerated in recent years by the operation of a land development scheme in the central brigalow region financed largely by loans from public funds. This has been one of the more successful land development projects ever operated in Australia, but while it has resulted in rapid clearing of about 500,000 acres (202,500 ha) of virgin brigalow land in its first four years of operation, development of permanent sown pastures free of regrowth has lagged behind the clearing program.

The comparative fertility of brigalow soils, which do not require fertilisers in the early years of use, and the receipt of both summer and winter rainfall, have led to a wide range of land-use. Sheep (for both wool and fat lambs) and beef cattle for sale at age 2–3 years are the main livestock enterprises. Cropping centres mainly on cereals in winter and grain sorghum in summer but a wide range of other crops is grown on a smaller scale; these include linseed, safflower, cotton, and pulses.

The only serious problem in livestock management relates to the presence of the cattle tick in the central and northern regions.

The great and continuing problem in land management in the brigalow region is the variability of the rainfall which ensures that the manager of land is never sure of the feed available on his pastures for more than a few months ahead, or of his crop until it is harvested.

10

WET TEMPERATE FORESTS AND HEATHS

D. F. PATON AND W. J. HOSKING

DISTRIBUTION

The wet temperate forests of south-eastern Australia, dominantly wet sclerophyll with isolated areas of temperate rainforest, extend as an almost continuous belt from Taree (lat. 32°S) along the coast of New South Wales, through eastern Victoria to the south coast of Tasmania (lat. 43·5°S). In New South Wales they extend inland from the coast approximately 40 miles (64 km) to the eastern edge of the Tablelands. In Victoria there are wet temperate forests in the highland areas to the south-east and south-west and on both the southern and northern slopes of the Great Dividing Range. There are extensive areas of wet temperate forests on King Island in Bass Strait and in the north, west, and south of Tasmania.

Wet heathlands are most extensive on gently undulating coastal plains in southern Victoria, on King Island and Flinders Island in Bass Strait, and along the west and north coasts of Tasmania. There are smaller areas, too, at intervals along the coast of New South Wales.

CLIMATE

The dominating climatic factor in the development of wet temperate forests is moderate to heavy rainfall greater than 35 in. (889 mm), well distributed throughout the year. In south-east Australia, wet temperate forests occur in areas receiving more than 2 in. (51 mm) each month. Rainfall figures for representative centres in wet temperate forests are shown in Table 10 : 1.

The driest period in N.S.W. forests is in spring (August–November), but in Victoria and Tasmania the driest period is in summer (January–March). In New South Wales summers are hot to very hot at lower altitudes and mild to warm elsewhere. Winters are mild to warm with occasional severe frosts in valley bottoms even near the coast. Further inland and especially at higher altitudes (e.g. Moss Vale, latitude 34° 34′S), winters are mild to cold with frequent severe frosts.

In the wet forest areas of Victoria and Tasmania, summers are mild to warm. Days with maximum temperatures in excess of 90°F (32°C) occur occasionally each year. Winters are mild to cold with frequent and severe frosts and occasional snow on all areas except those near the coast. At high altitudes frosts may occur even in summer. Temperature data for representative localities are listed in Table 10 : 2.

Wet heaths adjoin wet temperate forests on their seaward side. They occur in similar but generally lower rainfall conditions (approximately 30 in., 762 mm, per annum) in Victoria and Tasmania. Because of the lower altitude and maritime influences, the climate of heathlands is milder, summers are cooler, winters are less severe, and daily temperature ranges are lower than in forests. Frosts are recorded occasionally but are seldom severe.

SOILS

In both forests and heaths, leaching has been the dominant soil-forming process and over 90 per cent of the soils are classified as podzols or podzolics. The main exceptions are the leached kraznozems and recent alluviums developed on river flood plains. These occupy small areas relative to the podzolised soils (see Map 2) but are important agriculturally because they are the most productive in south-eastern Australia.

Within the wet temperate forest zone, podzolic soils occur on a wide range of parent materials including igneous, sedimentary, and metamorphic rocks. Geologically, the area is one of considerable structural complexity. In New South Wales, the underlying rocks are predominantly sandstones, shales, schists, serpentines, and granites. In Victoria, metamorphic rocks, mainly schists, gneisses, and grantie with

TABLE 10 : 1 Mean monthly rainfalls (mm), wet temperate forests

Locality	Lat. (S)	Long. (E)	Altitude		Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual	
			m	ft													mm	in.
N.S.W.																		
Moss Vale	34° 34′	150° 21′	673	2208	100	83	87	97	82	83	100	52	69	63	64	97	977	38·5
Berry	34° 46′	150° 41′	12	40	146	126	158	145	135	132	91	76	89	77	86	130	1391	54·7
Vic.																		
Warragul	38° 25′	146° 0′	114	373	61	60	74	87	96	94	95	110	100	112	92	86	1067	42·0
Beech Forest	38° 38′	143° 33′	457	1500	83	73	110	149	166	201	193	196	178	156	114	92	1711	67·4
Tas.																		
Burnie	41° 03′	145° 55′	7	24	46	42	52	78	89	120	124	115	94	96	67	63	986	38·8
Tewkesbury	41° 15′	145° 40′	504	1655	74	75	74	107	121	170	213	197	141	135	112	109	1528	60·1

TABLE 10 : 2 Mean daily temperatures, wet temperate forests

	Moss Vale N.S.W.		Berry N.S.W.[a]		Warragul Vic.[a]		Beech Forest Vic.		Burnie Tas.		Tewkesbury Tas.	
	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C
January max.	78·8	26·1	80	26·7	70	21·1	70	21·1	67·0	19·4	65·1	18·3
January min.	54·4	12·3	60	15·6	55	12·8	50	10·0	51·6	11·1	46·0	7·8
July max.	54·1	12·2	60	15·6	55	12·8	50	10·0	53·8	12·2	47·8	8·8
July min.	34·7	1·7	45	7·2	40	4·4	35	1·7	41·3	5·2	37·1	2·8

[a] Approximately only; taken from map of Australian isotherms.

some limestone are the most widespread parent materials in the eastern portion of the State, with sandstone, conglomerates, mudstone, and shales becoming common towards Melbourne. In the South Gippsland and Otway areas, Cretaceous sandstones and mudstones are most abundant. In Tasmania, granites, shales, mudstones, and sandstones are the dominant parent materials of podzolic soils with quartzites and schists also of considerable significance in the western section.

Most of the differences in profile characteristics of the podzolic soils are determined by the rocks on which they have developed, but because of the dominating effect of leaching, they have a number of characteristics in common. They are moderately to strongly acid throughout the profile, low in plant nutrients, and surface horizons are typically grey to grey-brown sandy loam to loams.

Podzolic soils carrying wet temperate forests in south-eastern Australia overlie a fairly deep, granular, yellow clay subsoil. All are grossly deficient in phosphorus and many are also deficient in molybdenum and/or potash. The strongly acid soils (pH less than 5·2) usually require lime for successful pasture establishment.

The kraznozems (or red loams) are derived from deeply weathered basic igneous rocks, mainly Tertiary basalts (Map 2). They are deep, friable clay loams with a strong granular structure extending into the deeper subsoil horizons and consequent good internal drainage. The colour of the surface soil is characteristically reddish brown. Throughout the profile, they are moderately to strongly acid in reaction.

Relative to most other soils of the high rainfall zones, the kraznozems are initially high in fertility, but phosphatic fertilisers are required for high production from pastures and crops. Molybdenum deficiency is also common and potassium has become deficient on some soils following long periods of cash cropping or removal of pasture as hay or silage. Lime is sometimes required for successful pasture establishment, but molybdenum has now largely replaced its use on established pastures (see Chapter 21). Nitrogen requirements of pastures are met mainly through the use of legumes, but there is an increasing use of nitrogen fertilisers for cropping and also for out-of-season pasture production, particularly on dairy farms. Having good structure and drainage, kraznozems are valued highly and are used for intensive farming, particularly dairying, and where topography is favourable for crop production.

Kraznozems are distributed throughout the temperate forest region at Robertson on the mid-south tablelands of New South Wales; at Warragul, Thorpdale, Mirboo North, and Leongatha in the Gippsland district of Victoria; along the north-west coast of Tasmania (extending approximately 20 miles (32 km) inland behind Smithton, and from Wynyard to Devonport), and in the north-east of Tasmania.

Extensive areas of alluvial soils are found along the valleys of the Manning, Hunter, Nepean, and Shoalhaven Rivers in New South Wales and the Snowy in Victoria and in the smaller river valleys along the south coast of New South Wales and in Victoria and Tasmania. Acid swamp soils carrying rainforest occur extensively in the north-west corner of Tasmania. Following draining and clearing, these are used for intensive dairy production.

In contrast to the wet temperate forests which are found only on deep and relatively fertile soils with well-drained subsoils, wet heaths occur on infertile soils with restricted internal drainage. Such conditions are usually found following podzolisation of siliceous parent materials either developed *in situ* or laid down as marine or aeolian deposits in coastal areas. The surface horizons are usually coarse textured, strongly acid grey sands to sandy loams or loams with moderate to heavy accumulations of undecomposed organic matter. Subsoils are frequently impermeable yellow clays situated at relatively shallow depths (8–20 in., 20–51 cm). The main occurrences of these soils are in southern Victoria, on the Bass Strait Islands, and in Tasmania. Humus podzols also occur in these areas.

Humus podzols are the dominant soils of the wet heathlands of King Island and of the north-west and west coasts of Tasmania. Internal drainage in groundwater podzols is impeded by the formation of an impermeable organic or ferruginous hard pan at the depth of the mean water table, commonly between 15 in. and 36 in. (38–91 cm). As a consequence these soils are commonly waterlogged to the surface during the wetter periods of the year. Under such anaerobic and strongly acid conditions, there is a substantial accumulation of undecomposed, fibrous plant material in the surface horizons.

Despite the unfavourable physical and chemical characteristics of their soils, substantial areas of wet heaths have been sown to pastures in the last twenty years, not only on soils with clay subsoils as in southern Victoria and on Flinders Island, but also on the humus podzols of the north-east coast and the north-west corner of Tasmania.

On heath soils, lime applied at or before sowing is usually essential for pasture establishment, as is also adequate superphosphate and copper. Potassium and sulphur deficiencies commonly occur after a few years under pasture. Cobalt is also deficient on many heath soils in Tasmania and must be regularly applied to maintain animal health.

Along the west coast and especially in the south-west portion of Tasmania, there are extensive areas of wet heaths along the valley bottoms and lower slopes of the numerous mountain systems. The soils, described as peaty podzols, have developed under conditions of high rainfall (in excess of 70 in. or 1778 mm per annum) on predominantly siliceous (quartzite) parent materials. These soils show little profile development, and consist mainly of an accumulation of coarse fibrous organic material gradually decreasing with depth. Because of their shallowness, very poor internal drainage (water table frequently at or near the surface), extreme acidity and poverty in plant nutrients, these soils have virtually no agricultural or pastoral potential.

VEGETATION

In south-eastern Australia wet temperate forests are mostly sclerophyllous, but where the annual rainfall is greater than 50 in. (1270 mm), with a minimum of at least 2 in. (51 mm) a month during the summer and soils are suitable, temperate rainforests predominate.

The main occurrence of rainforest is in northern and western Tasmania, where the dominant species is myrtle beech (*Nothofagus cunninghamii*). On soils of higher fertility such as those derived from basalt this species is almost completely dominant, but on soils of lower fertility sassafras (*Atherosperma moschatum*) becomes increasingly important. Both these species often provide almost a complete crown cover so that vegetation below the canopy is reduced to a ground cover of bryophytes. Other tree species include the endemic conifers Huon pine (*Dacrydium franklinii*) and King Billy pine (*Arthrotaxis selaginoides*) restricted to the west coast rainforest areas, and celery-top pine (*Phyllocladus aspleniifolius*) of more widespread distribution. Where the myrtle beech and sassafras canopy is more open, there is a dense tree and shrub understorey of blackwood (*Acacia melanoxylon*), musk (*Olearia argophylla*), and tree ferns mainly (*Dicksonia antarctica*) with some Cyathea in coastal gullies. On acid and less fertile soils, the common rainforest dominants may be replaced by species of *Eucryphia*, *Phyllocladus*, and *Anodopetalum*.

Elsewhere in Tasmania and also in Victoria, small areas of rainforest occur in gullies sheltered from drying winds and fire and possessing favourable moisture conditions and soils. In these situations the main species are silver wattle (*Acacia dealbata*), blackwood, sassafras, and in small areas myrtle beech. In the gully forests, a dense understorey of trees and shrubs consisting mainly of musk (*Olearia* sp.), blanket wood (*Bedfordia salicina*), Christmas bush (*Prostanthera lasianthos*), dogwoods (*Helichrysum* sp. and *Cassinia* sp.), and hazel (*Pomaderris apetala*), is invariably present (Pl. 13).

In the south coastal areas of New South Wales and extending into eastern Victoria, particularly in the coastal gullies, there are elements of subtropical rain forests. These are true vine forests and are characterised by a large number of species. *Eugenia smithii* is the dominant tree reaching 60 to 90 ft (18–27 m). Blackwood is often co-dominant. Eugenia is associated with *Tristania conferta* along creeks and river banks. Other less frequent species are *Rapanea howittiana*, *Acronychia laevis*, and *Elaeocarpus holopetalus*. The palm *Livistona australis* also occurs in a few areas. In addition there are seventeen species of lianes belonging to the genera Marsdenia, Smilax, Cissus, Eustrephus, and Clematis. Ferns are common.

At lower rainfalls and on relatively poorer soils, rainforests are replaced by wet sclerophyll forests. In the latter, the trees are various species of Eucalyptus, determined mainly by climate and soil parent material. Wet sclerophyll forests usually possess a tall shrub understorey (Pl. 14).

Fire influences the occurrence of rainforest and wet sclerophyll forests. Where fire frequency is between about 80 and 200 years, mixed forests in which tall emergent eucalypts overtop rainforest species are common. In Tasmania, much of the potential rainforest area is occupied by these mixed forests.

In New South Wales, the characteristic species of wet sclerophyll forests are the eucalypts, blackbutt (*E. pilularis*), flooded gum (*E. grandis*), white mahogany (*E. acmenioides*), swamp mahogany (*E. robusta*), tallowwood (*E. microcorys*), grey ironbark (*E. decepta*), and grey gum (*E. propinqua*). Other important genera are Angophora, Melaleuca, and Syncarpia.

Along the tablelands of south-eastern New South Wales and eastern Victoria, cut tail (*E. fastigata*), shining gum (*E. nitens*), mountain grey gum (*E. cypellocarpa*), manna gum (*E. viminalis*), and narrow-leaved peppermint (*E. robertsoni*) are the main tree species, with *E. sieberi*, *E. muelleriana*, *E. consideniana*, *E. maculata*, and *E. globoidea* becoming more frequent nearer the coast.

In Tasmania and west of the Snowy River in Victoria, where rainfall exceeds 40 in. (1016 mm) per annum, mountain ash (*E. regnans*) is the dominant wet sclerophyll forest species at elevations up to about 2500 ft and 3000 ft (762–914 m) respectively. At higher elevations it is replaced by alpine ash (*E. delegatensis*). Tasmanian blue gum (*E. globulus*) is common in south-eastern Tasmania.

In Tasmania and Victoria, the wet sclerophyll forests are characterised by a tall dense understorey of small trees and shrubs consisting mainly of blackwood, dogwood, silver wattle, mimosa (*Acacia verticillata* and *A. longessima*), hazel, musk, blanket wood, Christmas bush, sassafras, tallowwood (*Pittosporum bicolor*), pepper bush (*Drimys lanceolata*), oily bush (*Olearia ramulosa*), stinkwood (*Ziera arborescens*). There is a lower stratum of ferns including rattley fern (*Blechnum procerum*), bracken (*Pteridium aquilinum*), soft bracken (*Pteris tremula*), and tree ferns (*Cyathea* spp.).

Temperate wet sclerophyll forests are also found in the far south-west of Western Australia. These are discussed in Chapter 14.

The wet heathlands consist of sclerophyllous shrubs, usually less than 4 ft (122 cm) high. A feature of these communities is the low stature of several species normally tall on more fertile soils (Pl. 9).

In the Victorian and Tasmanian heaths, the tallest species are the tea trees (*Leptospermum scoparium*, *Melaleuca ericifolia*, *M. squarrosa*, and *M. squamea*), she-oak (*Casuarina stricta* and *C. bicuspidata*), and dwarf honeysuckle (*Banksia marginata*). Scattered but stunted eucalypts 4–6 ft (122–183 cm), often with a 'mallee' habit, are found in some of the better drained areas within these communities. These include peppermint (*E. radiata*) and South Gippsland Mallee (*E. kitsoniana*) in Victoria, and *E. salicifolia*, and *E. simmondsii* in Tasmania. Grass trees (*Xanthorrhoea australis*) are common in the heaths of the north-east coast of Tasmania, Flinders Island, and southern Victoria.

Smaller species less than 2 ft (61 cm) high are also numerous and include the 'heaths' (*Epacris impressa*, *E. lanuginosa*, *Sprengelia incarnata*, and *Leucopogon australis*), several woody legumes (*Aotus villosa*, *Dillwynia glaberrima*, *Bauera rubioides*), and a variety of restionaceous and cyperaceous plants (*Leptocarpus tenax*, *Lepidosperma filiforme*, *Restio oligocephalus*, *R. complanatus*, *Gymnoschoenus sphaerocephalus*).

Extensive areas of 'sedgeland' occupy approximately 3000-4000 sq miles (7776–10,368 km^2) of peaty podzols in the south-west and west coast regions of Tasmania. They differ from the other heath communities in the dominance of button grass (*Gymnoschoenus sphaerocephalus*). Button grass grows in tussocks 2–4 ft (61–122 cm) high and the term 'button grass plains' is commonly applied to areas dominated by this species. Other species that grow among the button grass are *Hypolaena fastigiata* and the so-called heath species listed above, but these are seldom common. Irregular patches of myrtaceous wet heaths consisting mainly of Melaleuca and Leptospermum species also occur in this part of Tasmania.

THE LIVESTOCK INDUSTRIES

Dairying is the main industry in the wet temperate forest zones of New South Wales, Victoria, and Tasmania. Approximately 80 per cent of the dairy cows in Tasmania are in areas originally covered with wet temperate forests. The situation is similar in Victoria but only about 30 per cent of the dairy cows in New South Wales are located in former wet sclerophyll forests.

Excepting the irrigated areas, the most productive dairy farms in Australia are in the south-eastern wet temperate forest zone which is estimated to account for 60 per cent of Australia's total dairy production. The principal dairy breeds are Jersey and Friesian, the former being preferred for butter fat and the latter for whole milk production. Illawarra Shorthorns are common in southern New South Wales. With the continuing trend from cream to bulk collection of whole milk by tanker, Friesians are increasing at the expense of Jerseys. Where milk is still separated for cream production on the farm, pig raising is a sideline activity. Some dairy farms also run cattle for beef.

On wet heaths the main farm enterprises are beef and prime lamb production. These enterprises are also important in the temperate forest areas. The most popular beef breeds are Hereford, Angus, and Shorthorn in that order. For prime lamb production, Merino, Corriedale, or Polwarth ewes are crossed with Border Leicester or Romney Marsh to produce the prime lamb mothers. These are mated wtih Southdown, Ryland, or Dorset Horn rams.

OTHER INDUSTRIES

There is little cropping except where soils and topography are suitable such as along the north coast of Tasmania, the Gippsland and Otway districts of Victoria, and at Robertson in New South Wales. Potatoes are grown in these areas particularly on kraznozem soils derived from basalts, often in association with dairying. Green peas and barley are also grown in northern Tasmania. Maize is grown for grain in New South Wales.

In their natural state wet temperate forests are highly valued for their timber. Not only are they a main source of milling timber but they support important paper pulp, plywood, and particle board industries. Extensive plantings of exotic pine forests, mainly *Pinus radiata*, have been undertaken on areas previously occupied by wet temperate forests in Tasmania, Victoria, and southern New South Wales. The importance of the timber industry may be gauged from the fact that only a small proportion (probably less than 20 per cent) of the total area is actually used for agriculture.

THE GRAZING LANDS

Both temperate rainforests and wet sclerophyll forests, with their well-developed canopies and a dense substratum of moderately tall trees and shrubs, create an environment in which there is practically no penetration of light to the forest floor. In this condition there are few grasses or other herbage species except an occasional occurrence of wire grass (*Tetrarrhena juncea*). As a consequence and in contrast to most other vegetation formations in Australia there are virtually no grazing lands in wet temperate forests. Rainforests and parts of the wet sclerophyll forests are classed as forest lands of low grazing value (see Map 4). In some forests repeated burning by both Aborigines and the early white settlers has stimulated colonisation by the indigenous grass, silver tussock (*Poa caespitosa* sens. lat.), and by introduced species such as brown top (*Agrostis tenuis*), Yorkshire fog (*Holcus lanatus*) and sweet vernal (*Anthoxanthum odoratum*). The area of these forest grazing lands is small and they are used mainly for grazing breeding cows and store cattle.

Stock poisoning due to stinkwood and to bracken fern commonly occurs in Tasmania where stock have access to forest areas in which these species are prevalent. Bracken fern poisoning also occurs in Victoria.

Where soils and climate are favourable, intensive agricultural development has followed forest clearing and many of the most productive pastures in south-eastern Australia are on land previously carrying wet temperate forests. These are discussed in a subsequent section.

There are a few grass species or other herbage plants in wet heathlands, particularly in those of King Island and in the north-west area of Tasmania, which in their natural state are grazed only to a very limited extent. Heaths are used mainly as 'runs' for dry dairy cattle for periods of 6–8 weeks during the winter, mainly to rest sown pastures rather than for the value of their grazing. Better grazing is obtained after burning, and this practice is common.

On the north-east coast of Tasmania, Flinders Island, and in Victoria, heath communities are frequently more open. Rainfall is also considerably lower (762 mm) and many of the soils are less acid and somewhat better drained. Under these conditions there are more grasses, e.g.

Danthonia, Stipa, and Themeda and other useful herbage species. Until about fifteen years ago much of this country was used for sheep grazing (1 wether to 5 acres, 2 ha) and occasionally for cattle, but since then pastures have been sown extensively. The remaining unsown areas are now grazed in association with substantial areas of sown pastures.

The sedgelands of west and south-west Tasmania are virtually unused for agricultural or pastoral purposes and are likely to remain so. Their main value would appear to be for recreational purposes and as water catchments for hydro-electricity. They are classed as lands of low grazing value (see Chapter 6, Map 4).

THE PASTURES

Many of the south-eastern wet temperate forests and heathlands still carry their original vegetation, and less than 20 per cent of the area is sown to pasture.

Pasture Establishment

The initial higher fertility of many of the wet forest soils permitted some cropping and pasture development without the use of artificial fertilisers for several years at least. For this reason, many of the forest soils, and particularly the kraznozems derived from basalt, were among the first to be used for agriculture in south-eastern Australia.

Much of the original clearing of temperate forests was carried out 50–100 years ago by slow and laborious methods. The larger trees were ringbarked and left and the smaller trees and undergrowth were cut by axe and burnt when dry. Pastures were then usually sown on the resultant ash-bed without further seedbed preparation. Land to be cropped, mainly with potatoes or oats for green feed and hay, was ploughed and fallowed, but cultivation by horse-drawn ploughs in formerly timbered country was difficult because of the large roots.

Plate 37 Clearing wet sclerophyll forest for pasture, north-western Tasmania (Commonwealth Department of Interior photo)

In the past twenty years, bulldozers have been used for clearing, although large machines are needed for the biggest trees and costs may be as high as $10 per tree. For this reason the largest trees are often left (Pl. 37). Contract clearing of tall timber at the Toolangi Potato Research Station, Victoria, cost about $200 per acre ($494 per ha) to bring the land to a stage suitable for potato experimental work (i.e. no roots to a depth of 12 in., 30 cm).

Bulldozed trees and shrubs are usually left in rows to dry for about a year before burning. In the meantime land between the windrows is ploughed. After burning, the windrow areas are cultivated and either included with the remainder of the paddock in final preparations or cultivated and sown later.

Commonly there is a cultivated fallow for 9 to 12 months before pasture is sown for the first time. In some localities potatoes may be grown on the cleared site for a year or two. This necessitates more thorough clearing than for pasture but the greater financial returns from potatoes helps to pay for clearing operations more rapidly. In Victoria and Tasmania oats or turnips are sometimes sown on newly cleared land to provide winter grazing. The land is then given a series of summer cultivations to prepare a fine, firm seedbed and to kill weeds, particularly bracken fern.

Most forest land was originally sown to pasture by hand broadcasting seed, usually on recently cleared and burnt but uncultivated areas. During the 1930s seed was often broadcast by using a small hand-turned broadcaster strapped on to the chest of the operator. About this time seed was also being mixed with fertilisers and sown by a fertiliser spreader or cereal drill.

In more recent years, although the broadcast sowing of seed and fertiliser by tractor-drawn spreaders and on the steeper areas by hand has continued, there has been an increase in the area sown by drill (often adapted to sow pasture seeds without pre-mixing with fertiliser). Sowing is usually done in autumn, but spring sowings are also common.

Although clearing and cultivation costs are low, particularly in comparison with forests, the low fertility of wet heathlands restricted their use until the discovery of their nutrient deficiencies in the late 1940s. Since then, extensive areas of heathland along the coasts of southern Victoria, northern Tasmania, and on Flinders Island have been sown to productive pastures.

Bulldozing may be necessary to remove eucalypts and the larger shrubs, but clearing is often done more cheaply by dragging a heavy chain across the area between two large tractors.

Burning the original vegetation greatly assists pasture establishment. By rolling, light discing, or rotary hoeing, a more complete and satisfactory burn is achieved. On unburnt areas incorporation of a large amount of undecomposed plant material into the soil makes it difficult to obtain a consolidated seedbed and reduces the amount of nitrogen available to young pasture plants.

Successful pasture establishment on heathland soils requires thorough cultivation and seedbed preparation for a minimum of 9–12 months before sowing. The first cultivation follows burning the original vegetation. Shallow ploughing, discing, or rotary hoeing to a depth of about 4 in. (10 cm) is usually all that is needed, but deeper cultivation is sometimes necessary to prevent the regrowth of some woody species. The cultivated land is then left fallow over the winter and until it is dry enough to carry tractors and cultivating implements at the beginning of the next summer.

Repeated summer cultivations with disc or tyned implements are required to control regrowth of native heaths and weed species. Later a smudger (leveller) and 'stump-jump' tyne harrows are used to make a seedbed for autumn sowing (February–April depending on soil moisture conditions). Spring sowings can seldom be undertaken on these soils because of their wetness.

Occasionally oats or turnips are sown as 'soil conditioning' crops when seedbeds are not satisfactory for pasture establishment. Such crops are usually poor and as they utilise the small amount of nutrients available in these soils they may reduce the vigour of the new pasture.

Heath soils are invariably acid and infertile and, consequently, adequate dressings of lime and fertilisers and inoculation of the legume seed are essential for satisfactory pasture establishment. These aspects are discussed later.

Species

The annual rainfall of both wet temperate forests and heaths in south-eastern Australia is moderate to heavy 35–70 in. (889–1778 mm) per annum and is well distributed throughout the year. The effective growing season is at least 9 to 10 months in most years. The rainfall of these areas is sufficient for a wide range of temperate perennial and annual pasture species including those of North European and Mediterranean origins (Drake and Kehoe 1954a, Martin 1954, 1960). Differences in species usage are due primarily to differences in latitude affecting temperatures and seasonal incidences of rainfall.

Perennial ryegrass, cocksfoot and white clover, all of English origin, were the species mainly sown by the early settlers on the fertile soils of temperate forests in Tasmania and Victoria. These three species, widely used for pastures a hundred years ago, are still the basic components of pasture communities throughout the wet forests and heathlands of south-eastern Australia. These pastures are classified as Temperate Perennial (Chapter 6, Pl. 31). In New South Wales, where the summer rainfall is higher, pastures also contain paspalum (*Paspalum dilatatum*).

Although perennial ryegrass is still widely known as 'English' ryegrass, very little of this seed is imported from England. The local ecotype 'Victorian' has been sown in Victoria for many years and in recent years there has been a pronounced increase in the use of the local ecotypes, 'Kangaroo Valley' in southern New South Wales and 'Tasmanian No. 1' in Tasmania.

The only other grass species commonly included in permanent pasture sowings in these areas are cocksfoot (New Zealand or English) and New Zealand short rotation ryegrass. The latter often partially replaces perennial ryegrass on high fertility soils to provide more autumn-winter feed in the first few years (Martin 1963). *Phalaris tuberosa* is sown to some extent in New South Wales, but rarely in the wet forest and heathland areas of Victoria and Tasmania.

White clover seed is mainly obtained from New Zealand, although seed is harvested in each of the three south-eastern states. Ladino white clover is widely sown in New South Wales.

As well as white clover, subterranean clover has been sown either alone or in mixtures in most of the wet forest areas of Tasmania (Martin 1960), Victoria, and southern New South Wales. It now occurs as a volunteer species in most pastures, its prevalence varying with seasonal weather conditions. Mt Barker is the common cultivar in Tasmania and Victoria but more recently Woogenellup has increased in popularity. Bacchus Marsh, Mt Barker, and Woogenellup are commonly sown in New South Wales.

Red clover (both cowgrass and Montgomery red cultivars) is the only other legume sown to any extent in permanent pastures. It is included to increase forage production in the dry summer period. Lucerne can also produce high quality green feed in the summer-autumn period but is relatively little used in the wet forest areas of Victoria and Tasmania except on the better-drained kraznozem soils in north-west Tasmania. Lucerne, however, is more frequently sown in southern New South Wales either alone at 8–12 lb per acre (9–13 kg per ha) or with cocksfoot at 2 lb per acre (2 kg per ha). Hunter River is the cultivar most commonly used, but Du Puits is being sown to an increasing extent, particularly in Tasmania.

In areas extensively cropped, such as along the north coast of Tasmania, temporary or short-term pastures are often sown between crops. The usual species are short rotation and/or Italian ryegrass together with white clover, red clover, and sometimes crimson clover.

Most permanent pastures in Victoria and Tasmania contain several species not now sown, but often included in sowings before 1930. The most frequent of these volunteer species are Yorkshire fog (*Holcus lanatus*), sweet vernal (*Anthoxanthum odoratum*), bent grass or brown top (*Agrostis tenuis*), crested dogstail (*Cynosurus cristatus*), suckling clover (*Trifolium dubium*), cluster clover (*T. glomeratum*), lotus major (*Lotus uliginosus*), birdsfoot trefoil (*L. corniculatus*), rib grass (*Plantago lanceolata*), and yarrow (*Achillea millefolium*).

Other volunteer species present in pastures throughout the wet temperate zone include soft brome (*Serrafalcus mollis* syn. *Bromus mollis*), hair grass (*Vulpia* spp.), and barley grass (*Hordeum leporinum*). As well as these three species the common volunteer species in pastures in New South Wales are: couch (*Cynodon dactylon*), narrow-leaf carpet grass (*Axonopus affinis*), paddock lovegrass (*Eragrostis leptostachya*), red grasses (*Bothriochloa* spp.), Parra-

TABLE 10 : 3 Sown pasture mixtures (lb per acre—approx. kg per ha)

	Perennial ryegrass[a]	Short rotation ryegrass	Cocksfoot	Phalaris tuberosa	White clover[b]	Sub. clover[c]	Red clover	Total
Wet Temperate Forests								
1. Permanent pasture								
N.S.W.								
Low fertility	6		2	4	1	4		11·0
	6				1·5	4	4	15·5
High fertility	8	4			2		2	16·0
				2	1·5	4	4	11·5
Victoria								
Low fertility	4		3		1	3	2	13·0
High fertility	8	4	3		1	3	2	21·0
Tasmania								
Low fertility	8		3		1·5	4		16·5
High fertility	15				1·5		3	19·5
	8		3		1·5		3	15·5
	6	6			1·5			13·5
2. Temporary pasture								
N.S.W.		10					5	15·0
Vic.		12			1		5	18·0
Tas.		12			1·5		3	16·5
Wet Heaths								
Vic.	3		3		1	3		10·0
Tas.	4				1·5	4		9·5

[a] New Zealand but with 'Kangaroo Valley' in southern N.S.W., 'Victorian' in Vic., and 'Tasmanian No. 1' in Tas.
[b] New Zealand or Ladino in N.S.W.; New Zealand in Vic. and Tas.
[c] Bacchus Marsh, Mt Barker, and Woogenellup in N.S.W.; Mt Barker and Woogenellup in Vic. and Tas.

matta grass (*Sporobolus capensis*), Yorkshire fog, suckling clover, cluster clover, haresfoot clover (*T. arvense*), hop clover (*T. campestre*), and spotted medic (*Medicago arabica*).

Species sown on wet heathlands are essentially the same as on the wet forest areas, but because of the extreme poverty of heath soils, particularly in nitrogen, main emphasis is given to the establishment and growth of legumes. For this reason rates of perennial ryegrass are reduced from the 8 to 15 lb per acre (9–17 kg per ha) usual on forest soils to 2 to 4 lb per acre (2–4 kg per ha).

Although the species are few, the combinations of sowing rates and mixtures are many. Some examples of pasture seed mixtures used in representative areas of wet temperate forests and heaths are listed in Table 10 : 3.

Fertilisers

Except for kraznozems formerly carrying wet temperate forests and which are relatively high in nitrogen and phosphorus, the soils of wet forests and wet heathlands in their natural states are invariably too low in both these elements to maintain satisfactory growth of pasture plants. This applies particularly to the wet heath soils which are so acutely deficient in both these nutrients that there is virtually no growth of sown species unless superphosphate is applied in amounts sufficient to meet the phosphorus needs of the species and to increase soil nitrogen levels by enhancing growth of the legumes. Other plant nutrients commonly deficient are molybdenum and potassium in wet temperate forest soils and copper, zinc, and potassium in the wet heath soils. All wet heath soils are very strongly acid and some of the wet forest soils are moderately to strongly acid. On such soils, lime is essential for satisfactory pasture establishment.

Nitrogen. To date nitrogen has been supplied mainly through the legumes in the pasture. High production therefore depends on vigorous growth of legumes, and many of the fertiliser and other management practices adopted are designed to this end.

In most newly cleared forests and heaths, it is necessary to inoculate legume seed with the appropriate Rhizobium strain. For the wet heathland soils in particular, seed inoculation may be the critical factor in pasture establishment (Paton 1957).

Adequate nitrogen fixation by the Rhizobium-host symbiosis of temperate legumes requires a soil environment which is not too acid. Legumes sown for the first time on moderately to strongly acid soils (pH 5·2 or less as determined on a 1 : 5 soil : water suspension) require some lime. Research in Tasmania has shown that for the very strongly acid soils (pH below 4·8) broadcast applications of ground limestone at 1 ton per acre (2510 kg per ha) made before sowing and worked in to the surface soil during final seed bed preparation are necessary (Paton 1960). For less acid soils (pH 4·8–5·2) 2 to 3 cwt per acre (251–376 kg per ha) of lime drilled with the seed at sowing gives satisfactory results on a wide range of soils. A similar need for lime has been indicated by research in Victoria although the critical pH levels appear to be somewhat higher. On soils of pH less than 5·2 inoculated seed is either drilled with a 1 to 1 mixture of ground limestone and superphosphate at 4 cwt per acre (502 kg per ha) (Drake and Kehoe 1954b) or 2 to 3 cwt per acre (251–376 kg per ha) of ground limestone with 2 cwt per acre (251 kg per ha) of superphosphate broadcast separately (Paton 1960). The latter method has, however, given unsatisfactory establishment on some high phosphate fixing kraznozem soils, apparently because of severe phosphorus deficiency in newly established plants resulting from separation of seed and fertiliser (Paton 1960).

Lime pelleting is now widely used for establishing pasture seeds on new land in Australia (see Chapter 22). It has the advantage of enabling the inoculated seed to be mixed with acid superphosphate for sowing. It also ensures that some lime is close to the germinating seed in soils in which the need for lime is marginal. The technique has its greatest application on soils of moderate acidity (pH no lower than 5·3) or where the pH of strongly acid soils has been raised to this level by prior application of lime. Lime pelleting cannot replace conventional heavy dressings of lime required on strongly acid soils of wet heathlands and some forests. Although lime coating is not essential when seed is drilled with lime or lime-superphosphate mixtures it is commonly practised.

As a result of the steady fall in its price, nitrogen fertiliser is now fairly commonly used to boost 'out of season' production, especially of perennial or short-rotation ryegrass pastures in the dairying areas of Tasmania and Victoria. For this purpose, nitrogen as sulphate of ammonia, ammonium nitrate or urea, is applied at 50 lb N per acre (56 kg per ha) in April-May or July to increase production in late autumn-early winter or later winter-early spring. Nitrogen is being increasingly used also on oat forage crops and kikuyu pastures in central districts of New South Wales. Nitrogen is sometimes applied to irrigated pastures in early spring, summer, or autumn.

Phosphorus. Phosphatic fertiliser in the form of superphosphate was first applied to sown pastures to any extent in the early 1920s. Responses were spectacular and carrying capacity was doubled and even trebled. Subsequently, application of superphosphate has come to be regarded as an essential and normal management practice on all wet temperate forest soils. For the establishment of pastures on virgin soils, superphosphate is applied at 3 cwt per acre (376 kg per ha). Most sown pastures in wet temperate forest and heathlands subsequently receive regular autumn applications at 1·5–2 cwt per acre (188–251 kg per ha) (Paton 1960).

The regular use of superphosphate for a number of years raises the phosphorus level of soils to the extent that responses of pastures to further applications decline. This applies particularly to pasture production in the spring. The rate at which available phosphorus accumulates following applications of superphosphate is determined by the characteristics of the soil and the management it receives. On some soil types responses to superphosphate are frequently difficult to measure when a total of about 1 ton per acre (2510 kg per ha) of superphosphate has been applied in the preceding 10–14 years.

The phosphorus requirements of wet heathland soils are similar to those of wet forests. An initial dressing of 3 cwt per acre (376 kg per ha) superphosphate is about the minimum for satisfactory pasture establishment on most of these soils. Annual applications of superphosphate at 1·5 to 2 cwt per acre (188–251 kg per ha) are necessary for at least the first few years following establishment. There is, however, evidence from some of these soils that despite an extremely low initial phosphorus status, there is rapid accretion of available phosphorus and responses to further dressings of phosphate may be small or non-existent after as little as 0·5 ton per acre (1255 kg per ha) of superphosphate has been applied.

Potassium. Potassium deficiency in pastures was first recognised in Victoria in the early 1930s, but it was not until the early 1950s that the extent and severity of the deficiency in both Victorian and Tasmanian pastures were appreciated (Newman 1956, Paton 1956b) (Fig. 21 : 3a, Table 21 : 7). This was followed by a rapid and spectacular increase in potash usage. In 1953, approximately 300 tons of potash fertiliser were used on Victorian pastures and 100 tons on Tasmanian pastures. The corresponding figures in 1966 were 27,500 and 3800 tons respectively. Pasture responses to potassium have been obtained also on the south coast of New South Wales (Strang 1963). In New South Wales potash usage on pastures was 34 tons in 1963 and 560 tons in 1966.

Most of the heavier textured soils of rainforests have a relatively high initial potassium status and it is only after extensive periods of heavy cash cropping or removal of pasture as hay or silage that potassium becomes deficient (Paton 1956a; Hosking 1961). However, not all soils with a history of heavy cropping or fodder conservation are potassium deficient. Notable among these are some kraznozems on basalt in northern Tasmania which have been continually cropped, particularly with potatoes and oaten hay, for sixty or eighty years to the end of World War II and then sown to pastures which were cut regularly for hay. On the other hand, pasture on soils of similar appearance and history may frequently show severe potassium deficiency symptoms.

Symptoms of potassium deficiency are a marked decline in clover production except in urine patches; an increase in the proportions of various weed species such as catsear (*Hypochoeris radicata*), other flatweeds (*Taraxacum* spp. and others), and sorrel (*Rumex acetosella*); and development of specific potassium deficiency symptoms on the leaves of legumes (Hosking 1965).

When potassium deficiency is severe, an initial dressing of 1 cwt per acre (125 kg per ha) of potassium chloride is near the optimum on a wide range of soils. The maintenance dressings required vary with the soil and particularly with the system of management. When cut for hay or silage, subsequent dressings of 1 cwt per acre (125 kg per ha) are required. When grazed for intensive dairy production annual dressings of 0·5 to 1 cwt per acre (63–125 kg per ha) are common. For less intensive cattle or sheep grazing, the annual maintenance requirement is 0·25 to 0·5 cwt per acre (32–63 kg per ha).

Most of the wet heathland soils have a low initial potassium status and consequently potash fertilisers generally become necessary within the first few years of pasture establishment. Frequently an application of 1 cwt per acre (125 kg per ha) of potash is made in the second year and annual dressings of 0·25–0·5 cwt per acre (32–63 kg per ha) are advisable.

Sulphur. As with potassium a deficiency of sulphur is most likely on light textured soils. Severe sulphur deficiency has been found on several wet heathland soils along the north coast of Tasmania, on Flinders Island, and in Victoria (Fig. 21 : 3a).

In contrast, responses to sulphur in New South Wales and parts of Victoria have been recorded on a wide range of soils derived from basalts, granites, and sedimentary rocks (Drake and Curnow 1967). A few responses to sulphur have also been obtained in Tasmania on heavy-textured soils derived from basalt.

Annual applications of sulphur at 20–30 lb per acre (22–34 kg per ha) are generally required to correct sulphur deficiency. As superphosphate contains about 11 per cent sulphur, severe sulphur deficiency is unlikely on areas regularly top-dressed with superphosphate at rates approaching 2 cwt per acre (251 kg per ha).

Lime. Lime is frequently needed for pasture establishment on strongly acid soils (Drake and Kehoe 1954b; Hosking 1957a; Paton 1960). In most instances, the main effect of lime is to promote satisfactory nodulation of legumes, although other effects such as the correction of aluminium or manganese toxicities may also be involved (Kehoe and Curnow 1963). Heavy lime dressings have also reduced leaching losses of phosphorus on heath soils (Paton and Loneragan 1960).

Up to the end of World War II, 0·5 to 1 ton per acre (1255–2150 kg per ha) of lime was commonly broadcast on established pastures, particularly on kraznozems in Tasmania and

Plate 38 Effect of copper on the establishment and growth of perennial ryegrass-white clover pastures on former wet temperate heathland, north-western Tasmania: (left) no copper (right) copper applied (Department of Agriculture, Tasmania, photo)

Victoria. Marked responses were frequently obtained. It is now known that the main effect of lime on most of these soils is to increase the availability of molybdenum to pasture plants (Paton 1960). Consequently molybdenum instead of lime is now usually applied to established pastures.

Molybdenum. Molybdenum deficiency in the pastures of several wet forest areas of Tasmania was discovered in 1945 (Fricke 1945 a and b). Since then, pasture responses to molybdenum have been obtained in many of the wet forest areas of Tasmania (Paton 1956a), Victoria (Hosking 1957b), and New South Wales (Strang 1955; Wetherall 1963) (Fig. 21 : 3d). Molybdenum deficiency is by far the most widespread trace element deficiency in the wet temperate forests of south-eastern Australia (Table 21 : 7). It is corrected by applying 1 to 2 oz per acre (70–140 g per ha) molybdenum as sodium molybdate or molybdenum trioxide. A single application may be effective for at least 5 years.

It is estimated that the proportion of pastures in wet forest areas now treated with molybdenum is approximately 75 per cent in Tasmania, 50 per cent in Victoria, and 15 per cent in New South Wales.

Copper. The wet heathland soils of southern Victoria, King Island, Flinders Island, and Tasmania are invariably deficient in copper to some degree (Newman 1956, Paton 1956c). In many areas the deficiency is so acute that no legume growth is obtained unless copper is applied (Pls. 38, 39; Fig. 21 : 3b).

An initial application of copper equivalent to 7 lb per acre (8 kg per ha) of copper sulphate is sufficient for maximum pasture production. Residual effects persist for as long as ten years in some areas but as the copper requirements of animals are higher than those of pasture species, maintenance applications are needed to sustain high animal production. In Tasmanian wet heathlands, 5 lb copper sulphate per acre (6 kg per ha) is applied every four years.

Plate 39 Temperate perennial pasture of perennial ryegrass and white clover (left) sown on wet temperate heath (right), north-western Tasmania (Department of Agriculture, Tasmania, photo)

Copper deficiency is not known to limit pasture growth on any soils of wet temperate forests, but a deficiency in animals is suspected in some places.

Zinc and boron. Responses to zinc have been recorded on wet heathland soils on King Island, Flinders Island, and along the north coast of Tasmania (Fig. 21 : 3c). Zinc deficiency has not been recorded on wet temperate forest soils (Table 21 : 7).

Responses to boron have been recorded in pastures on the Southern Tablelands of New South Wales and also on some very strongly acid wet heathland soils on the west coast of Tasmania following heavy applications of lime. Boron deficiency is also common in turnips and other Brassicae forage crops (e.g. chou moellier) grown on kraznozem soils in northern Tasmania, and this deficiency has been noted in turnips on kraznozems in Victoria. However, significant responses by pastures to boron have not been recorded on these soils.

Cobalt. Legumes have responded to cobalt on sandy soils in both Western Australia and South Australia. There have been no cobalt responses in the pastures of south-eastern Australia but cobalt deficiency in grazing animals is widespread in the coastal wet heaths of northern Tasmania and the Bass Strait islands. Applications of cobalt are made therefore to most of the sown pastures of wet heath soils in these areas. The customary application is 12 oz per acre (840 g per ha) of cobalt sulphate every second year.

A response in animal health and production to cobalt has also been reported on a kraznozem soil on basalt in the Rocky Cape district (latitude 40° 55′S) of north-western Tasmania (Thain 1955).

TABLE 10 : 4 Response by grass-clover pastures to fertilisers at selected centres: lb dry matter per acre (approx. = kg per ha)

FOREST SOILS				
Superphosphate		0	+	L.S.D. 5%
Fitzroy Falls	(N S W.)[a]	2530	5020	370
Hallora	(Vic.)[a]	3720	5900	700
Deloraine	(Tas.)[a]	3380	4930	930
Potassium		0	+	
Fitzroy Falls	(N.S.W.)	3570	4431	370
Drouin West	(Vic.)	1230	2360	342
Nilma North	(Vic.)[b]	3780	6400	920
Latrobe	(Tas.)	3260	5200	640
Deloraine	(Tas.)	1430	3140	620
Molybdenum		0	+	
Barramunga	(Vic.)	350	1320	210
Drouin West	(Vic.)	2110	2640	487
West Ridgley	(Tas.)	6120	7500	220
HEATH SOILS				
Superphosphate		0	+	
Flinders Island	(Tas.)[a]	1480	4280	810
Potassium		0	+	
Foster	(Vic.)	920	2610	737
Walkerville	(Vic.)	666	1645	264
Waterhouse	(Tas.)	2910	4480	660
Copper		0	+	
Koonwarra	(Vic.)	820	1230	332
Flinders Island	(Tas.)[b]	3950	6280	870
Lime at Sowing		0	+	
Koonwarra	(Vic.)	1120	3040	865
Smithton	(Tas.)	580	2610	320

[a] Areas had received some superphosphate previously.
[b] Figures represent full year's growth. Other figures are for part of year only.

ANIMAL PRODUCTION

Throughout both wet temperate forests and wet heathlands, permanent pasture is the basis of livestock production. Except where cropping is carried out as an integral part of the farm program, resowing is usually undertaken only where there has been death of pasture species as a result of dry conditions, insect attack, or faulty management. Some pastures in the wet forest areas of Victoria and Tasmania are more than fifty years old, and if adequately fertilised and properly managed, are very productive. Production from permanent pastures is greatest in spring (September to December). In Victoria and Tasmania summer production is low in most years because of low rainfall from January to March. Stock are not housed at any stage of the year and invariably winter is the period of greatest feed shortage and sets the limit to stock carrying capacity and production (see Fig. 12 : 5).

While the efficiency of pasture utilisation can be increased by the correct timing of calving and/or lambing to ensure that the period of maximum stock feed requirements coincides with the period of maximum pasture growth, additional measures have to be taken to supplement the feed available from pastures during periods of greatest shortage—winter and summer in Victoria and Tasmania.

Throughout the southern areas most supplementary feeding is with pasture hay or sometimes with silage made from surplus spring growth. Not uncommonly, about 20 per cent of a dairy farm in the wet forest area is closed in September for fodder conservation in November-December. In normal years, 2 tons per acre (5020 kg per ha) of grass hay are obtained and this provides about 1 ton of pasture hay per cow per year. Silage is fed mainly during the dry summer-autumn period and hay is fed during late autumn-winter.

Particularly in the intensive dairying areas of Tasmania, but to a much smaller extent in Victoria and southern New South Wales, fodder crops are grown to provide supplementary summer-autumn or winter feed. For winter feed, green-feed cereals (usually oats), chou moellier and turnips are sown. For summer feed in Tasmania, rape or chou moellier is commonly sown in October-November. Maize, sorghums, Japanese millet, and turnips are sown for this purpose in Victoria and New South Wales. In recent years, lucerne has also become increasingly important for green forage during summer-autumn in some of the dairying areas in northern Tasmania. Most forage crops are grazed *in situ*, frequently with the aid of an electric fence to reduce wastage through trampling.

Nitrogen fertiliser is applied to raise pasture production in late autumn-early winter and early spring on dairy farms in Tasmania and Victoria.

In recent years spray irrigation of pastures has become widespread even in the relatively high rainfall areas of northern Tasmania (annual rainfall 34–45 in., 864–1143 mm) and Victoria to provide green pasture for dairy cows during the dry summer.

Pasture harrowing to spread dung is carried out to a limited extent on some dairy farms while spraying to control insects or weeds is conducted where infestations are severe.

In wet temperate forest lands where dairying is the predominant form of livestock production, farms may be as small as 50 acres (20 ha). But small farms are not economic and the trend is to aggregation of neighbouring properties and increase in average farm size. Farms are now commonly between 100 and 200 acres (40–81 ha) with many larger holdings. Most dairy farms are subdivided into about 15–20 small paddocks each of 8–10 acres (3–4 ha). These paddocks are usually grazed rotationally (see Chapter 27). Strip grazing with the aid of electric fences may be practised during periods of rapid pasture growth and at other times to ration out a limited amount of specially saved or produced feed, for example following application of nitrogenous fertilisers or for feeding off forage crops.

A typical dairy herd consists of about 50 milking cows, but herds of 100–120 are not uncommon. In Tasmania, Victoria and alluvial soil areas of New South Wales the average carrying capacity is about 0·5 milking cows per acre (1·2 per ha). The best farms may carry up to 0·75 cows per acre (1·8 per ha). To these figures 0·1 cow should be added for the equivalent of dry and replacement stock carried on the farm. In Victoria, southern New South Wales, and Tasmania, butter fat production ranges from about 100 to 200 lb per acre (112–224 kg per ha).

Subdivision is less intense on lands formerly covered with wet temperate heaths where the major agricultural industries are beef, fat lamb and wool production. Paddock sizes range from 20 to 50 acres (8–20 ha) and some form of rotational grazing is generally practised.

Some farmers 'autumn-save' pasture by putting all the stock on a part of the farm, supplementing their feed if necessary, and keeping the 'saved' area until winter when pasture growth is slow (see Chapter 27). Set stocking ewes and lambs on the one paddock from lambing to weaning is being increasingly practised.

Most sheep properties also run cattle to diversify production, utilise excess pasture growth, and keep pastures short for sheep. Carrying capacities of sheep properties are from 3 to 5 fat lamb ewe equivalents per acre (7–12 per ha). The average wool yield is about 10 lb (4·5 kg) per sheep. Lambing percentages of 100–120 per cent are common. Beef production ranges from 100 to 400 lb per acre (112–448 kg per ha) dressed weight. Most cattle are sold at 18–24 months at a dressed weight of 450–600 lb (204–272 kg). Average calving percentage is about 90.

IMPEDIMENTS TO ANIMAL PRODUCTION

Throughout Tasmania and Victoria the most troublesome insect pests are underground grass caterpillars (*Oxycanus* and *Oncopera* spp.), cockchafers (*Aphodius pseudotasmaniae*, *A. howitti*), red-legged earth mite (*Halotydeus destructor*), pea mite (*Penthaleus major*), and lucerne flea (*Sminthurus viridis*). Army cutworms (*Persectania ewingi*) and grasshoppers occasionally cause severe damage, particularly on some coastal areas. In New South Wales, the pea mite, cockchafers, red-legged earth mite, cutworms, lucerne flea, black beetle (*Heteronychus arator*), crickets (*Teleogryllus commodus*), and various grasshopper species are the main insect pests.

In Victoria and Tasmania, damage to perennial pastures by cockchafers and underground grass caterpillars is frequently severe and may result in the complete destruction of the pasture cover. Lucerne flea, red-legged earth mite and pea mite can reduce pasture production during winter and spring and make it unattractive to stock. Lindane and DDT have been widely used for the control of many pasture pests, but the need to limit chlorinated hydrocarbon residues in animal products has meant a revision of the list of insecticides recommended for the treatment of pastures. In the dairying areas of Tasmania, chlorfenvinfos and carbaryl are currently recommended for underground grass caterpillar and cockchafer control respectively.

The most important disease of pasture plants is the rust (*Puccinia coronata*) which makes ryegrass less acceptable to animals. Subterranean clover stunt virus occurs occasionally, particularly in newly sown pastures, but is of little economic significance. A rust fungus (*Uromyces trifolii*) also attacks subterranean clover and suckling clover in some seasons. Leaf spots (*Pseudopeziza trifolii* and *P. medicaginis*) on red clover and lucerne and *Pseudoplea trifolii* on white clover are common.

In New South Wales, ergot (*Claviceps paspali*) is widespread on paspalum and causes ergot sickness in cattle.

Spraying for control of pasture diseases is seldom undertaken.

If the density of perennial grasses in a pasture is reduced, invasion by various weed species occurs. In Victoria and Tasmania, under conditions of low soil fertility, the species which replace the sown species are Yorkshire fog, soft brome, sweet vernal, hair or silver grass, browntop, catsear and other flat weeds, rib grass (*Plantago lanceolata*), sorrel, buttercup (*Ranunculus* spp.), and English daisy (*Bellis perennis*).

Where low soil fertility is the reason for the loss of the sown species and ingress of weeds, application of the appropriate fertiliser, frequently potash and/or molybdenum, is a corrective treatment.

Where the perennial grasses have been killed by a drought or insect attack, and soil fertility is relatively high, species such as capeweed (*Arctotheca calendula*), storksbill (*Erodium* spp.), chickweeds (*Stellaria media* and *Cerastium vulgare*), and barley grass (*Hordeum leporinum*) are common invaders.

Although regarded as weeds, all the above species are edible and in many instances it is doubtful if their presence seriously reduces animal production.

Other weeds that increase because of decline in density of sown species include spear thistle (*Cirsium vulgare*) and slender thistles (*Carduus pycnocephalus* and *C. tenuiflorus*). These species which are not generally eaten by stock may become troublesome. Most weed spraying in pastures is for control of thistles and capeweed by hormone type weedicides such as 2,4-D and MCPA.

Other weed species of local importance throughout some of the higher rainfall areas of Tasmania and Victoria are ragwort (*Senecio jacobaea*), blackberry (*Rubus fruticosus*), bracken fern, perennial thistle (*Cirsium arvense*), and oxeye daisy (*Chrysanthemum leucanthemum*). With the exception of the latter two, these weeds usually occur in rough semi-improved or neglected areas where either management is poor or cultivation impracticable. Rushes (*Juncus* spp.) and docks (*Rumex* spp.) are the most common weeds in poorly-drained heathlands.

Biddy-biddy burr (*Acaena anserinifolia*) can be a problem on sheep properties in the hills of south Gippsland in Victoria.

Several weeds occurring in Victoria and Tasmania are also found throughout the wet temperate forest area of New South Wales. These include bracken, blackberry, spear thistle, slender thistle, variegated thistle (*Silybum marianum*), oxeye daisy, sorrel, and rushes.

A native plant, Bergalia tussock (*Carex longibrachiata*), is a weed of grazing lands on the south coast of New South Wales. Blady grass (*Imperata cylindrica* var. *koenigii*) may also be troublesome on newly cleared forest lands.

In Tasmania and Victoria, there are relatively few serious animal diseases. Reproductive diseases and mastitis are perhaps the major disorders in dairy cattle. Various metabolic diseases (e.g. upsets in the calcium and magnesium levels) are also common. Bloat causes losses in some years. Pulpy kidney in lambs, pregnancy toxaemia, footrot, worms, and ryegrass staggers in some seasons, are the main sheep diseases.

LAND VALUES

Most of the land in this zone in Australia is held under freehold tenure. Land values vary considerably depending on nearness to facilities (market, transport, shopping centre, school, etc.), standard of the buildings, acreage, general level of productivity, and potential for intensive crop production. In the more remote areas of Tasmania the price of cleared forest country sown to pasture is about $100 per acre ($247 per ha). In Victoria and Tasmania where transport and other facilities are good, prices ranging from $200 to $600 per acre ($494–$1682 per ha) are obtained. In Victoria, prices at the higher levels often contain a component calculated by the purchaser as an additional value per unit area due to the fact that a city milk contract goes with the farm and cannot be transferred to another. In Tasmania, prices of $400–$500 per acre ($988–$1235 per ha) are obtained for highly improved forest land suitable for intensive vegetable production. In New South Wales prices of pasture land on former wet forests and heaths range from $50 to $500 per acre ($124–$1235 per ha).

11

DRY TEMPERATE FORESTS AND HEATHS

R. J. NEWMAN

DISTRIBUTION

Dry sclerophyll forests extend from southern Queensland to the south-west of Western Australia. In eastern and southern Australia they occupy the upper slopes of the Great Dividing Range, the Warrumbungle Mountains in inland New South Wales, the Central Highlands and Grampians in Victoria, the Mt Lofty Ranges in South Australia, and the high country of north-east of Tasmania. The distribution of dry sclerophyll forests is determined less by rainfall than by soil nutrients and they occur for example on Kangaroo Island, South Australia, and along the eastern and south-eastern coasts where soils are low in nutrients. Dry heaths are associated with dry sclerophyll forests on soils of even lower nutrient status in south-western Victoria, eastern Victoria, and Kangaroo Island.

In Western Australia the principal dry sclerophyll forest community is jarrah (*Eucalyptus marginata*). Dry heaths occur on the Dandarragan Plateau, the coastal strip east of Gibson and on sandplains throughout the south-west (Map 3). These Western Australian communities are described in Chapter 14.

There are communities floristically related to dry sclerophyll forests in sub-tropical Queensland but for the most part these are more open and grassy and are classified as woodlands (see Chapters 4 and 8).

CLIMATE

The climate of the southern part of Australia is essentially modified Mediterranean in character. Under the influence of mid-latitude westerly winds, winter and spring rains are of high reliability. In eastern Victoria and southern New South Wales, rainfall is fairly evenly distributed throughout the year, but summer rainfalls are erratic and often ineffective for pasture growth. Monthly rainfall averages for a number of centres within the sclerophyll forest zone are given in Table 11 : 1.

Summers are hot and dry and in the south sown pastures are dry from December to March or April. The growing season varies from five to eight of the cooler months of the year and is suited to annual pasture species and drought resistant perennials (see Chapter 1).

Average daily maximum and minimum temperatures for a number of centres are given in Table 11 : 2.

SOILS

The dominant soils of temperate dry sclerophyll forests from the Adelaide Hills of South Australia to northern New South Wales are podzolic and solodic (see Chapter 3, Map 2). These are described by Northcote (1960) as seasonally hard-setting surface soils, usually

TABLE 11 : 1 Average monthly rainfall (mm) for various centres within the dry sclerophyll forest zone

Place	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Annual mm	Annual in.
Adelaide (S.A.) lat. 34° 55′S	20	20	24	44	69	74	66	62	51	45	31	26	532	21
Ararat (Vic.) lat. 37° 17′S	26	39	32	43	56	63	67	67	66	54	46	46	605	24
Cobden (Vic.) lat. 38° 34′S	38	45	49	62	78	84	84	99	86	78	66	54	823	32
Longford (Tas.) lat. 41° 36′S	34	33	42	49	57	64	66	66	59	62	42	51	625	25
Crookwell (N.S.W.) lat. 34° 28′S	58	48	66	66	64	95	97	91	76	75	58	73	867	34
Tamworth (N.S.W.) lat. 31° 05′S	77	54	51	37	28	54	49	39	44	50	63	76	622	24

TABLE 11 : 2 Average daily maximum and minimum temperatures (°C) for January and July

Month	January		July	
Place	Max. °C	Min. °C	Max. °C	Min. °C
Adelaide (S.A.)	29·0	17·2	15·5	7·5
Ararat (Vic.)	26·5	11·5	11·0	4·5
Oatlands (Tas.)	21·5	18·0	9·5	1·5
Crookwell (N.S.W.)	26·7	11·0	9·4	−0·5
Tamworth (N.S.W.)	33·2	18·5	15·8	2·7

sandy loams or loams of variable depth with yellow clayey subsoils, whole coloured for at least their upper 6 inches. No subsurface (A_2) horizon is present and the reaction is generally acid throughout, varying from pH 5·2 to 6·0 in the surface soil. There are, however, variations within this broad group and some soils are neutral in reaction throughout the profile. The soils are generally shallow and are formed mostly on sandstones, mudstones, schists, or granites. Dry sclerophyll forests are also found on calcareous sands, terra rossa, and rendzina soils in the south-east of coastal South Australia and in the western coastal area of Victoria. These soils are not hard-setting and are generally sandy loams, or loams and alkaline in reaction. Another group of soils on which dry sclerophyll forests are found are red podzolics. These are hard setting, lack a subsurface (A_2) horizon and are acid throughout the profile.

The soils of heaths associated with dry sclerophyll forests are leached acid sands or sandy loams. The depth of the surface horizon which is darkened with organic matter is variable and passes into a bleached subsurface horizon. A cement layer or pan-like horizon known as coffee rock is present at a depth of 12–36 in. (30–91 cm) below the surface. Because of the characteristically impermeable nature of the subsoil, these usually dry soils may become waterlogged for periods following heavy and prolonged rains. The pH of the surface soils ranges between 4·8 and 5·7.

THE AGRICULTURAL INDUSTRIES

The grazing lands and sown pastures of dry sclerophyll forests and heaths are used principally for wool, fat lamb, beef, and in the higher rainfall areas of Tasmania and Victoria to a limited extent, for dairy production. On native grass grazing lands, wool growing is the main enterprise and the principal breeds of sheep are Merino, Polwarth, Corriedale, and Comeback.

Fat lamb production is associated with wool production on land sown to annual or perennial pastures. Such pastures support between 2 to 4 ewes and their lambs per acre (5–10 per ha) depending upon rainfall. The breeds commonly used for fat lambs are Border Leicester × Merino, Dorset Horn, Corriedale × Romney Marsh and Southdown.

Beef is produced mainly on sown pastures and is generally combined with some form of sheep husbandry. The types of farming in dry sclerophyll forest and heath lands are illustrated in Table 11 : 3 which shows the livestock and farming industries for above 20 in. (508 mm) annual rainfall zones of south-eastern Australia.

TABLE 11 : 3 Percentage of all farms engaged in various agricultural enterprises

Farm Industry	N.S.W.	Vic.	S.A.	Tasmania
	%	%	%	%
Sheep only	65·8	57·4	54·2	60·2
Sheep + Cattle	27·2	19·0	12·3	6·7
Sheep + Cereals	—	4·4	17·5	8·7
Other	7·0	19·2	16·0	24·4

Dairying is a minor industry in dry sclerophyll forest lands and is confined to the higher rainfall districts adjoining wet sclerophyll forests where pastures of perennial grasses and legumes can be established. The main breeds of dairy cattle are Jersey, Guernsey, and Friesian and their crosses. In parts the high rainfall forest areas have been cleared for pome and stone fruit growing.

VEGETATION

Dry sclerophyll forests have an overstorey of one or more species of Eucalyptus, 10–30 m tall, an understorey of sclerophyllous shrubs belonging principally to Proteaceae, Epacridaceae, and Leguminoseae, and a discontinuous herbaceous layer of tussock grasses (see Map. 3, Pl. 15). Grasses characteristic of dry sclerophyll forests include *Danthonia pallida*, *Poa caespitosa* sens.

lat., *Dichelachne sciurea*, *D. crinata*, and *Themeda australis*, but the composition and density of the ground layers vary widely. In some dry sclerophyll forests the grass layers are similar in composition and densities to those of adjacent temperate woodlands or wet sclerophyll forests. The shrub layer, too, is variable. On soils of low fertility, shrubs are dense and grasses few or absent. On soils with a clay subsoil near the surface the community is a heath composed essentially of shrubs forming the understorey of the adjacent forest (Pl. 10).

The principal tree species of the dry sclerophyll forests of the east coast of New South Wales are *Eucalyptus micrantha* (scribbly gum), *E. piperita* (Sydney peppermint), *E. acmenioides* (white mahogany), and *E. gummifera* (red bloodwood). These species extend into sub-tropical Queensland where they are associated with heaths on coastal lowlands (see Chapter 7). In inland New South Wales and parts of Victoria the characteristic dry sclerophyll forest community is *Eucalyptus rossii*—*E. macrorrhyncha* (red stringybark). Other species commonly present include *E. dives* (broad-leaved peppermint), *E. radiata* (narrow-leaved peppermint), *E. polyanthemos* (red box), *E. elaeophora* (apple box), and *E. maculosa* (spotted gum). *E. sideroxylon* (ironbark) and *E. dealbata* (tumbledown gum) are associated in dry sclerophyll forests throughout the drier woodlands of New South Wales. Further south in Victoria and in South Australia the most extensive dry sclerophyll forest is a community of *E. baxteri* (brown stringybark)—*E. obliqua* (messmate). On podzolised white sands in South Australia *E. baxteri* is associated with *E. viminalis* (manna gum). *E. baxteri* is the only tree in many forests of South Australia; the common understorey species are *Pteridium esculentum* (bracken), *Xanthorrhoea australis* (grass tree), *Hibbertia stricta*, and *Acacia* spp. On lateritic soils, a dwarf form of *E. baxteri* is associated with *E. cosmophylla* (scrub gum), *Casuarina striata* (she-oak), *Banksia ornata* (desert banksia), *Hakea* spp., and a number of other *Proteaceae* and *Epacridaceae*, in a heath-like community. Towards the drier limits of its range in South Australia it merges with a mallee of *E. diversifolia*. *Eucalyptus obliqua*, the wettest form of dry sclerophyll forest, occurs in the Mt Lofty Ranges of South Australia and in the north-east of Tasmania. In the wetter parts of their ranges and on more fertile soils *E. obliqua* communities are wet sclerophyll forests.

The common shrubs of both forests and heaths belong to the genera Banksia, Leptospermum, Astroloma, Hibbertia, Persoonia, Acacia, Pultenaea, Leucopogon, Epacris, and Xanthorrhoea. Typical dry heath communities are *Leptospermum juniperinum* (prickly tea-tree)—*Banksia marginata* (silver banksia); *Banksia ornata* (desert banksia); and *Leptospermum nitidum*—*Calytrix sullivanii*.

There are extensive ecotonal areas in which the dominants are dry sclerophyll forest species but the structure of the communities, the grazing lands and the pastures that can be established on them are those of temperate woodlands or wet sclerophyll forests. The grazing lands and pastures described in this chapter are those of typical dry sclerophyll forests and associated dry heath communities.

THE GRAZING LANDS

The low density and high fibre content of grasses and other herbaceous species of dry sclerophyll forests limit the value of their grazing lands. Some like the dry heaths have few herbaceous species and little or no grazing value in their original state. These are classified as heath lands of low grazing value (Map 4). In inland New South Wales the only grazing in many dry sclerophyll forests is provided by the coarse tussock grasses *Danthonia pallida* and *Poa caespitosa* sens. lat. The latter is common also in high rainfall areas where it is frequently associated with *Themeda australis* and *Dichelachne* species. These grazing lands are shown in the map as temperate tall grass, but in areas cut for firewood or felled and burnt in the early years of settlement, there has been an ingress of introduced species such as *Trifolium arvense* (haresfoot clover), *T. angustifolium* (narrow-leaved clover), *Aira caryophyllea* (silvery hair grass), *Hypochaeris radicata* (catsear), and species of *Bromus*. Without fertilisers, these too have low values for grazing. On more fertile soils in parts of southern Victoria and South Australia, clearing has been followed by the entry of more palatable species from adjacent woodlands and wet sclerophyll forests and herbaceous strata have increased in density and improved in species composition (Pl. 40). Grazing values

Plate 40 Dry sclerophyll forest on tops and upper slopes of hills above temperate woodlands. Tree densities reduced by ringbarking, central Victoria (Department of Agriculture, Victoria, photo)

have further increased by the naturalisation of the cool season annuals *Trifolium dubium* (yellow suckling clover), *T. procumbens* (hop clover), and T. *glomeratum* (clustered clover). These species, though not highly productive, increase the quality of the feed available. These grazing lands are used mainly for wool production and carry from 0·25 to 0·75 dry sheep per acre (0·6–1·8 per ha) depending on the density and species composition of the community.

With the correction of soil nutrient deficiencies many of the dry sclerophyll forests and heaths will grow productive pastures, and during the past 15–20 years there has been a rapid increase in the area of dry sclerophyll forests sown to pastures in South Australia and Victoria. This relative increase is illustrated in Table 11 : 4 which shows the proportion of rural properties sown to pastures in the above 20 in. (508 mm) annual rainfall zones of south-eastern Australia.

TABLE 11 : 4 Proportion of all properties sown to pastures: > 508 mm rainfall

	N.S.W. %	Vic. %	S.A. %	Tas. %
Sown pasture	59·5	83·1	75·0	25·1

THE PASTURES

The pastures of the dry sclerophyll forests and dry heaths are of two main types, temperate perennial grass-annual legume, and Mediterranean annual, although all the forests in the high rainfall areas are capable of supporting perennial grasses.

The establishment of productive pastures on dry sclerophyll forests and dry heaths has been made possible by the discovery and correction of soil nutrient deficiencies of phosphorus, sulphur, and molybdenum and in some cases of copper and zinc as well, the latter particularly on dry heath lands (Fig. 21 : 3c).

The legume on which sown pastures are based is principally *Trifolium subterraneum* (subterranean clover) but in north-eastern Tasmania and coastal areas of New South Wales and Victoria where rainfall exceeds 25 in. (635 mm) annually and is not confined to the winter months, *Trifolium repens* (white clover) may be locally important.

The commonly sown cultivars of subterranean clover are the early midseason Bacchus Marsh, Woogenellup (Marrar), and the late mid-season Mt Barker and Howard, but in South Australia where the growing season ends in October the early maturing cultivars Geraldton and Yarloop are better adapted and more productive. In parts of Victoria and in New South Wales where spring rains continue until December the late maturing Tallarook is sown.

Hunter River lucerne (*Medicago sativa*) is sown on the sandy soils of Kangaroo Island and in the southern parts of South Australia and Victoria. It is sown as a hay crop throughout the dry sclerophyll forest zone, but principally on the floodplains of rivers and creeks.

The Australian commercial cultivar of *Phalaris tuberosa* is the best adapted perennial grass for most of the soils and climates of the dry sclerophyll forests and heaths and is commonly sown with subterranean clover in a two species pasture community. Perennial ryegrass is sown with white clover in climatically more favourable environments but these two species are more typical of the pastures of wet sclerophyll forests.

Perennial veldt grass (*Ehrharta calycina*) is sown on a small area of deep sandy soils in South Australia. In northern New South Wales where the proportion of the annual rainfall in summer months is relatively high, *Chloris gayana* (Rhodes grass) and *Paspalum dilatatum* (paspalum) are sown to some extent on dry sclerophyll forest soils. In the lower rainfall areas the annual *Lolium rigidum* (Wimmera ryegrass) is commonly sown with subterranean clover and in many areas volunteer introduced species *Hordeum leporinum* (barley grass) and *Serrafalcus mollis* syn. *Bromus mollis* (soft brome) are useful components of pastures in which perennial species have not been sown. These annual cool season species are of value because of their high rates of growth in late autumn and winter. The long awns of barley grass, however, are troublesome to sheep in spring and a major source of vegetable fault in wool. As soils increase in fertility, annual pastures are liable to invasion by introduced species such as capeweed (*Arctotheca calendula*).

Plate 41 Dry sclerophyll forest felled for sowing to pasture, Heytesbury, Victoria (Department of Agriculture, Victoria, photo)

Methods adopted for establishing sown pastures in areas of dry sclerophyll forests and heaths depend on the density of the original vegetation, the topography of the land, and the soil type. Where the original forest still exists, the trees are bulldozed and pushed into windrows and later burnt (Pl. 41). Commonly parts of the forests were ringbarked or felled for timber in the early days of settlement. In such cases, stumps and dead trees where they are dense are either burnt *in situ* or bulldozed into heaps for burning. Where not subject to erosion land is ploughed or surface cultivated and left fallow for a period of at least six months. It is then reworked with disc cultivators, harrowed and sown to pasture. Seeds and fertiliser, and if required, lime, are drilled or broadcast in the autumn. Drilling gives better establishment, particularly on sandy soils.

Much of the forest land is hilly and often too steep and erodible for conventional methods of cultivation. Here, the methods of establishment used are those which disturb the soil as little as possible, and it is common to sow directly into native grasses by a sod-seeder or chisel plough, or on very steep country from the air. Where grazing lands have a good cover of useful temperate short grasses, *Danthonia* spp. and *Stipa* spp., clovers may be sown directly into the community by a chisel seeder, sod-seeder or combine. Chisel or sod-sowing is undertaken during the autumn following the opening rains of the season. It has proved an effective and cheap method of improving these kinds of grazing lands. For this method of establishment to be successful, however, new techniques had to be developed. These included the use of lime, a lime-superphosphate mixture, or lime pelleted seed to ensure effective nodulation and survival of clovers (see Chapter 22).

Sowing from the air necessitates the use of molybdenum with superphosphate and of lime-coated clover seed. A good grass cover helps the establishment of clovers sown on undisturbed ground and for this reason grazing animals are usually excluded for a considerable period before sowing steep hilly land. Establishment is slower and productivity in the early years is lower in comparison with methods involving cultivation and complete destruction of native grasses, but by aerial sowing many thousands of acres of land previously thought unproductive now support productive clover pastures. Although clovers can be established from aerial sowings it is difficult to establish grasses in this way and subterranean clover dominant pastures present problems in animal husbandry. Not only is the risk of clover disease greater (see Chapter 26) but production of herbage is more variable than on pastures containing perennial grasses.

A rise in soil nitrogen levels under clover pastures is accompanied by an ingress of annual and biennial species as barley grass, capeweed, and thistles. The establishment of perennial grasses in such communities is difficult without the aid of contact herbicides such as paraquat and diquat to destroy annual weeds. *Phalaris tuberosa* has been introduced directly into clover pastures with the aid of such chemicals and as a result carrying capacities have been increased markedly. On formerly unproductive hill country in Victoria experimental pastures of subterranean clover and *Phalaris tuberosa* are carrying 4 sheep per acre (10 per ha).

Methods of establishing pastures on heaths differ from those used on dry sclerophyll forest lands. The initial clearing operations are rolling or pulling followed by burning. Heath lands are sandy and deep ploughing is unnecessary. Shallow cultivations are preferred as they ensure that whatever fertility is present is retained at the surface where the pasture seeds will be sown. Ploughing buries the most fertile layer and brings subsurface layers of lower fertility to the surface with consequent poor establishment of pasture. Most heath soils are acid and require lime, either broadcast in amounts of 1 ton of agricultural lime per acre (2509 kg per ha) or drilled with the seed at 2–3 cwt per acre (250–375 kg per ha). Superphosphate, potash, and trace elements are broadcast on the surface.

Phosphorus is the main deficiency of most soils of the southern forests and ordinary superphosphate adequately supplies the needs of pasture plants for both phosphorus and sulphur. However, on sandy soils of the southern and on all soils of the northern forests sulphur deficiency is much greater and a sulphur fortified superphosphate is necessary. A few forest soils contain relatively large amounts of phosphorus, and on these the main mineral requirement of newly sown pastures is sulphur. In such circumstances gypsum or elemental sulphur is used in the early stages of pasture development, although commonly superphosphate is applied as well.

The amount of superphosphate needed in the early stages of development of pastures varies but on most soils is of the order of 2–3 cwt per acre (250–375 kg per ha) in the year of establishment. This is followed by applications at the same rate each autumn for the next three or four years. Large amounts of superphosphate are necessary if pastures on dry sclerophyll forest soils are to become highly productive within a short time of sowing. It is generally considered that about 10–16 cwt per acre (1254–2006 kg per ha) of superphosphate has

Plate 42 Effect of molybdenum on establishment and growth of *Phalaris tuberosa* and *Trifolium subterraneum*, dry sclerophyll forest at Stawell, Victoria (Department of Agriculture, Victoria, photo)

to be applied before annual rates can be reduced.

Molybdenum is a widespread and characteristic deficiency of dry sclerophyll forest soils (Pl. 42). Since first recognised by Anderson and Oertel (1946) in South Australia, molybdenum deficiency has been shown to be widespread throughout Victoria, Tasmania, New South Wales, and in parts of Western Australia. The deficiency is corrected by applying ammonium molybdate or molybdenum oxide at 2–3 oz per acre (140–210 g per ha) and it is usual to apply them in superphosphate. The effect of applying 2 oz per acre (140 g per ha) of molybdenum to acid grey-brown solodic loams typical of the dry sclerophyll forest soils of central Victoria is shown in Table 11 : 5.

The residual value of molybdenum varies according to soil type and rainfall. Usually 2 oz per acre (140 g per ha) of molybdenum is sufficient for 10 years, particularly where the rainfall is less than 20 in. (508 mm) per annum. However, where rainfall is higher, residues are less. Applications may have to be repeated every 6–7 years if the rainfall is of the order of 30 in. (762 mm) per annum.

TABLE 11 : 5 Effects of molybdenum on pasture yields; grey-brown solodic soils of Victoria

Locality	Yields (dm) lb/acre; approx. kg/ha	
	No molybdenum	Molybdenum
Elmhurst	1120	7014
Buangor	963	4883

Copper and zinc deficiencies are common on soils of dry heaths and on the sandy soils of dry sclerophyll forests in Victoria and South Australia. Deficiencies are usually corrected by applying 7 lb of copper sulphate and 7 lb of zinc sulphate per acre (7·8 kg per ha) although higher amounts are sometimes used. A manganese deficiency has been recorded on sandy soils in the south-east of South Australia and on Kangaroo Island.

Potassium is a widespread deficiency of acid sandy soils, and on such soils is required for both establishment and maintenance of sown pastures.

Fertiliser requirements of pastures on acid sands carrying dry sclerophyll forest (*E. baxteri*) and dry heath (*Xanthorrhoea* spp.) are illustrated in Table 11 : 6.

TABLE 11 : 6 Response of subterranean clover pasture to nutrients and lime, grey sandy loam, pH 5·5, Dartmoor, Victoria

Fertiliser treatment lb per acre (approx. kg per ha)	Relative yields of herbage
No fertiliser	0
Superphosphate 224	0
Superphosphate 224 + copper sulphate 7	6
Superphosphate 224 + lime 1120 + copper 7	24
Superphosphate 224 + lime 1120 + copper 7 + zinc 7 + Mo 0·125	48
Superphosphate 224 + lime 1120 + copper 7 + zinc 7 + Mo 0·125 + potash 112	100

Early attempts to establish pastures on dry sclerophyll forest and heath soils by methods successful on more fertile and less acid woodland soils failed, and it was not until the need for molybdenum, lime, and inoculation of seed with rhizobium was recognised that success was achieved (see Chapter 21). Stunted clover seedlings in newly-established pastures are generally indicative of nodulation failure and are common on many strongly acid (pH 5·0) heath soils. Nodulation failures may be due to the absence of rhizobia effective for subterranean clover. This is the case in many of the heath soils of Tasmania and New South Wales, but in Victoria rhizobia that will effectively nodulate subterranean clover are already present in most forest soils. Their presence is usually indicated by cluster and suckling clovers in native grazing lands. In these circumstances nodulation can be increased by creating a soil environment in which rhizobia already present can multiply. It is commonly found that when clovers are sown without inoculation or lime on acid soils, nodulation is confined to a few scattered plants, particularly when sowing is done from the air or by ground equipment with minimum cultivation. Multiplication of rhizobium can be increased by cultivation or by raising the pH of the rhizosphere by drilling small amounts of lime with the seed (Anderson and Moye 1952; Newman 1955, 1966; Paton 1960; and Tiver 1955). Rates of calcium carbonate as low as 56 lb per acre (63 kg per ha) are effective applied in this way. The effect of lime is twofold. It provides an environment favourable for multiplication of rhizobium and improves germination of clover seed sown mixed with acid superphosphate (Pittman 1944).

Experiments on the Southern Tablelands of New South Wales (Anderson and Moye 1952) showed that if molybdenum is not deficient small amounts of lime drilled with the seed were just as effective as heavier amounts broadcast. Results in Victoria and Tasmania have been similar to those in New South Wales and 2–3 cwt per acre (250–375 kg per ha) of lime or lime mixed with superphosphate drilled with the seed have given good results on moderately acid soils (pH 5·5–5·8). The use of lime-pelleted or lime-coated seed has also been satisfactory on such soils. Loneragan *et al.* (1955) showed that if applied to the seed as a coating amounts of lime as low as 5 lb per acre (5·6 kg per ha) promoted satisfactory nodulation. Similar results were obtained by Newman (unpublished) on both shallow acid soils of hilly country and acid sandy soils of dry heaths in western Victoria. Adjustment of the pH of the rhizosphere by sowing lime-coated seed has prevented aggravation of copper and zinc deficiencies following application of large quantities of lime. It was shown that the zinc requirement of pastures on sandy heath soils in western Victoria increases when heavy applications of lime are applied at sowing.

Clovers can be established satisfactorily and productive pastures can be developed on hilly forest soils by aerial sowing or by ground broadcasting lime-coated seeds provided molybdenum is applied with superphosphate. However, on strongly acid sands and sandy loams with pH values below 5·0, applications of lime as high as 1 ton per acre (2509 kg per ha) are necessary. The seed may then be broadcast or drilled with 1–2 cwt per acre (125–250 kg per ha) lime or with premixed lime and superphosphate or basic superphosphate at rates of 3–4 cwt per acre (376–502 kg per ha).

Fertilisers are usually applied in autumn, the commencement of the growing season for pastures in the temperate zone. The aim is to stimulate herbage production in the winter when growth is slow and feed is scarce. The usual practice is to apply 90–224 lb per acre (100–250 kg per ha) of superphosphate annually where the yearly rainfall is 20–25 in. (508–635 mm) and somewhat higher rates in wetter districts.

If potassium is deficient it is applied mixed with superphosphate in the proportion of 3 : 1, or 2 : 1 superphosphate and potash at rates up to 3 cwt per acre (375 kg per ha) annually.

Copper is required both for pasture growth and for animal health, particularly on sandy heath soils. In the higher rainfall districts it is usual to apply copper every 3–4 years, but in lower rainfall areas, less frequent applications suffice.

ANIMAL PRODUCTION

In most of the temperate dry sclerophyll forests pastures commence growth when autumn rains are adequate to germinate clover and to promote growth of perennial grasses. Growth during the winter is slow and often does not exceed 600 lb of dry matter per acre (672 kg per ha). As temperatures increase growth rates increase rapidly and between 70 and 75 per cent of the annual dry matter is produced during 10–12 weeks in the spring. Cessation of pasture growth depends on how soon temperatures become too high and soil moisture too low for continued vegetative growth. Pastures mature in early summer, and except in areas where there are summer rains, no further growth takes place until the following autumn. The pattern of pasture growth means that there is likely to be a feed shortage in the autumn and winter months, a surplus in the spring, and only mature dry herbage, much of it of low nutritive value, in the summer. A shortage may occur also in late summer as the standing dry feed is depleted by consumption and by disintegration.

These periods of feed shortage influence the number of stock carried on farms. Where stocking rates are more than 4 sheep per acre (10 per ha) feed shortages are accentuated and supplementary feeding is necessary. This is usually done by feeding pasture hay conserved on the farm, oats either as grain or as hay grown on the farm, or fodder purchased elsewhere. Stocking at lower rates reduces the need to conserve fodder, but even at sub-optimal stocking rates, hand feeding of stock, particularly ewes and cattle, is necessary in most years. This is usually done by conserving surplus spring feed as hay.

Management varies slightly according to the livestock enterprise. Where wool growing is the main industry animals are usually set stocked for extended periods irrespective of fluctuations in pasture production. Set stocking for intervals determined by the availability of pasture is practised for fat lamb production. Beef cattle are also set stocked but there is some movement of cattle round the farm. On dairy farms the herd is moved frequently from paddock to paddock, not necessarily on a rotational system, but as far as possible to permit maximum intake.

Stock numbers have increased with area under sown pasture and with the amount of superphosphate applied. There has been a rise too in the level of nutrition of animals, particularly of sheep, and this is expressed in greater wool production and in higher lambing percentages.

More than half the properties in the dry sclerophyll forest zone are classified as sheep only, a reflection of the characteristics of the pastures and grazing lands and of the severity of feed shortages. Properties running sheep and cattle together are mostly in New South Wales and Victoria. Size of sheep flocks ranges from 1200 to 10,000, most farms being within the range of 1200 to 4000 sheep. The number of sheep carried per acre on sown pastures is from 2·5 to 5 dry sheep equivalents per acre (6·25–12·5 per ha) and the wool cut per head from 8 to 12 lb (3·6–5·4 kg) depending upon breed and district. In the higher rainfall areas and on the more productive pastures, fat lamb production is an important industry. Pastures are commonly stocked at 3–4 ewes and lambs per acre (7·4–9·8 per ha) and lambing percentages of 110 are not uncommon.

Cattle are generally marketed as young beef, 8–10 months old, weighing 450–500 lb (204–227 kg). Cattle turned off at 15–18 months weigh from 800 to 900 lb (363–408 kg).

In Victoria on the better pastures of the dry sclerophyll forests butter fat production is 150–180 lb per acre (168–202 kg per ha) at carrying capacities of from 1 to 1·5 cows to 2·5 acres (1–1·5 per ha).

IMPEDIMENTS TO ANIMAL PRODUCTION

The main disorders of sheep are internal parasites, chiefly black scour worms (*Trichostronglus* spp.), and external parasites such as blowfly, keds, lice, and itch mites. Common infectious diseases are balanitis, black disease, enterotoxaemia, foot abscess, and footrot.

Metabolic disorders on grass dominant pastures are phalaris staggers, phalaris sudden-death, and ryegrass staggers (see Chapter 26). Pregnancy toxaemia also occurs on sown pastures.

The main diseases of cattle are bloat, contagious abortion (brucellosis), grass tetany, Johne's disease (*Mycobacterium paratuberculosis*), and mastitis.

Weeds are widespread throughout the dry sclerophyll forests but their content in sown pastures is variable and depends on management and seasonal conditions. Pastures heavily grazed during dry periods may subsequently be invaded by thistles and other weeds.

Common weeds of annual pastures in southern forests are capeweed, storksbill (*Erodium botrys*), and crowsfoot (*E. moschatum*). There are several introduced thistles, the commonest being black or spear thistle (*Cirsium vulgare*).

The principal weeds of grazing lands are bracken fern, which is common in many of the original dry sclerophyll forest communities on sandy soils, and the two introduced species, serrated tussock (*Nassella trichotoma*) and St John's wort (*Hypericum perforatum* var. *angustifolium*). The two latter, once weeds of major economic significance, have been largely controlled by sown pastures. St John's wort is widely distributed through the dry sclerophyll forests of north-eastern Victoria and parts of southern and central New South Wales. Ingestion of the plant by stock causes photosensitisation and blistering of unpigmented skin. It was demonstrated by Moore and Cashmore (1942) that St John's wort can be controlled by competition from subterranean clover which is able to shade the weed during the cooler months of the year when St John's wort is in a rosette stage of growth (see Chapter 23).

Serrated tussock, a perennial grass from Argentina, is established in dry sclerophyll forests and woodlands in the Central and Southern Tablelands of New South Wales. It is high in fibre and of little or no grazing value. Its control by chemicals, burning, and the establishment of sown pastures has been demonstrated by Campbell and Annand (1962).

The most widespread and destructive insects of sown pastures are the red-legged earth mite (*Halotydeus destructor*) and the blue oat mite (*Penthaleus major*). Several hatchings of these insects occur during the growing season of clover pastures and severe damage to young clover may occur. Lucerne flea (*Sminthurus viridis*) may also cause damage in some seasons (see Chapter 24).

Damage to both clovers and grasses during the winter and early spring months may result from attacks by the pasture cockchafer.

LAND VALUES

The system of land tenure is mostly freehold. Properties vary from 100 to 10,000 acres (40–4000 ha) depending on the class of land, the rainfall, the proportion of sown pastures to native grazing lands, and the kinds of husbandry practised. A few properties as large as 30,000 acres (12,000 ha) still exist, but these depend wholly on low productive grazing land.

Market prices for land change rapidly but current prices for properties with sown pastures in Victoria are from $100 to $400 per acre ($247–$988 per ha). Heath land in the south-east of South Australia sown to phalaris and subterranean clover is valued at $50–$70 per acre ($124–$173 per ha). Here the average farm size is 1500 acres (607 ha). The lower figures apply to properties in low rainfall districts where wool production is the main farm industry and the higher figure to dairy or mixed farms in the higher rainfall districts.

12

SOUTH-EASTERN TEMPERATE WOODLANDS AND GRASSLANDS

R. MILTON MOORE

DISTRIBUTION

Temperate woodlands extend in a broad continuous belt from approximately 27°S lat. in southern Queensland to the lower south-east of South Australia. There is a narrow strip, too, running north and south of Adelaide and a large area in the south-western corner of Western Australia (see Chapter 14). In Tasmania there are woodlands in the north-east and in the Midlands as far south as 42°S lat. Throughout the woodland zone there are small patches of treeless grassland usually on colder sites or heavier textured soils than those of the adjacent woodlands. The largest of these are in the western districts of Victoria, the Monaro and Liverpool Plains of New South Wales, and the Darling Downs of Queensland (see Chapter 6).

In eastern Australia temperate woodlands lie between shrub woodlands or mallee to the west and dry sclerophyll forests to the east (Map 3). They are interspersed with dry sclerophyll forests which occupy the upper slopes of hills and ridges throughout the woodland zone (Pl. 41).

CLIMATE

Climates vary from Mediterranean in South Australia and the south-west of Western Australia to summer rainfall dominant in northern New South Wales and southern Queensland (see Figs. 1 : 7, 1 : 8) where temperate and subtropical woodlands converge. From southern Queensland temperate woodlands extend southwards to Victoria on both sides of the 20 in. (508 mm) annual isohyet. The annual rainfall range is from approximately 30 to 16 in. (762 to 406 mm) in eastern Australia and from 27 to 14 in. (686 to 356 mm) in the south-west of Western Australia. Climatic data for a number of stations throughout the mesophytic woodland zone of eastern Australia are given in Table 12 : 1.

It will be seen that Canberra (Southern Tablelands) averages roughly 2 in. (51 mm) of rain a month and 48 per cent falls within the six winter months. The proportion of the annual rainfall received in the summer declines southwards and increases northwards. At Adelaide the rainfall from April to September averages 14 in. (356 mm) and 68 per cent of the total. In south-eastern Queensland the rainfall for the same period is approximately 10 in. (254 mm) and the proportion is only 36 per cent of the annual total.

West of about 24 in. (610 mm) in northern New South Wales, 20 in. (508 mm) in southern New South Wales, and north of 19 in. (483 mm) in southern Victoria, the woodlands are drier but changes in seasonal rainfall distribution patterns with latitude are similar to those in the more mesophytic woodlands (see Table 12 : 2).

The 24–27 in. (610–686 mm) in northern New South Wales, the 20 in. (508 mm) in southern New South Wales, and the 19 in. (483 mm) annual isohyets in Victoria roughly divide areas of naturalised annual species of Trifolium and Medicago and are the inland boundaries of sown perennial pasture grasses. They are also the approximate eastern and southern boundaries of the main wheat-growing areas of Victoria and New South Wales. In South Australia where rain is more winter incident the inland limits of subterranean clover and of sown perennial grasses are at the 16 and 18 in. (406 and 457 mm) isohyets respectively.

Winters are moderately cold and radiation frosts are common, particularly on the tablelands of the Great Dividing Range (see Fig. 1 : 3). The lowest minimum (to 1956) recorded at Canberra, A.C.T., is 18·1°F (−7·7°C); at Adelaide, S.A., 32·0°F (0°C); at Hamilton, Vic., 23·0°F (−5°C); at Armidale, N.S.W., 14°F (−10°C), and at Oatlands, Tas., 9°F (−12·8°C).

TABLE 12 : 1 Climatic data for towns in or near temperate woodlands on solodic or solodised solonetzic soils

(rainfall in mm, temperatures in °C, elevation in metres)

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	% rain May–Sept.	Locality	Lat.	Elevation
Mean max. temp.	29·1	29·4	26·8	21·3	17·2	13·8	13·2	14·8	17·7	21·4	25·0	27·8	21·5		Clare, S.A. (Lower North Ranges)	33° 50′	396
Mean min. temp.	13·4	13·7	11·5	8·2	5·9	4·2	3·4	3·8	5·1	7·3	9·9	12·3	8·2				
Mean rainfall	23	29	21	39	73	78	73	84	76	47	32	38	613	62·6			
Mean max. temp.	29·3	29·8	27·4	22·8	19·3	16·0	15·5	16·8	19·3	22·5	25·6	28·1	22·7		Adelaide, S.A. (Adelaide Plains)	34° 56′	43
Mean min. temp.	16·1	16·5	15·0	12·4	10·4	8·1	7·4	7·9	9·0	10·9	13·0	14·9	11·8				
Mean rainfall	19	28	22	37	63	74	63	65	61	39	31	32	534	61·0			
Mean max. temp.	21·4	21·8	19·2	15·8	12·7	10·0	9·5	11·0	13·4	15·8	18·6	20·3	15·8		Oatlands, Tas. (Midlands)	42° 18′	432
Mean min. temp.	8·0	8·3	6·8	4·9	2·9	1·8	1·2	1·9	3·1	4·3	5·7	7·2	4·7				
Mean rainfall	36	42	46	53	46	54	48	47	42	59	51	61	585	40·5			
Mean max. temp.	25·1	25·9	23·4	19·0	15·6	12·8	12·3	13·4	15·5	18·2	20·6	23·3	18·8		Hamilton, Vic. (Western District)	37° 45′	187
Mean min. temp.	10·4	11·3	9·9	7·9	6·2	4·6	4·1	4·7	5·7	6·7	7·9	9·5	7·4				
Mean rainfall	28	37	36	54	67	67	70	78	76	63	51	49	676	53·0			
Mean max. temp.	28·0	27·3	24·4	19·1	15·3	11·3	10·9	12·9	16·3	19·6	23·0	26·5	19·6		Canberra, A.C.T. (Southern Tablelands)	35° 18′	581
Mean min. temp.	13·3	13·3	11·3	7·3	3·8	1·9	1·1	1·9	3·9	6·8	9·6	12·0	7·2				
Mean rainfall	54	54	45	55	43	43	39	50	38	58	50	51	580	36·7			
Mean max. temp.	27·0	26·4	24·0	20·2	16·2	12·9	12·2	14·0	17·6	21·3	24·5	26·3	20·2		Armidale, N.S.W. (Northern Tablelands)	30° 31′	1016
Mean min. temp.	13·6	13·2	11·2	7·5	4·0	1·6	1·0	1·3	3·8	7·3	10·2	12·4	7·3				
Mean rainfall	99	71	57	47	37	59	54	39	53	60	73	87	736	32·9			
Mean max. temp.	30·2	29·3	27·5	24·8	20·8	18·0	17·3	19·2	22·6	26·0	28·6	29·9	24·5		Warwick, Qld (South East)	28° 14′	453
Mean min. temp.	17·1	16·7	15·1	11·2	7·2	4·4	3·3	3·6	6·6	10·7	14·1	15·8	10·5				
Mean rainfall	85	62	54	35	32	43	46	27	38	53	73	88	636	29·3			

Source: Bureau of Meteorology 1956.

TABLE 12 : 2 Climatic data for towns in or near temperate woodlands on red-brown earths, grey and brown cracking clays, or black earths
(rainfall in mm, temperatures in °C, elevation in metres)

	Jan.	Feb.	Mar.	April	May	June	July	Aug.	Sept.	Oct.	Nov.	Dec.	Year	% rain May–Sept.	Locality	Lat.	Elevation
Mean max. temp.	29·0	29·3	26·6	21·1	17·3	13·9	13·4	14·9	19·4	21·4	25·0	27·6	21·6		Kapunda, S.A. (Lower North)	34° 21′	245
Mean min. temp.	14·2	14·7	12·8	10·0	7·9	6·0	5·3	5·8	6·9	8·8	12·9	13·2	9·9				
Mean rainfall	21	24	21	30	53	55	55	66	58	43	33	32	491	58·5			
Mean max. temp.	29·4	30·1	26·8	21·4	17·2	13·7	13·3	15·0	17·8	21·2	25·0	28·1	21·6		Horsham, Vic. (Wimmera)	36° 40′	138
Mean min. temp.	12·9	13·3	11·0	8·3	6·0	4·6	3·8	4·4	5·5	7·3	9·8	11·8	8·2				
Mean rainfall	19	31	19	31	45	50	48	48	50	38	32	35	446	54·0			
Mean max. temp.	30·6	29·6	27·0	21·8	17·8	13·0	12·5	14·9	18·9	22·3	26·3	29·6	22·0		Temora, N.S.W. (South-western Slopes)	34° 27′	292
Mean min. temp.	15·8	15·8	13·4	9·0	5·1	2·8	1·9	2·9	5·0	8·0	11·4	14·3	8·8				
Mean rainfall	50	42	45	36	31	47	37	38	30	45	41	31	473	38·7			
Mean max. temp.	35·0	34·1	31·4	26·4	21·4	17·4	16·7	18·6	22·7	27·1	31·0	33·9	26·3		Gunnedah, N.S.W. (North-western Slopes)	30° 58′	267
Mean min. temp.	18·3	17·5	15·1	10·5	6·2	3·4	2·6	3·4	6·1	9·9	13·9	16·1	10·3				
Mean rainfall	56	49	41	33	30	49	44	35	34	47	50	69	537	35·8			

Source: Bureau of Meteorology 1956.

SOILS

Temperate woodlands are found on five principal great soil groups: podzolic, solodic and solodised solonetz, red-brown earths, black earths, and grey and brown cracking clays (see Chapter 3). Podzolic, solodic and solodised solonetzic soils, mostly described by Stephens (1953) as red and yellow podzolics, occur on rolling landscapes and are common soils of temperate woodlands on the eastern and wetter side of the 20 in. (508 mm) annual rainfall isohyet from central New South Wales to Victoria. There are extensive areas also of solodic and solodised solonetzic soils in Tasmania, New South Wales, and southern Queensland (see Map 2).

Red-brown earths (Prescott 1931) are chiefly on the western and drier side of the 20 in. (508 mm) annual rainfall isohyet. They are leached to a lesser degree than the podzolics and solodics and contain calcium carbonate at least in the lower horizons. Grey and brown cracking clays (the grey and brown soils of heavy texture of Stephens 1953) vary from clay loams to clays, generally contain calcium carbonate in the surface horizons, and are alkaline in reaction. The driest of the temperate woodlands are on these heavy-textured soils which are also widely distributed in the adjacent semi-arid shrub woodlands (see Chapter 16).

Black earths are also heavy in texture and have gilgai micro-relief. There are small areas of black earths in the lower north of South Australia, and larger areas south of Gunnedah, N.S.W., and on the Darling Downs, Queensland. The surface soils are alkaline or slightly acid becoming alkaline with depth.

In the eastern part of the mainland, temperate woodland soils east and south of the 20 in. (508 mm) annual isohyet are generally acid at the surface, those to the west and north tend to be neutral or alkaline.

VEGETATION

It is convenient to consider temperate woodlands in two groups determined by floristic affinities, soils, and rainfall. One group is mostly on acid, solodic and solodised solonetz and to a lesser extent podzolic soils, in areas receiving at least 19 in. (483 mm) of rain annually. The other woodlands are mostly on neutral or alkaline red-brown earths, black earths, and grey and brown cracking clays, and except in northern New South Wales and southern Queensland where they occur in areas receiving up to 27 in. (686 mm), they are mostly on the drier side of the 20 in. (508 mm) annual isohyet.

Woodlands on Solodic, Solodised Solonetz, and Podzolic Soils

In New South Wales the *Eucalyptus melliodora* (yellow box)–*E. blakelyi* (red gum) community (Pryor 1939, 1954) is characteristic of acid solodic and solonetzic soils in areas receiving between 19 and 28 in. (483 and 711 mm) of rain annually (Pl. 43). It occurs extensively on the slopes and tablelands of New South Wales and on the northern side of the Great Dividing Range in Victoria. In southern New South Wales *E. albens* (white box) also grows on acid solodic soils, mostly on the western slopes of the range on slightly drier sites than the yellow box–red gum community. The two communities form ecotones with each other but usually are differentiated sharply from the dry sclerophyll forests of *E. macrorrhyncha* (stringy bark) and *E. rossii* (brittle gum) occupying the upper slopes and tops of hills throughout the eastern woodland zone. In northern New South Wales communities of *E. albens* belong with the drier group of woodlands since they occur there on alkaline black earths.

In northern temperate woodlands, *E. blakelyi* is replaced by a variant or closely related species, *E. tereticornis* (red gum) which is common also in sub-tropical and tropical woodlands (see Chapter 8).

Another red gum, *E. camaldulensis* (river red gum) is a dominant on solodic soils derived from basalts and alluviums, in southern Victoria and the lower south-east of South Australia. Swamp gum (*E. ovata*) and manna gum (*E. viminalis*) are frequent associates of *E. camaldulensis*, the former particularly in wet situations (Pl. 44). Between the 24 and 26 in. (610–660 mm) annual isohyets in Victoria, *E. camaldulensis* and *E. melliodora* form communities with *E. aromaphloia* (apple box) and *E. elaeophora* (long-leaved box) on brown and yellow podzolic soils. On sandy soils *E. melliodora* is frequently associated with *E. leucoxylon* (yellow or blue gum) and in places both species are found with *E. hemiphloia* syn.

Plate 43 Temperate woodland of *Eucalyptus melliodora* (yellow box) and *E. blakelyi* (red gum): Temperate Shortgrass grazing land of *Stipa falcata* and *Danthonia carphoides*, Southern Tablelands, New South Wales (CSIRO photo)

Plate 44 Temperate woodland: partly cleared *Eucalyptus ovata* woodland, Temperate Shortgrass grazing land, western Victoria (Soil Conservation Authority, Victoria, photo)

Plate 45 Temperate woodland of *Eucalyptus hemiphloia* syn. *E. moluccana* (grey box) and *Casuarina luehmannii* (buloke). Mostly cleared (foreground) showing Temperate Shortgrass grazing land on brown clay soil with gilgais, Wimmera district, Victoria (Soil Conservation Authority, Victoria, photo)

E. moluccana (grey box), a species more characteristic of the group of woodlands on heavy-textured soils.

E. leucoxylon is the characteristic species of woodlands between the 20 and 30 in. (508–762 mm) annual isohyets in South Australia. It occurs on solodic soils, podzols, and red-brown earths. It is often the only tree species, but in the vicinity of Mt Lofty and the Flinders Ranges it is associated with either *Acacia pycnantha* (golden wattle) or *Casuarina stricta* (she-oak). *E. leucoxylon* occurs also with *E. viminalis* in sheltered valleys (Specht and Perry 1948), with *E. cladocalyx* (sugar gum) near water courses in the Flinders Ranges and on Kangaroo Island, and with *E. fasciculosa* (pink gum) in the south-east (Crocker 1944).

In southern Victoria and in South Australia where sclerophyll forests of *E. baxteri* (stringy bark) or *E. obliqua* (messmate) abut or intergrade with woodlands, the herbaceous layers of the two communities are often similar.

There is a large area of woodland on light-textured soils within the 20 and 25 in. (508 and 635 mm) annual isohyets in the south-west of Western Australia. The principal tree species are *E. fecunda* var. *loxophleba* (York gum) and *Acacia acuminata* (jam). Other species in the more southerly part of this community are *E. occidentalis* and *E. cornuta* (gimlet). To the west of the York gum-jam woodland there is a community dominated by *E. redunca* var. *elata* (wandoo) that has features of both woodland and dry sclerophyll forest. These communities are described in Chapter 14.

At elevations above 1000 ft (305 m) in eastern Victoria, *E. camphora* (swamp gum) replaces *E. camaldulensis* along water courses and forms woodlands with *E. stellulata* (black sally). The latter also forms sub-alpine woodlands with *E. pauciflora* or *E. niphophila* (snow gums) and *E. rubida* (candle bark) at elevations of 4500 ft (1372 m) in the highlands of eastern New South Wales and Victoria (Pl. 28). On the lower slopes of depressions in which cold air accumulates there are small patches of *E. pauci-*

flora woodland at elevations as low as 1800 ft (550 m) on the tablelands of New South Wales and Victoria. In some places, for example Canberra, the floors of such depressions are treeless.

In the Midlands of Tasmania between Kempton and Launceston (lat. 42°S and 41°S) *E. pauciflora*, *E. ovata*, and *E. salicifolia* are associated in a woodland on solodic soils derived principally from dolerite. Understorey shrubs include *Banksia marginata* and *Acacia dealbata* (silver wattle). Swamp gum occupies the moister and *E. salicifolia* the drier sites. In Tasmania as in the highlands of the eastern mainland *E. pauciflora* is the principal, and often the only tree species on elevated plains, and on the sides and floors of valleys in which cold air accumulates.

Because of their discontinuous tree and continuous herbaceous strata and relative rarity of shrubs, these communities are commonly classified as savannah woodlands, but there is considerable structural variation within the one floristic community. *E. albens*, for example, frequently forms tall woodlands and *E. camaldulensis* often has a forest form particularly along watercourses.

Originally the common species of the herbaceous layers of these woodlands were the tall warm season perennials, *Themeda australis* (kangaroo grass), *Stipa aristiglumis* syn. *S. bigeniculata* (plains grass) or closely related species, and *Poa caespitosa* sens. lat. syn. *P. australis* (tussocky poa). Themeda has a wide distribution in both temperate and tropical Australia (see Chapters 4 and 6) but as the proportion of summer rainfall increases Stipa and Poa are gradually replaced by the sub-tropical grasses, *Dichanthium sericeum* (Queensland bluegrass) and *Bothriochloa* spp., and neither extends much north of the New South Wales-Queensland border.

The true grasslands within the woodland zone differ little in composition from the herbaceous communities of their adjacent woodlands. The largest areas of *Themeda australis-Stipa aristiglumis-Poa caespitosa* sens. lat. grasslands are in western Victoria (Pl. 27) and on the Yass Plains of New South Wales, but there are many small patches in cold air basins and plateaux throughout the eastern tablelands. In similar sites at elevations above 4500 ft (1372 m) the grasslands are sub-alpine and the principal species are *Poa caespitosa* sens. lat. (snow grass) and *Danthonia nudiflora* (see Chapters 4 and 6).

Woodlands on Red-brown Earths, Black Earths, and Grey and Brown Clays

On the drier side of the 19 in. (483 mm) annual isohyet in the south and the 27 in. (686 mm) in the north, the most common temperate woodlands are those dominated by grey box. There are three variants or closely related species, *Eucalyptus hemiphloia* syn. *E. moluccana*, *E. microcarpa*, and *E. woollsiana*, all known as grey boxes. *E. hemiphloia* rather than the taxonomically correct *E. moluccana* is used in descriptions of communities in Victoria and New South Wales because *E. moluccana* does not appear to be generally used in these States. The soils characteristic of grey box woodlands are red-brown earths, black earths, and grey cracking clays (see Chapter 3). Near Horsham (17·5 in., 445 mm annual rainfall) in the Wimmera region of Victoria there are woodlands of *Casuarina luehmannii* (buloke) on flat plains of grey clay soils. There are large areas, too, in which buloke is associated with *E. hemiphloia* on brown cracking clays (Pl. 45). On solonetzic and solodic soils with gilgais (see Chapter 3) both species are associated with *E. leucoxylon* and *E. camaldulensis*.

Further north in Victoria, woodlands of *E. hemiphloia* occur on red-brown earths and extend through central and northern Victoria into New South Wales. Woodlands of *E. woollsiana* have been described by C. W. E. Moore (1953a and b) in southern New South Wales and in the north-west of that State by Biddiscombe (1963). Trees may be 70 ft (21 m) high and their crowns may form a more or less continuous stratum. These communities have been classified as tall woodlands (Beadle 1948). *E. woollsiana* is commonly associated with *Callitris columellaris* syn. *C. glauca*, *C. hugelii* (cypress pine) on sandy soils, *Angophora floribunda* syn. *A. intermedia* on gravelly soils, *Casuarina cristata* (belah) on brown calcareous clays, and with *E. conica* (fuzzy box) on alluvial soils. *Casuarina luehmannii* is found with *E. woollsiana* in most communities except those with *Casuarina cristata*. *E. woollsiana* is largely replaced by a related species, *E. pilligaensis* (narrow-leaved box), at latitude 30°S in a tall woodland community of similar structure.

Shrubs and low trees are common in grey box woodlands and the species include several, *Heterodendrum oleifolium* (rosewood), *Geijera parviflora* (wilga), *Acacia deanei* (black wattle), and *Eremophila mitchellii* (sandalwood), characteristic of the *E. populnea* shrub woodlands with which *E. woollsiana* woodlands merge to the west (see Chapter 16). A small edible tree, *Brachychiton populneum* (kurrajong), is present in both woodlands.

E. microcarpa has been recorded with *E. hemiphloia* and *E. woollsiana* but there is some uncertainty about the field identification of these three species.

Grey box extends into southern Queensland and *E. hemiphloia* grows in association with *E. melliodora* and *E. albens* on shallow, so-called trap-rock soils (lithosols and shallow solodics).

The counterparts of grey box communities in South Australia are the *E. odorata* (peppermint gum) woodlands on red-brown earths described on the lower foothills of the Mt Lofty ranges and along the coast of St Vincent Gulf by Wood (1937), and on Eyre Peninsula by Crocker (1946 a). The only native shrubs common in *E. odorata* woodlands are *Acacia pycnantha* and *A. armata*, but where tree numbers have been reduced the woodlands have been colonised by the European olive (*Olea europaea*) and by a South African composite, *Osteospermum moniliforum* (Wood 1937). In its wetter phase the *E. odorata* community intergrades with *E. leucoxylon* and in its drier, north of latitude 34°S, with mallee. The driest woodlands in South Australia are those in which *Casuarina stricta* is a principal species. This community has affinities with the *C. luehmannii* woodlands of the Victorian Wimmera and has tree and shrub species, e.g. *Callitris columellaris* and *Pittosporum phillyreoides* in common with semi-arid shrub woodlands (see Chapter 16). The most mesophytic of the South Australian woodlands on red-brown earths is the *E. leucoxylon-E. calcicultrix* community described by Specht (1951) in the lower south-east.

With the exception that *Themeda avenacea* was seemingly a dominant on black earths and grey and brown cracking clays, the original species of the herbaceous layers of southern grey box and *E. odorata* woodlands were similar to those of the more mesophytic woodlands to the east (Tables 12 : 3, 12 : 4). As on solodic and solodised solonetz soils, tropical and subtropical species become more common on heavy-textured soils towards the northern limits of the temperate woodlands.

Dry temperate woodlands in Western Australia are represented by a tall woodland of *E. salmonophloia* (salmon gum) and *E. salubris* (gimlet) (see Chapter 14).

There are patches of true grassland on black earths and grey and brown clay soils throughout the temperate woodlands. The most extensive of these are in the Wimmera district of Victoria, the Liverpool Plains of New South Wales, and the Darling Downs of Queensland. Other treeless grasslands of this type occur on the Monaro Plains of New South Wales (see Chapters 4 and 6).

THE AGRICULTURAL INDUSTRIES

Most of Australia's 167 million sheep are run on the pastures and shortgrass grazing lands of temperate woodlands (see Fig. 6 : 1). For example, about 50 million of the 71 million sheep in New South Wales are in the temperate woodland zone. Most of the sheep are Merino but in the higher rainfall woodlands of Tasmania and Victoria, Polwarth and Corriedale are also common. Fine Merino wool is produced mainly in Tasmania and on the tablelands of New South Wales.

The production of prime lamb is also a major industry in the temperate woodland zone, particularly in the cereal growing areas. Commonly Merino ewes are mated to British breeds such as Border Leicester to produce first cross lambs or the ewes from this cross are mated to Dorset Horn rams for the production of faster growing second cross lambs.

Most holdings have some cattle (see Fig. 6 : 2), commonly Hereford or Aberdeen Angus, and although proportionately cattle numbers are small compared with sheep they have increased in recent years as a result of a rise in beef prices and a decline in wool values.

The main wheat growing areas of New South Wales and of north-central and southern Victoria were formerly grey box woodlands. Cereal growing is also a major enterprise in the temperate woodlands of the lower north of South Australia and on the black earths of north-western New South Wales and the Darling

Downs of Queensland. Because of the high proportion of annual rainfall received in summer the Darling Downs produces maize, grain sorghum, sunflower, cotton, and millet as well as winter-growing cereals, safflower, and linseed.

Most wheat farms run sheep for wool, mutton, and fat lamb production and nearly all fatten cattle as well. Pigs, poultry, and dairying are sideline activities on small farms particularly those near centres of high population.

Except on the Darling Downs and on irrigation areas (see Chapter 18) dairying is not a major industry in the woodland zone.

Cotton, maize, and sorghum are grown on the irrigation area of the north-western slopes of New South Wales and rice is an important crop in the Riverina irrigation districts of the southern part of that State.

There are important wine-producing areas in former temperate woodlands and apple and pear orchards are common on dry sclerophyll forests adjacent to woodlands.

THE GRAZING LANDS

Woodlands on Solodic, Solodised Solonetz, and Podzolic Soils

The Australian pastoral industry began when access was obtained to the temperate woodlands across the Great Dividing Range in New South Wales. Because of the wide spacing of the trees and the high proportion of grass it was possible to stock many of the woodlands without felling or ring-barking trees.

Most of present-day grazing lands of temperate woodlands are disclimax communities in which the predominant grasses are short cool season species of Danthonia and Stipa (Pls. 43, 44, 45). They are classified now as Temperate Shortgrass grazing lands, but before European settlement the dominants were tall warm season perennial tussock grasses (Table 12 : 3, Chapter 6).

Changes in botanical composition from continued grazing are shown in Table 12 : 3. The data are from a *Eucalyptus melliodora-E. blakelyi* woodland in New South Wales but they are representative also of changes resulting from grazing *E. camaldulensis* woodlands and *E. leucoxylon* woodlands in Victoria and South Australia. The principal difference is the lesser frequency of short summer-growing grasses in disclimax woodlands in the south because of the more predominantly winter rainfall. The opposite is true in southern Queensland and northern New South Wales where most of the rain is in the summer months. Here, the ratio of warm season to cool season perennials in disclimax grazing lands is higher and in the trap-rock and granite areas of southern Queensland the principal grasses are *Bothriochloa decipiens* (pitted bluegrass), *Dichanthium sericeum* (Queensland bluegrass), *Sporobolus elongatus* (rat-tail grass), *Themeda australis*, and species of Stipa, Chloris, Aristida, and Eragrostis.

Further south on the New England Tablelands, N.S.W., where 60 per cent of the annual rain falls between October and March (Table 12 : 1), the cool season perennial, *Danthonia caespitosa* (ringed wallaby grass), is more common but the other grasses are still mainly the warm season species, *Themeda australis, Enneapogon nigricans, Panicum effusum,* and *Eragrostis trachycarpa*. Themeda withstands grazing better in summer rainfall areas than it does further south. It is favoured too, by the local practice of burning grazing lands to remove the dry debris of warm season species before growth commences in spring.

A warm season perennial, *Bothriochloa macera* syn. *B. ambigua* (red grass), a native species closely related to *B. decipiens* (pitted bluegrass), frequently becomes dominant in woodlands from northern to central New South Wales. According to C. W. E. Moore (1953b, 1957) red grass in the more southern parts of its range tends to invade areas from which surface soil has eroded following the death of other more palatable perennial grasses through heavy grazing. Grazing lands of red grass are of low productivity.

Table 12 : 3, in effect, illustrates stages in the evolutionary development of so-called 'improved pastures' in a region of uniformly distributed rainfall. By altering the composition from predominantly tall warm season to predominantly short cool season perennial grasses, sheep themselves were responsible for the initial improvement. This modification in turn enabled accidentally introduced cool season legumes and grasses, fruits and seeds of which were distributed by sheep, to establish and so raise nutritive values and carrying capacities still further.

Before the introduction of domestic livestock

TABLE 12 : 3 Species changes resulting from grazing in herbaceous communities of *Eucalyptus melliodora-E. blakelyi* woodlands. Species with presence values greater than 50 per cent (R. M. Moore 1967a)

SOILS: Solodised solonetz. pH 5·9 (1 : 5 suspension).
RAINFALL: 23 in. (584 mm) per annum—distribution uniform.
LOCALITY: Southern Tablelands, N.S.W.
ALTITUDE: 610 m above sea level.

Themeda australis-Stipa aristiglumis-Poa caespitosa sens. lat.
(Tall warm-season perennial tussock grasses)
GRAZING
↓
Stipa aristiglumis-Poa caespitosa sens. lat.-*Stipa falcata*
↓
Stipa falcata-Danthonia carphoides-Danthonia auriculata
(Short cool-season perennial grasses)
↓
Danthonia carphoides-Danthonia auriculata
(Short cool-season perennials)
|
↘ Native species from more arid communities ↘
Enneapogon nigricans, *Chloris truncata*, *Tripogon loliiformis*, *Panicum effusum*, *Vittadinia triloba*, *Euphorbia drummondii*, *Convolvulus erubescens*
(Short warm-season species)
GRAZING
↓
Danthonia carphoides-Danthonia auriculata
|
↘ Mediterranean annuals ↘
Trifolium glomeratum, *Vulpia bromoides*, *Bromus* spp., *Hordeum leporinum*, *Composites*, *Erodium cicutarium*, *Aira caryophyllea*
(Exotic cool-season annuals)
|
Enneapogon nigricans, *Chloris truncata*, *Panicum effusum*, *Vittadinia triloba*, *Eragrostis brownii*
(Short warm-season perennials)

GRAZING AND SUPERPHOSPHATE
↓
Vulpia bromoides, *Bromus rigidus*, *Erodium cicutarium*, *Trifolium glomeratum*, *Cirsium vulgare*
(Exotic cool-season annuals)
|
Chloris truncata, *Eragrostis cilianensis*, *Chenopodium carinatum*, *Polygonum aviculare*
(Warm-season species)

temperate woodlands had few herbaceous legumes and those present, mainly species of Glycine, Desmodium, and Zornia, responded poorly to superphosphate (Begg 1963). In contrast the widely distributed introduced clovers, *Trifolium glomeratum* (cluster or ball clover), *T. dubium* (suckling clover), *T. campestre* (hop clover), and *T. tomentosum* (woolly clover) responded markedly to superphosphate and provided the impetus to a more positive approach to the improvement of grazing lands. In the 1930s it became common practice to apply superphosphate to grazing lands in which thes clovers were present, and even though initiall the amounts applied were small and sub-optima increases were obtained in levels of dry matte and protein available to sheep in winter. In th red gum woodlands of South Australia, fo example, superphosphate applied annually a 224 lb per acre (251 kg per ha) for four year increased the proportion of volunteer *Trifoliu* spp. from 8 to 70 per cent. Better pasture production in winter enabled annual carrying capacities to be raised 25–50 per cent.

The biggest advance in animal production in temperate woodlands followed recognition of the higher production potential of one of these volunteer' clovers, the self-regenerating species, *Trifolium subterraneum* (see Chapter 20). Initially seed of this species was mixed with superphosphate and broadcast on undisturbed or lightly cultivated grazing lands of the higher rainfall temperate woodlands on acid podzolic, solodised solonetz, and solodic soils. With continued applications of superphosphate the density and productivity of subterranean clover increased, soil nitrogen levels were raised, and Danthonia and other native perennials were replaced by Mediterranean annual grasses and forbs (R. M. Moore 1959, 1962, 1966, 1967a, 1967b).

In northern temperate woodlands where there were fewer volunteer clovers, improvement of grazing lands was slower. Another factor that delayed improvement was the poor response of grazing lands on basaltic soils to the low levels of superphosphate initially applied. These soils were subsequently discovered to be sulphur rather than phosphorus deficient and required the equivalent of 3–6 cwt per acre (376–752 kg per ha) of superphosphate to supply their sulphur requirements.

In the more mesophytic woodlands of *E. pauciflora* and *E. salicifolia* in Tasmania, and in the colder and wetter montane and sub-alpine woodlands of the highlands of the south-eastern mainland, the proportion of *Poa caespitosa* sens. lat. is higher than in *E. melliodora-E. blakelyi* woodlands. Poa species are dominant, too, in treeless grasslands associated with these woodlands but because they have been burned more frequently the grasslands often have higher proportions of *Themeda australis*. Introduced species such as *Poa pratensis* (Kentucky bluegrass), *Rumex acetosella* (sorrel), and *Trifolium repens* (white clover) are common on disturbed sites.

Woodlands on Red-brown Earths, Black Earths, and Grey and Brown Clays

The grazing lands of the drier grey box and peppermint box woodlands on red-brown earths were originally similar in composition to those on podzolic, solodised solonetz, and solodic soils but the proportions of the species probably differed and total densities and basal areas were almost certainly lower.

Changes in herbaceous components as a result of grazing a *E. woollsiana* woodland are shown in Table 12 : 4. In contrast to the higher rainfall woodlands *Stipa falcata* is more common than *Danthonia* spp. in the disclimax herbaceous community of the *E. woollsiana* woodland. The common form of *Stipa falcata* here is more robust than in the higher rainfall areas and it appears to increase in size as rainfall decreases. The uncertainty of the taxonomic position of *S. falcata* has been noted in Chapter 6.

The disclimax communities of the grey box-peppermint box woodlands differ from those of the more mesophytic red gum-yellow gum woodland complex principally in having higher densities of Medicago and of *Hordeum leporinum*, and lower densities of Trifolium, Bromus, and Aira. Also, the change from warm-season perennials to cool-season annuals in grey box and peppermint box woodlands takes place rapidly even if superphosphate is not applied.

O. B. Williams (1956) described the disclimax grazing lands of a *Eucalyptus woollsiana-Callitris glauca* syn. *C. columellaris* community on a sandy loam soil (pH 6·7) near Deniliquin, N.S.W. (annual rainfall 15·7 in., 399 mm). The dominant grass was *Stipa falcata* which had a specific frequency of 100 and a basal area of 1·3 per cent. The total basal area of perennial species was 1·6 per cent so that Stipa contributed 82 per cent of the basal area of perennials.

At their drier limits where the grazing lands of the grey box woodlands intergrade with those of the semi-arid shrub woodlands or with mallee, chenopodiaceous shrubs belonging to the genera Kochia, Atriplex, and Bassia become more common.

The effects of grazing *Eucalyptus odorata* woodlands are similar to those in *E. woollsiana* woodlands and except for fewer short warm-season perennials the resulting disclimax communities are composed of the same or closely related species.

Progressive changes in grazed *E. hemiphloia-Casuarina luehmannii* woodlands on grey and brown clays are shown in Table 12 : 5. *Danthonia caespitosa* is frequently a dominant in southern disclimax grazing lands on heavy-textured soils. In northern woodlands and grasslands the dominants are usually *Stipa aristi-*

TABLE 12 : 4 Changes resulting from grazing in herbaceous communities of *Eucalyptus woollsïana* woodlands. Species with presence values greater than 50 per cent (R. M. Moore 1967a)

SOILS: Red-brown earths. pH 6·9 (1 : 5 suspension).
RAINFALL: 20 in. (508 mm) per annum—distribution uniform.
LOCALITY: South-western Slopes, N.S.W.
ALTITUDE: 292 m above sea level.

Themeda australis-Stipa aristiglumis-Poa caespitosa sens. lat.
(Tall warm-season perennials)
GRAZING
↓
Stipa aristiglumis-Poa caespitosa sens. lat.-*Stipa falcata*
↓
Stipa falcata-Danthonia caespitosa
(Midgrasses, cool-season)
↓
Stipa falcata
↓
Enneapogon nigricans, Chloris truncata, Sida corrugata, Wahlenbergia gracilis, Vittadinia triloba, Euphorbia drummondii, Convolvulus erubescens, Helichrysum apiculatum
(Short warm-season perennials)
|
Mediterranean annuals ↘ *Hordeum leporinum, Medicago minima, M. polymorpha, Trifolium glomeratum, Vulpia bromoides, Aira caryophyllea, Moenchia erecta, Carthamus lanatus, Arctotheca calendula, Erodium cygnorum*
(Mainly exotic cool-season annuals)

GRAZING
↓
Hordeum leporinum, Medicago minima, M. polymorpha, Erodium cygnorum, Vulpia bromoides, Carthamus lanatus, Aira caryophyllea, Salvia verbenacea, Arctotheca calendula
(Mainly exotic cool-season annuals)
|
Chloris truncata, Enneapogon nigricans, Wahlenbergia gracilis, Sida corrugata
(Warm-season perennials)
|
Euphorbia drummondii, Eragrostis cilianensis, Xanthium spinosum
(Warm-season annuals)

glumis and *Danthonia linkii.* The cool season annuals in these communities are principally *Medicago* spp. (burr medics) and *Hordeum leporinum* (barley grass). These species are also characteristic of the drier parts of *E. woollsiana, E. albens, E. odorata* temperate woodlands and the wetter parts of the *E. populnea* and *Acacia pendula* shrub woodlands (see Map 5).

In southern Queensland Stipa and Danthonia are largely replaced by *Dichanthium sericeum* and *Bothriochloa decipiens* and warm season annuals replace some of the cool season annuals, for example *Dactyloctenium radulans* (button grass), *Tragus australianus* (small burr grass), *Boerhaavia repens* (tar vine) increase, and *Hordeum leporinum* and, to a lesser extent, burr medics decrease.

THE PASTURES

Mediterranean Annual Pastures

The pastures that develop on grazing lands sown to subterranean clover and regularly given superphosphate are composed almost invariably of volunteer species of Bromus, Vulpia, Erodium, and one or more composites as well as the sown clover (see Table 12 : 3, Pl. 32).

On most of the acid and neutral soils of temperate woodlands the addition of phosphorus and/or sulphur in superphosphate has been sufficient to meet the nutrient requirements of subterranean clover (see Fig. 21 : 3 and Table 21: 7). Phosphorus is the main deficiency except for some basaltic soils which are sulphur rather than phosphorus deficient. Molybdenum

TABLE 12 : 5 Changes resulting from grazing in herbaceous communities of *Eucalyptus hemiphloia-Casuarina luehmannii* woodlands. Species (Themeda excepted)[a] with presence values greater than 40 per cent (data R. M. Moore).

SOILS: Grey and brown cracking clays. pH 8·1.
RAINFALL: 18 in. (457 mm) per annum—predominantly winter.
LOCALITY: Wimmera, Vic.
ALTITUDE: 138 m above sea level.

Stipa aristiglumis—(Themeda avenacea?)
(Tall warm-season perennials)

GRAZING
↓
Stipa aristiglumis-Danthonia caespitosa
↓
Stipa falcata-Danthonia carphoides,
(Short cool-season perennials)
|
Medicago minima, M. polymorpha,
Erodium cygnorum, Crassula sieberiana
(Cool-season annuals)
↓
Medicago minima, M. polymorpha,
Hordeum leporinum, Lolium rigidum,
Erodium cygnorum, Carthamus lanatus,
Euphorbia drummondii, Lamium amplexicaule,
Vulpia bromoides, Scleropoa rigida,
Crassula sieberiana
(Cool-season annuals mainly exotic)

[a] *Themeda avenacea* was present in stands completely protected from grazing but these were few in number

too, may be deficient in some temperate woodlands, particularly in ecotones with dry sclerophyll forests (see Chapters 11 and 21).

In the first few years following application of superphosphate, clover may be dominant in annual pastures. Stock grazing clover-dominant pastures, particularly the cultivars Yarloop and Dwalganup which are high in oestrogens, may be affected by 'clover disease' and lambing percentages may fall to 30 per cent or less (see Chapter 26). The naturalised annual grass, *Lolium rigidum* (Wimmera ryegrass), is frequently sown with subterranean clover, but except on self-mulching soils the grass often regenerates poorly. The dependence of a balanced grass-clover pasture on high levels of both phosphorus and nitrogen in the soil has been demonstrated by Willoughby (1954). In practice grass dominance is achieved by applying high amounts of superphosphate in the early years of a pasture. Nitrogen is obtained from fixation by clovers and where volunteer species of Trifolium are established it is not usually necessary to inoculate clover seed with Rhizobium before sowing. Subterranean clover contributes from 50 to 90 lb nitrogen per acre (56–100 kg per ha) per cwt (125 kg) of superphosphate applied and fertiliser nitrogen is not commonly applied to either annual or perennial pastures in the temperate woodlands of Australia (see Chapter 21).

Annual applications of superphosphate are generally considered necessary for the maintenance of winter production by annual pastures. Continued applications increase organic matter levels in soils and in Mediterranean environments annual pastures may function similarly to crop-fallow systems in which high levels of nitrogen accumulate in autumn as a result of mineralisation during the dry summer. At levels of soil nitrate nitrogen above 25–40 ppm in the surface 10 cm, clover pastures may be invaded by the nitrophilous weeds, *Carduus pycnocephalus*, *C. tenuiflorus*, and *Onopordum acanthium* (Moore 1967b). The effect of these species on animal production is uncertain but at high densities there is some evidence that they may reduce the growth of clover by shading, prevent livestock from gaining access to some of the pasture, and occasionally may be responsible for nitrate poisoning. The control of thistles by perennial grasses is discussed in Chapter 23.

Annual pastures are still the most common sown pastures even in the higher rainfall woodlands capable of growing perennial grasses. Establishment is relatively cheap and large areas can be sown rapidly and without large investments in machinery.

Below annual rainfalls of about 18 in. (457 mm) in South Australia, 19–22 in. (483–559 mm) in Victoria and southern New South Wales, and 24–27 in. (610–686 mm) in northern New South Wales, temperate perennials other than lucerne usually cannot be grown, and except for small areas of xerophytic tropical grasses at the northern limits of the temperate woodlands, the pastures of low rainfall woodlands are mainly annual (see Map 5).

Subterranean clover is the principal legume on soils that are acid in reaction and it is sown extensively in ley pastures on red-brown earths, solodised solonetz, and solodic soils in the higher rainfall parts of the wheat-growing areas of New South Wales, Victoria, and South Australia. It is commonly sown at 1–2 lb per acre (1–2·2 kg per ha) with the last wheat crop before pasture. In central and south-western New South Wales subterranean clover is used in this way to control skeleton weed (*Chondrilla juncea*), a deep-rooted summer-flowering perennial weed of wheat (Moore and Robertson 1964). The common cultivars of subterranean clover sown at the drier parts of its range are the early maturing Geraldton, Dwalganup, Yarloop, and Woogenellup (see Chapter 20).

Subterranean clover is replaced on the neutral and alkaline soils of the grey box and peppermint box woodlands by volunteer burr medics (*Medicago polymorpha* syn. *M. hispida* var. *denticulata*), *M. minima*, and *M. laciniata*, or by the sown cultivars, Jemalong and Cyprus, of barrel medic (*M. truncatula* syn. *M. tribuloides*). Other sown medics are paragosa medic (*M. rugosa*), adapted particularly to alkaline clay soils, and snail medic (*M. scutellata*), commonly drilled with the last crop of wheat before pasture on the black earths of South Australia and the Darling Downs, Queensland. Sown species are spineless or have straight spines and unlike most of the naturalised burr medics do not adhere to wool and so reduce its market value. Medics are sown between 18 and 10 in. (457 and 254 mm) annual rainfalls in South Australia and between 27 and 22 in. (686 and 559 mm) in northern New South Wales and southern Queensland. They are naturalised in southern and south-eastern Australia well beyond the lowest rainfall limits to which they are sown (see Map 5). Barley grass (*Hordeum leporinum*), storksbill (*Erodium cygnorum*), and introduced composites commonly volunteer in communities of annual medics (see Tables 12 : 4 and 12 : 5).

The dividing line between annual Trifolium and Medicago appears to be determined by rainfall, length of growing season, pH, and other soil factors (see Map 5). Reduced availability of nutrients such as zinc on alkaline soils may be involved, because the subterranean clover cultivar Clare which tolerates low zinc levels can be grown on soils in which other cultivars fail.

Zinc deficiencies have been recorded on a number of alkaline and neutral soils including red-brown earths and black earths in South Australia and on grey and brown clays in the Victorian Wimmera (see Fig. 21 : 3c).

Except in rotation with wheat crops, medic pastures are grown without superphosphate or other fertilisers despite the fact that most of the red-brown earths and grey and brown clays are phosphorus deficient.

The effects of nitrogen and phosphorus singly and in combination on the composition of a cool season annual pasture containing species of Medicago were determined by Myers and Moore (1952). Plots which had received nitrogen alone for more than twenty years were dominated by capeweed (*Arctotheca calendula* syn. *Cryptostemma calendula*). The plots receiving phosphorus alone contained mainly annual medics, and those receiving both nitrogen and phosphorus were annual grass dominant. The treatments were applied between rows of citrus trees and the failure of the phosphorus treated plots to change from medic to grass dominance was thought to be due to utilisation of legume-fixed nitrogen by adjacent trees. The fertiliser effects are seemingly in agreement with those obtained by Willoughby (1954) on annual pastures of subterranean clover.

Volunteer pastures of medics and barley grass contain varying proportions of native pioneer species, depending upon the degree of disturbance to which they have been subjected. Common weeds are saffron thistle (*Carthamus lanatus*), Bathurst burr (*Xanthium spinosum*), capeweed, and heliotrope (*Heliotropium europaeum*) (Pl. 48).

The ecology of Mediterranean annual pastures has been reviewed by Rossiter (1966b).

Temperate Perennial Grass-Annual Legume Pastures

Perennial grass pastures besides controlling weeds are considered to be more productive in dry periods than annual pastures, but where germinating rains in the autumn have a high reliability, there may be little or no difference in productivity (Neal-Smith 1942). In dry autumns germination is delayed, and the productivity of annual pastures is reduced below that of perennial pastures which usually produce shoots even in the absence of rain.

Australian commercial phalaris (*Phalaris

Plate 46 Temperate perennial grass—annual legume pasture (*Phalaris tuberosa—Trifolium subterraneum*) on former temperate woodland, northern Victoria (Department of Agriculture, Victoria, photo)

tuberosa) is the outstanding perennial grass for eastern temperate woodland pastures (Pl. 46). Above 25 in. (635 mm) of rain annually it is commonly replaced by perennial ryegrass, and below 18 in. (457 mm) in the south and about 24 in. (610 mm) in the north it gives way to annuals (see Map 5). Phalaris will withstand heavy grazing pressures and once established will survive prolonged droughts.

Although of Mediterranean origin, the cultivar Australian is more persistent under grazing in the woodlands of eastern Australia receiving rain in both winter and summer than in the woodlands of south-western Western Australia where the summers are hot and dry and the climates more typically Mediterranean. The reduction of the root system of phalaris by sustained grazing may reduce its capacity to survive hot dry summers in soils in which root penetration is restricted (Moore 1967b). Commonly pastures in woodlands with Mediterranean climates are annual, while those in areas receiving a relatively high proportion of summer rain are potentially perennial.

Phalaris may be difficult to establish where soil nitrogen levels have been raised by subterranean clover. The mineralisation of nitrogen following cultivation stimulates the growth of rapidly growing cool season annuals which compete with autumn sown phalaris. The advantages of spring sowing to escape competition by annuals have been demonstrated by Hutchings (1967). Spring sown plants were ready for grazing six months after sowing and by late winter were able to be grazed continuously at 4 sheep per acre (10 per ha). Floral initiation was stimulated in autumn sown plants exposed to low winter temperatures. Flowering reduced tillering and increased summer dormancy.

Phalaris is usually sown on a well-prepared seed bed at 2 to 4 lb per acre (2–4·5 kg per ha) and unless seed is already present in the soil, 2–3 lb per acre (2–3 kg per ha) of subterranean clover is invariably sown also. Commonly grass-clover mixtures are sown with 1–2 cwt per acre (125–251 kg per ha) superphosphate and it is usual to top-dress annually with superphosphate. Molybdenum, if deficient, is applied at 1–2 oz per acre (70–140 g per ha) with the initial application of superphosphate. Mineral nutrition of phalaris pastures is discussed more fully in Chapter 21.

Established pastures of *Phalaris tuberosa* and subterranean clover are remarkably free of weeds, but as soil nitrogen levels increase invasion by thistles, Cirsium, Carduus, Onopordum, and by *Hordeum leporinum*, may occur subsequent to heavy stocking or a dry period.

In the Midlands of Tasmania where summers are cool and evaporation low and in parts of New England and western Victoria where the rainfall is high in comparison with the rest of the woodland zone, perennial ryegrass (*Lolium perenne*) is a common companion species of subterranean clover (Map 5).

White clover may replace subterranean clover wholly or in part in environments such as the New England where the annual rainfall is more than 30 in. (762 mm) and more than 60 per cent falls in the summer. The cultivar of subterranean clover sown in such environments is the late maturing Tallarook.

Pastures of perennial ryegrass are frequently cut for hay in Tasmania and Victoria and as a result some have become potassium deficient (see Fig. 21 : 3a). Frequently-mown pastures are commonly invaded by the weedy grasses, Yorkshire fog (*Holcus lanatus*) and sweet vernal (*Anthoxanthum odoratum*).

In areas of northern New South Wales and southern Queensland receiving less than about 25 in. (635 mm) the most commonly sown perennial is lucerne, but *Sorghum almum* and buffel grass (*Cenchrus ciliaris*) are sown to some extent on black earths and grey and brown cracking clays.

ANIMAL PRODUCTION ON GRAZING LANDS

It is difficult to estimate the carrying capacity of the original *Themeda australis-Stipa aristiglumis-Poa caespitosa* sens. lat. communities because of their instability under grazing. In winter Themeda is dry and low in both protein and digestible carbohydrates and it is difficult to breed sheep on grazing lands in which this species is dominant.

Although invaded by short warm season species from more arid communities and by introduced cool season annuals, the disclimax community of cool season perennials, *Stipa falcata*, *Danthonia carphoides*, and *D. auriculata*, is relatively stable under grazing. It was the ability of these communities to withstand grazing that gave south-eastern temperate woodlands their early pre-eminence for Merino wool production.

The year-long carrying capacity of cool season Stipa-Danthonia communities in southern areas is 1 to 1·5 ewes per acre (2·5–3·7 per ha). In addition to providing a higher level of nutrition for most of the year the shorter and more open Stipa-Danthonia community furnishes less cover than Themeda for the larva of internal parasites. Carrying capacities are less in northern temperate woodlands where 80–95 per cent of the grasses are warm season perennials and there is an acute shortage of green feed and crude protein in winter.

The limitations of grazing lands of warm season species for animal production were revealed in a study by Roe, Southcott, and Turner (1959) at Armidale, N.S.W. The treatments imposed were continuous grazing at 1 sheep to 1·25 acres (0·5 ha), 1 sheep to 0·75 acres (0·3 ha), 1 sheep to 1 acre (0·4 ha), and rotational grazing of four sub-plots one week on and three weeks off at a rate of 1 sheep per acre (0·4 ha). Half the sheep on each treatment received regular dosages of phenothiazine for control of internal parasites. Continuous and rotational grazing had similar effects on wool production, pasture production, botanical composition, and worm infestation (see Chapter 27). Wool production per unit area of land was highest at the heaviest stocking rate. The amount of green feed available fluctuated seasonally and was the determining factor in sheep liveweight changes and in the diameter of wool fibres. Green feed was most deficient in the winter when it fell to as low as 10 per cent of the total amount of feed available to the animals. As a result worm burdens were high and sheep drenched with phenothiazine gained more weight from November to August and produced significantly more wool than control sheep.

Department of Agriculture experiments on granite soils at Shannon Vale in New England showed that at stocking rates of 1 sheep per acre (0·4 ha) deaths among sheep on grazing lands during winter were high and it was impossible to breed sheep (Cotsell 1958).

In southern Queensland the still lower proportion of cool season species deepens the winter trough of production and carrying capacities of grazing lands on granitic and trap-rock soils are a sheep to 1·5–2 acres (0·6–0·8 ha) or a cattle beast to 10 acres (4 ha).

Because of naturalised medics and the large areas of green crop and stubble land grazed in wheat-sheep areas it is difficult to estimate accurately the carrying capacity of the Stipa-dominated grazing lands of grey and peppermint box woodlands, but it appears to be about a sheep to 1·5–2 acres (0·6–0·8 ha).

ANIMAL PRODUCTION ON PASTURES

In temperate woodlands wool, beef, and lamb are produced by continuous year-long grazing of sown pastures either alone or in conjunction with crops or grazing lands of native species.

Dry matter production from sown pastures is higher than from grazing lands (about 2·5 times as much on the Northern Tablelands according to Atkinson, Walker, and Reis 1958) but the shape of their annual production curves is similar. Despite the persistence of winter and summer troughs in availability of green feed (see Fig. 12 : 1) more animals can be carried per unit area and weight gains per head are higher on sown pastures. On the Southern Tablelands of New South Wales, for example, weaner sheep on Danthonia-Stipa Temperate Shortgrass grazing land stocked at 1·125 per acre (2·8 per ha) increased from 55 to 80 lb (25 to 36 kg) liveweight between April and September. The gain during the same period on a phalaris-clover pasture stocked at 3·375 per acre (8·34 per ha) was from 55 to 111 lb (25–50 kg) per head (Anon. 1953).

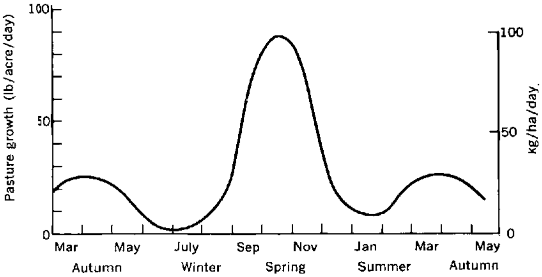


Fig. 12 : 1 Seasonal pattern of growth of perennial pastures yielding 10,000 lb dm per acre (11,200 kg per ha), Armidale, N.S.W. (from Hilder 1956)

Troughs in quantity of pasture available to animals in winter and in quality in summer accentuate problems of effectively utilising pastures. High grazing pressures in these two periods do not adversely affect phalaris and the problem is principally one of animal nutrition. In a study of the relationship between amount of green pasture available and liveweight gains in sheep Willoughby (1958, 1959) found that maximum intake and weight gain were not attained until 1400 lb per acre (1568 kg per ha) of dry matter as green pasture was available to the animals (see Fig. 12 : 2). When amounts available were below this level substantial increases in liveweight were made for small increments in green feed. Conversely, above this level large increases in green feed availability had little effect on liveweight. Losses in weight on dry phalaris-clover during summer depended more on the initial weight of the sheep—the heavier the sheep the greater the weight loss—than on the amount of dry pasture available. Weight losses were only slightly reduced when the amount of dry material was greatly increased. The importance of pasture quality in summer on wool production has been stressed by McFarlane (1965).

Sharkey and Hedding (1964) found that maximum growth of wool (1·8 mg/cm^2/day) by Corriedale wethers grazing a Wimmera ryegrass-subterranean clover pasture at Werribee, Victoria, took place when the green feed available was 1800 lb per acre (2016 kg per ha).

Attempts to increase the quantity of pasture available in periods of expected seasonal shortages by reducing the area accessible to stock at other times have not improved animal production (see Chapter 27).

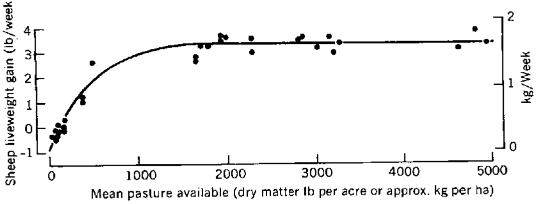


Fig. 12 : 2 Pasture intake in relation to pasture availability, phalaris-clover pasture (from Willoughby 1958)

A different approach was tried by Biddiscombe (1964) who complemented a phalaris-clover pasture with pastures of other perennial grasses having different seasonal production curves. The system worked well for a few years—*Bromus inermis* in summer, and *Dactylis glomerata* cv. Brignoles in winter, increased wool production by 18–20 per cent in comparison with phalaris in the same periods. But at the high stocking rates employed, 9·6 sheep per acre (24 per ha), perennials other than phalaris did not persist.

Average stocking rates on phalaris-clover pastures are about 3 sheep per acre (7·5 per ha), but there is evidence both experimental and practical that, except on dry shallow soils, phalaris pastures will carry about 5 sheep per acre (12·5 per ha) year long without supplementation by hay or other conserved fodder. Reasons for differences between stocking rates and carrying capacities are, difficulties in obtaining the extra sheep required, labour problems, and the additional costs involved. Nevertheless there has been a 40 per cent increase in Australian sheep numbers during the last twenty-five years, most of which has been in the temperate woodland zone. The rise in sheep numbers has been responsible for nearly all of the 64 per cent increase in wool production in the same period.

Economic aspects of stocking rates on phalaris-clover pastures have been studied by Byrne (1968) who found that optimal rates for Merino sheep on experiments at Canberra were 4–6 ewes per acre (10 to 15 per ha). It is claimed that these rates are not likely to be altered by more than 0·5 sheep per acre (1·25 per ha) by variations in the price of wool, labour costs, and in the opportunity cost of capital.

In Tasmania, perennial ryegrass-subterranean clover pastures carry 3·5–4·5 sheep (dry sheep equivalents) per acre (9–11 per ha). Similar pastures in western Victoria are commonly stocked with 6 dry sheep equivalents per acre (15 per ha).

In northern Victoria perennial pastures of phalaris and subterranean clover average 3 to 4 sheep per acre (7·5–10 per ha) and annual pastures of clover and volunteer species about 2–3 per acre (5–7·5 per ha).

The effects of sown pastures on animal production and husbandry systems on the Northern Tablelands of New South Wales were examined by G. T. McDonald (1968). Between 1960 and 1965 the area of sown pastures increased from 86,000 to 1,503,000 acres (34,830 to 608,715 ha), and livestock numbers from 4,944,951 to 8,281,333 sheep equivalents (7 sheep = 1 cattle beast), after remaining virtually unchanged for fifty years. Each acre (0·4 ha) of pasture supported an additional 1·97 sheep units and 83 per cent of the increase in stock numbers in the period 1960–5 was due to higher production from sown pastures. Sheep increased by 90 and cattle by 40 per cent in this period. Wool production increased from 19·7 to 44·5 million lb (approximately 9 to 20 million kg), an increase as McDonald notes proportionately greater than the increase in the number of sheep shorn. Average fleece weights increased from 7·6 to 9·2 lb (3·4 to 4·2 kg) per sheep. It was calculated that 57 per cent of the increase in wool production could be ascribed to the effects of sown pastures on sheep numbers. The remainder of the increase was due to higher wool production per sheep. There are 2·5 million acres (1 million ha) or 63 per cent of the Northern Tablelands suitable for pastures, still unsown.

On the trap-rock and granitic soils of southern Queensland where the principal sown species are lucerne and barrel medics, carrying capacities are 1·5 to 2 sheep per acre (3·7 to 5 per ha) or a cattle beast to 4 acres (1·6 ha).

The carrying capacities of Mediterranean annual pastures based on subterranean clover are between 2 and 4 sheep per acre (5 and 10 per ha). In the higher rainfall woodlands up to 3 ewes per acre (7·5 per ha) can be carried continuously without reduction of productivity per head.

Annual pastures appear to be as productive as perennial pastures at low to moderate stocking rates. Estimates by Neal-Smith (1942) based on mean dry matter yields from exclosures cut at the end of each growing season for 5 years were 740 g per sq metre for perennial (phalaris), and 830 g per sq metre for annual pastures. Average stocking rates were slightly less than 4 sheep per acre (10 per ha). In environments to which they are adapted phalaris pastures are more stable than annual pastures at high grazing pressures. In Victoria Sharkey and Hedding (1964) found that a Wimmera ryegrass-clover pasture was relatively stable in composition when grazed at 3 sheep per acre (7·5 per ha) but both sown

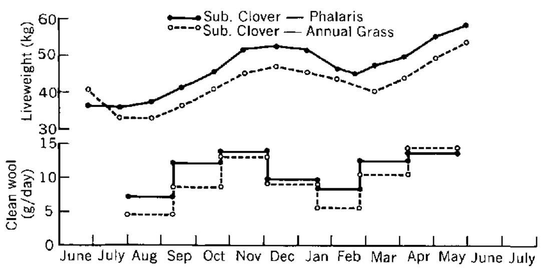


Fig. 12 : 3 Seasonal pattern of wool growth and liveweights of sheep on sown temperate perennial grass-annual legume and Mediterranean annual pastures, Canberra, A.C.T. (from Williams and Schinckel 1962)

species were eliminated at 6 sheep per acre (15 per ha). In a direct comparison of a phalaris-clover with an annual grass-clover pasture at Canberra, Arnold and McManus (1960) found that sheep grazing at 4 and 6 per acre (10 and 15 per ha) were heavier, and produced more wool per head and per unit area on pastures containing the perennial grass. At 2 sheep per acre (5 per ha) production from both pastures was similar.

Seasonal patterns of wool growth and of liveweights of sheep on annual and perennial pastures are shown in Fig. 12 : 3.

Throughout the temperate woodlands most properties breed their own replacement sheep, and it is common to mate sheep in autumn (March/April) for lambing in spring (August/September) during the peak period of pasture production (see Fig. 12 : 1). Lambing percentages average between 70 and 80 for Merino and 80 and 90 for crossbred. Adult sheep are usually shorn two months after lambing but in some areas, notably the Southern Tablelands of New South Wales, breeding ewes may be shorn prior to lambing. Unless grasses with sharp awns, for example *Hordeum leporinum* or *Bromus rigidus*, are present lambs are not shorn until they are 13–14 months old. Sheep are dipped for control of external parasites, lice (*Damalinia ovis*) and keds (*Mellophagus ovinus*) 3–4 weeks after shearing. Lambs are usually weaned in December or January but in dry seasons they may be weaned at 12 to 14 weeks. Cast-for-age ewes are sold after weaning, and culled ewe hoggets at the time of mating. Flock rams are usually purchased from breeders of stud sheep.

Prime lamb production on properties in which animal production is solely or mainly from pastures and grazing lands is a subsidiary enterprise to wool production. Culled and cast-for-age Merino ewes are mated to Border Leicester rams to produce a first cross lamb. Mating of Border Leicester × Merino ewes to Dorset Horn rams for production of second cross lambs is a specialised industry of the wheat and sheep producing areas and of the higher rainfall woodlands where proportions of sown pastures on properties are high.

There are arguments for and against both spring and autumn lambing. The system adopted depends on the seasonal feed and labour situation on individual properties and the market situation. From a production viewpoint there appears to be merit in lambing at the spring flush of pasture growth in southern areas.

Bourke (1964) studied effects of farming systems on prime lamb production on annual pastures at Cowra, N.S.W. Border Leicester × Merino ewes were mated with Dorset Horn rams in autumn or spring. Autumn mated ewes produced a greater weight of saleable lamb than spring mated. In Tasmania where lambing is usual in June–July, a time when pasture growth is slow, Jefferies and Dreaver (1962) estimated that 20–30 per cent of lambs cannot be marketed off their mothers. Turn-off was not improved by rotational grazing and the most efficient system appeared to be to set stock ewes and provide ‘a creep area’ accessible only to lambs. Arnold and Bush (1962) found no differences in wool or fat lamb production from ewes on continuously grazed or on ‘autumn saved’ pastures of phalaris-subterranean clover at Canberra. There was an effect of stocking rate, and lamb production at 7 ewes per acre (17·5 per ha) was no higher than at 4 ewes per acre (10 per ha).

Wool production from Merino sheep on both medic and subterranean clover pastures averages from 9 to 11 lb (4 to 5 kg) per head. Production is rather higher—12 to 13 lb (5·4 to 6 kg) at low elevations in the warmer districts of southern Queensland and slightly lower, 8·5 lb (3·9 kg), at colder and higher altitudes on the Northern Tablelands of New South Wales.

There is little or no seasonal movement of livestock, and except during droughts when agistment (grazing rights) may be bought on other properties, livestock are generally held on the one property throughout the year.

According to the Commonwealth Bureau of Census and Statistics there were about 6 million beef cattle in southern Australia in 1965. Beef production is mostly subsidiary to other forms of agricultural production and in New South Wales more than 50 per cent of rural holdings have some beef cattle, mostly fewer than fifty in a herd (Carraill 1967).

In temperate woodlands the ratio of sheep to cattle on properties ranges from 50 : 1 to 5 : 1 and averages about 20 : 1. Many graziers believe that feed on pastures and grazing lands grazed by both sheep and cattle is of a higher quality than that grazed by either alone. The experimental evidence for this is not unequivocal but results of studies at Rutherglen, Victoria, where Aberdeen Angus steers and Border Leicester × Merino cross ewes were run singly and in combination (1 steer to 4 sheep) at three stocking rates on subterranean clover pastures, indicate advantages to sheep grazed with cattle (Hamilton 1968). Ewes were 6 lb (2·7 kg) heavier, cut 0·8 lb (360 g) more wool, and their lambs were 11 lb (5 kg) heavier, when grazed with steers than when grazed alone. Steers weighed the same whether grazed alone or in combination with sheep.

Only in the sclerophyll forests of hill country in south-eastern Australia is cattle production a sole enterprise. In such areas cattle are sold at weaning to properties on adjacent woodlands for fattening. In the drier woodlands farmed for cereals, store cattle or weaners are frequently purchased and fattened for 6–8 months on annual pastures grown in rotation with crops.

Beef cows are usually mated to calve in late winter before the spring flush of grass growth in August–September, but autumn calving is becoming more popular where sown pasture is available. Calving percentages range from 60 to 95 per cent and average about 80 per cent. Heifers are mated at 15 months of age or when they attain a liveweight of about 600 lb (272 kg). Three to five per cent of bulls are run with the cows for 10 to 12 weeks in the mating season, commonly October–November. Cows calve at pasture and the calves are weaned at 7 to 10 months when they are between 400 and 600 lb (181 and 272 kg). Steer calves are either sold at these weights as store cattle or retained for sale later as fat cattle. Because of the dry condition of both sown pastures and native grazing lands in summer, growth of cattle is not continuous and animals may have to be kept until 18–20 months of age to attain a marketable weight of 800–1000 lb (363–453 kg). Culled cows and bulls are sold for processed beef. Most cattle are sold by auction at saleyards nearest the holdings and then trucked to points of consumption or export for slaughtering.

In Tasmania calves gain about 1·8 lb (0·8 kg) and fat cattle from 0·5 to 1 lb (0·22–0·45 kg) per day on sown pastures of perennial ryegrass and subterranean clover. Vealers are sold at 5–6 months of age weighing 450 lb (204 kg), and fat cattle are usually sold at 2 years weighing 900–1100 lb (408–499 kg). Beef production in the Western District of Victoria is similar except that fattening time is generally longer than in Tasmania because of a more pronounced feed shortage from summer to early autumn. Throughout most of the mesophytic woodlands in New South Wales and Victoria, excepting high rainfall areas such as Tumut and Muswellbrook, N.S.W., where steers weighing 600-850 lb (272–385 kg) are sold at 12 months of age, weights are commonly 450–600 lb (204–272 kg) at 12 months, and 800–900 lb (363–408 kg) at 15–18 months.

In woodlands on trap-rock and granite soils in southern Queensland it takes about two years for a steer to reach 700 lb (318 kg) at a stocking rate of a beast to 4 acres (1·6 ha). Calving percentages vary between 65 and 90 per cent.

Turn-off ages and weights in the grey box woodlands are fairly similar to those from the higher rainfall woodlands because of the grazing available from crops such as oats. In the Wimmera, Victoria, vealers weighing 400 lb (181 kg) are sold at 9 months and steers weighing 800 lb (363 kg) at 18 months. At Wagga, N.S.W., yearling steers are commonly 800 lb (363 kg) and at Gunnedah in northern New South Wales vealers are sold at 7 to 10 months when they are between 450 and 650 lb (204–295 kg) and steers at 14 to 20 months when 600 to 1000 lb (272–454 kg).

IMPEDIMENTS TO ANIMAL PRODUCTION

Properties vary widely in applying prophylactic measures against parasites and diseases but most sheep are drenched two or three times annually for control of liver fluke (*Fasciola hepatica*) and vaccinated twice during their life against black disease (*Clostridium novyi*). On properties with a high proportion of sown pastures both lambs and adult sheep are vaccinated against enterotoxaemia (*Clostridium perfringens*). Frequently prime lamb mothers are vaccinated before lambing to protect lambs during early life from enterotoxaemia and tetanus. Lambs are commonly drenched at weaning for control of internal parasites. In wet summers it may be necessary to drench all sheep at 2- to 3-week intervals to control the large stomach worm (*Haemonchus contortus*).

Sheep blowflies (*Lucilia cuprina* and *Calliphora augur*) are prevalent in eastern Australia and it is becoming customary to 'Mules' lambs at marking. In this operation excess skin folds in the crutch of wrinkly sheep are excised to reduce the number of focal points for fly strike.

Hypocalcaemia and hypomagnesaemia may occur in ewes lambing on green oats or grass dominant pastures.

Muscular dystrophy in young lambs up to 4–6 weeks of age on sown pastures of the Northern Tablelands has been shown to be due to a deficiency of selenium. It is becoming common on properties with a high proportion of sown pastures to grazing lands to administer selenium orally to ewes prior to lambing and to lambs at marking.

Losses from pregnancy toxaemia among winter lambing ewes may be high in cold tableland areas, particularly if the season is dry. In wet conditions foot-rot caused by the fusiform bacterium *Sphaerophorus nodosus* in association with the microscopic parasite *Spirochaeta penortha* may be troublesome throughout the woodland zone.

Breeding cows are vaccinated for brucellosis (*Brucella abortus*). In most properties cattle are vaccinated once in a lifetime for blackleg (*Clostridium feseri*) and twice yearly for enterotoxaemia. All cattle over 8 months of age are drenched at least once yearly for control of liver fluke, and young cattle are given drenches for worms at 5–6 months and 12–15 months.

There is always a risk of bloat on clover pastures but the incidence appears to be highest on the white clover pastures of the Northern Tablelands where cattle losses may occasionally be as high as 10 per cent.

Species sown in pastures are frequently responsible for metabolic disorders in livestock (see Chapter 26). Sheep on phalaris-dominant pastures may develop staggers or may die suddenly and the risk of sudden death appears to be greater on rotationally than on continuously grazed pastures and when soil nitrogen levels are high (Moore and Hutchings 1967). Sheep on perennial ryegrass pastures also may develop staggers. Clover disease may occur among sheep on annual pastures containing high proportions of oestrogenic cultivars of subterranean clover. Photosensitisation of unpigmented areas of skin is increasingly incident on volunteer annual pastures of the medics *M. polymorpha* and *M. minima*.

The principal weeds of the higher rainfall woodlands are thistles (see Chapter 23). In the drier woodlands burr medics, barley grass, *Stipa* spp., *Aristida* spp., *Xanthium spinosum* (Bathurst burr), and *X. pungens* (Noogoora burr) are the principal components of vegetable fault in wool. Wild heliotrope (*Heliotropium europeum*) is prevalent in south-western New South Wales and is a frequent cause of toxaemic jaundice in sheep (see Chapter 26). Darling Pea (*Swainsona galegifolia*), a native plant fairly common in the north-west of New South Wales, contains a neurotoxin that causes staggers in animals. Other poisonous plants are Paterson's curse (*Echium lycopsis* syn. *E. plantagineum*), which has a wide distribution in South Australia, Victoria, and southern New South Wales; soursob (*Oxalis pes-caprae*), an introduced plant high in oxalate, common on red-brown earths in South Australia; and the two Cape tulips (*Homeria breyniana* and *H. miniata*) which occur in dense but localised patches, principally in Victoria, South Australia, and Western Australia.

Insect pests of pastures and grazing lands are most damaging in Tasmania, the Western District of Victoria, the south-east of South Australia, the south-west of Western Australia, and the Northern Tablelands of New South Wales (see Chapter 24). The pasture cockchafer (*Aphodius howittii*), the underground grass grub (*Oncopera* sp.), and the field cricket (*Teleogrullus commodus*), frequently damage pastures in southern Victoria and South Australia. Dry winters favour both the cockchafer and

Oncopera. The red-legged earth mite (*Halotydeus destructor*) is common on subterranean clover in Victoria, South Australia, and Western Australia. In temperate woodlands of northern New South Wales the most prevalent pasture pests are a complex of scarabs (*Sericesthes* spp.) and the clover weevil, *Amnemus quadrituberculatus*.

LAND VALUES

Most of the land, particularly in the southern part of the temperate woodland zone, is freehold. Values are determined by a complex of factors not all related to productivity.

In Tasmanian woodlands, values range from $80 to $260 per acre ($198 to $642 per ha) and property sizes from 50 to 12,000 acres (20–4860 ha). The average market value of land in the red gum woodlands of the Western District of Victoria is about $100 per acre ($247 per ha) and properties are usually more than 2000 acres (810 ha) in area. From the Central Highlands of Victoria to the Holbrook–Culcairn–Albury district of New South Wales land capable of growing Mediterranean perennial grass-annual legume pastures is about $100 per acre ($247 per ha). Hill country sells for $40 per acre ($99 per ha) and irrigable land, for example in the Loddon District of Victoria, brings $160 per acre ($395 per ha). Property sizes range from 100 acres (40 ha) for dairying to 6000–8000 acres (2430 to 3240 ha) for wool and beef production.

In most of the southern woodlands of New South Wales values average about $80 per acre ($198 per ha) for wool producing country. Land held on lease rents from 75 cents to $2.00 per acre ($1.85 to $4.94 per ha) per annum. Property sizes vary greatly but are usually 2000–3000 acres (810–1215 ha); the largest are from 12,500 to 20,000 acres (5062–8100 ha).

From the Central Tablelands of New South Wales northwards grazing land suited to pastures of phalaris and subterranean clover is valued at about $40 per acre ($99 per ha), arable land at $80 an acre ($198 per ha), and hill grazing lands at about $25 per acre ($62 per ha).

Dairy and irrigation farms range in value from $300 to $700 per acre ($741 to $1729 per ha).

Trap-rock and granite lands in southern Queensland have values of $16–26 per acre ($39–$64 per ha) and $20–$30 per acre ($49–$74 per ha) respectively.

Land in the grey box woodlands, the wheat-sheep zone, is mostly freehold and is valued at $80–$140 per acre ($198–$346 per ha). Property sizes vary markedly depending on whether the emphasis is on the production of cereals or wool.

13

SUB-ALPINE AND ALPINE COMMUNITIES

A. B. COSTIN

GENERAL LOCATION AND ENVIRONMENT

Sub-alpine and alpine areas are not of great importance as grazing lands in Australia, either on the basis of area (about 0·1 per cent of Australia) or the value of grazing products (less than 0·1 per cent of the value of sheep and cattle production). However, the study of grazing in these high mountain areas has helped to clarify some of the more general problems of free ranging grazing, and this chapter is presented with these in mind.

Sub-alpine and alpine areas are restricted to south-east Australia; there are approximately 2000 square miles (5184 km^2) on the mainland in Victoria and New South Wales, and 2500 square miles (6480 km^2) in the island state of Tasmania. It will be seen from Map 3 that in New South Wales and the adjacent Australian Capital Territory most alpine areas occur as one more or less continuous tract—the Snowy Mountains and their northern extension towards Canberra; there is also a small outlier on the Barrington Tops, west of Newcastle. The Victorian areas are more widely scattered. Those in Tasmania are mainly confined to the large Central Plateau.

The sub-alpine and alpine communities are clearly defined naturally. Their lower limit is the winter snow line (continuous snow cover of at least one month) at about 4500 to 5000 ft (1372 to 1524 m) in Victoria and New South Wales and 3000 ft (914 m) in Tasmania. Mean annual precipitations vary from about 30 in. (762 mm) in some of the drier sub-alpine areas to more than 100 in. (2540 mm) in the alpine areas above the tree line. The corresponding mean monthly temperatures range from maxima of 75°F (24°C) to less than 50°F (10°C), to minima from 25°F (−4°C) to less than 20°F (−7°C). Frosts are common, being experienced in every month of the year.

The lower limit of the winter snow line is usually delineated by a marked change from tall eucalypt forest to more stunted sub-alpine tree vegetation (Pl. 28). With increasing elevation, at approximately 6000 ft (1829 m) on the mainland and 4000 ft (1219 m) in Tasmania, the tree communities give way to a variety of alpine types. At these high levels, long-lasting snowpatches may persist from one year to the next, but there are no permanent snowfields.

Despite the wide range of acid to basic rock types, the soils are uniformly acid to strongly acid throughout, and low in available nutrients. In the mainland areas, alpine humus soils are the most important group, with smaller occurrences of lithosols, peats, and other groundwater soils (see Chapter 3). In Tasmania the lithosolic and groundwater types are relatively more important. Representative analytical data are given by Costin (1954) and Stace *et al.* (1968).

VEGETATION

Although the sub-alpine and alpine vegetation has been considerably modified by fires and grazing, its original character can still be recognised.

Sub-alpine woodlands are the climatic climax vegetation in the sub-alpine belt, the characteristic dominants being *Eucalyptus niphophila* on the mainland and *E. coccifera* and *E. gunnii* in Tasmania. Species of *Nothofagus* also occur on the Barrington Tops of New South Wales, on the Baw Baw Plateau of Victoria, and in Tasmania. In the mainland areas the understorey has a strong herbaceous component characterised by snowgrasses (*Poa caespitosa* sens. lat.) and a wide range of perennial herbs and scattered shrubs. The shrub elements are more conspicuous in Tasmania.

Under mainland conditions the trees extend to about 6000 ft (1829 m), above which alpine herbfields are the climatic climax with heaths in rocky situations. In Tasmania, the trees give way at about 4000 ft (1219 m) to extensive alpine heaths.

TABLE 13 : 1 Major plant communities of Australian sub-alpine and alpine areas

Structural unit	Main dominants	Distribution
Sod tussock grassland[a]	*Poa caespitosa* (sens. lat.) *Danthonia nudiflora* *Calorophus lateriflorus* *Themeda australis*	Widespread along valleys and in basins of cold air drainage, especially in sub-alpine areas.
Tall alpine herbfield[a]	*Celmisia longifolia* *Poa caespitosa* (sens. lat.) *Helipterum incanum* var. *alpinum* *Danthonia frigida*	The main alpine community above tree line on mainland; restricted in Tasmania.
Short alpine herbfield[a]	*Plantago muelleri* *Montia australasica* *Caltha introloba* *Brachycome stolonifera* *Ranunculus inundatus*	Local occurrence beneath alpine snow patches with persistent (> 8 months) snow cover, especially on mainland.
Fen[a]	*Carex gaudichaudiana* *Danthonia nudiflora* *Festuca muelleri* *Eleocharis acuta* *Poa caespitosa* (sens. lat.)	Widespread locally in wet, acid, almost level alpine and sub-alpine situations, influenced by mineral soil.
Bog[a]	*Carex gaudichaudiana* *Sphagnum cristatum* *Epacris paludosa* '*Epacris serpyllifolia*' auctt. *Callistemon sieberi* *Richea continentis* *Restio australis* *Carpha nivicola* *Astelia* spp.	Widespread locally in wet, acid valley situations and around hillside springs, both in alpine and sub-alpine areas; relatively little influence of mineral soil.
Fellfield[b]	*Coprosma pumila* *Colobanthus* sp. *Epacris petrophila* *Veronica densifolia* *Ewartia nubigena* *Kelleria tasmanica* *Helipterum incanum* var. *alpinum*	Local alpine occurrences above persistent snow patches and in very wind-exposed situations.
Cushion heath[b]	*Abrotanella forsterioides* *Donatia novaezelandiae* *Phyllachne colensoi* *Pterygopappus lawrencei* *Astelia* spp. *Oreobolus* spp.	Wet alpine situations in Tasmania.
Heath[a]	'*Epacris serpyllifolia*' auctt. *Epacris* spp. *Kunzea muelleri*	Locally common in damp situations marginal to bog.

Structural unit	Main dominants	Distribution
Heath[b]	*Oxylobium ellipticum* *Podocarpus lawrencei* *Lissanthe montana* *Phebalium ovatifolium* *Orites lancifolia* *Prostanthera cuneata* *Acacia alpina* '*Hovea longifolia*' auctt. *Drimys vickeriana* *Leucopogon hookeri* *Bossiaea foliosa* *Kunzea muelleri* *Kunzea peduncularis* *Baeckea gunniana* *Callistemon sieberi* *Pherosphaera hookeriana* *Microcachrys tetragona* *Diselma archeri*	Widespread in rocky situations, especially in Tasmania.
Sub-alpine woodland[a]	*Eucalyptus niphophila* *E. stellulata* *E. pauciflora* form. *pendula*	Widespread sub-alpine community on mainland.
Sub-alpine woodland[a]	*Eucalyptus coccifera* *E. gunnii*	Widespread sub-alpine community in Tasmania.

[a] Communities suitable for grazing.
[b] Communities unsuitable for grazing.
For further details of communities see Costin (1954) and Davies (1965).

Under conditions of cold-air drainage into semi-enclosed upland valleys, the tree communities are commonly replaced by large treeless 'high plains', characterised by grassland communities, generally similar to those under the woodlands (Pl. 28). Where the cold-air drainage is pronounced, the lower limit of these grasslands can be depressed by as much as 1500 ft (457 m) below the normal sub-alpine level. These lower 'high plains' are severe habitats climatically, owing to the high incidence of frosts combined with the relative lack of winter/spring snow cover which at higher elevations provides effective insulation to soils and vegetation.

Wet areas, both in the sub-alpine and alpine belts, support a variety of bog, fen, and cushion heath (in Tasmania) communities, usually with marginal wet heaths containing a variety of epacridaceous and myrtaceous species. Snow patch and fellfield vegetation have more local occurrence under conditions of prolonged snow cover and exposure to strong winds.

The main features of the above communities are summarised in Table 13 : 1. A typical vegetation distribution pattern is shown, for the Bogong High Plains in Victoria, in Fig. 13 : 1.

With fires and grazing, considerable modification of the above communities has occurred. The trees, although easily killed by fire, normally regenerate from the lignotubers. However, selective browsing of the regenerating shoots by sheep can kill the trees, producing large areas of disclimax heath and grassland. The treeless communities (both climax and disclimax) and the woodland understorey have also been opened up by fires and grazing, exposing bare ground favouring shrub invasion. The peaty swamp and snow patch communities have undergone considerable modification by trampling, in places leading to stream incision and drainage. There are also more subtle changes in species composition; these are described in greater detail below.

LIVESTOCK INDUSTRIES

Because of the limitations imposed by relative inaccessibility, steep and broken terrain, poor soils, and restricted growing and grazing seasons, the sub-alpine and alpine areas have rarely been used for more than store cattle and wool-growing

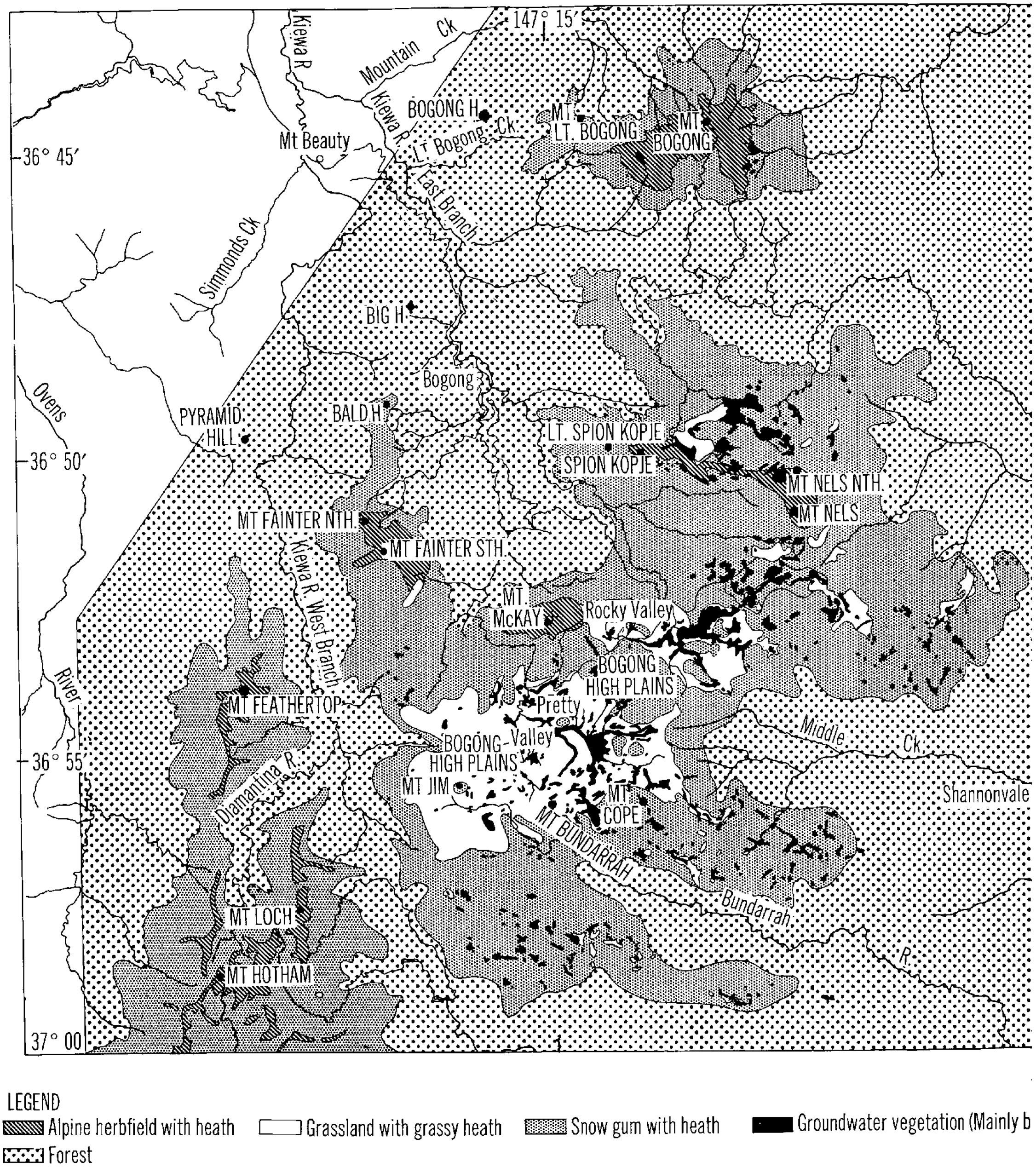


Fig. 13 : 1 Vegetation map of Bogong High Plains and environs

purposes. Choice of livestock depends to a considerable extent on the degree of dingo-infestation of surrounding areas. Thus, most of the Victorian areas, which are scattered as small units surrounded by steep, heavily-timbered country, are given over to cattle (cf. Fig. 13 : 1), in contrast to the larger, more continuous areas in th
Snowy Mountains and the Tasmanian Centr
Plateau, with relatively less surrounding ti
bered country, which are used more for Merin
sheep. Within the one area the pattern is simila
most of the accessible parts of the Snow

Mountains were used for wool growing but the less accessible country, surrounded by unoccupied forest land, has been used for cattle.

Historically, there have been changes in grazing use which deserve comment. The permanent settlement of lower country more than a hundred years ago was soon followed by the discovery of the grazing potential of the higher areas and its exploitation during the snow-free months. During this early period shepherding was still considered necessary in Australia and stockmen remained with flocks and herds during most of the grazing season. In some cases, at the lower sub-alpine limits where there was least hazard from heavy snow, permanent settlement was attempted, to be abandoned later as the limitations of the country, both for permanent grazing and for permanent human occupation, became apparent. Nevertheless, the demand for summer grazing continued to grow, not only as a supplement for lowland pastures in the vicinity, but as drought relief grazing for more inland areas. Some of the most serious damage to the soils and vegetation still apparent in the sub-alpine and alpine areas was initiated during the heavy relief grazing earlier this century (e.g. 1901 and 1914). Then followed the period when the sub-alpine and alpine areas were used for regular summer grazing almost exclusively by neighbouring landholders. This is still the situation in parts of Victoria and Tasmania, although in New South Wales most of the sub-alpine and alpine areas have been withdrawn from grazing progressively since 1944 in the interests of catchment protection and nature conservation. In the 1950s, before extensive withdrawal from grazing of leasehold land occurred, livestock numbered approximately 500,000 dry sheep equivalents in New South Wales, 250,000 in Victoria, and 160,000 in Tasmania.

The increasing emphasis on water supply, national park and nature conservation values is likely to result in further reduction of grazing in the sub-alpine and alpine areas in future years. There are few major obstacles in giving effect to such landuse decisions, since virtually all of the land (except for some freehold on the Central Plateau of Tasmania) is held as short-term leases, on which there has been relatively little investment in pastures, fences, buildings and other tenant-right improvements.

THE GRAZING LANDS AND PASTURES

'Rangeland' grazing implies low overall levels of utilisation of native vegetation by livestock which are largely uncontrolled and unconfined and are therefore able to exercise a wide range of choice with respect both to the areas and to the species selected for grazing. In this context, management simply consists of driving livestock to the higher areas in early summer, and bringing them down for the winter months.

The boundaries of individual grazing leases are occasionally well fenced, but for the most part fences are not well maintained and often do not exist. Natural features—shelter, water, preferred grazing types, etc.—are more important in the distribution of livestock than boundary fences.

The length of the grazing period is usually fixed by regulation from about the beginning of December to the end of May, and maximum stock numbers are usually specified for a particular grazing lease. Although once widespread, the practice of spring (and more commonly autumn) burning to encourage more palatable growth is now prohibited in New South Wales and Victoria, but it still continues in the Central Plateau of Tasmania. Salt is sometimes put out during summer to facilitate the autumn muster of cattle. If it is a particularly warm, humid summer and sheep blowflies are troublesome, an occasional paddock muster is made to crutch flyblown sheep. However, apart from the climatic and nutritional limits of the grazing lands, the sub-alpine and alpine areas are regarded as 'healthy' stock country; low stock densities, unrestricted stock movements, and frequent occurrences of frost even during the snow-free season, keep these areas free from liver fluke and other internal parasites normally prevalent in moist grazing lands.

In general, therefore, range management is non-existent, and virtually no pastures have been sown although the temperate perennial pasture species *Lolium perenne*, *Poa pratensis*, and *Trifolium repens* have become naturalised in some disturbed areas (see Table 6 : 1).

STOCKING RATES, GRAZING INTENSITIES, AND LIVESTOCK PERFORMANCE

The distribution of grazing pressures in most sub-alpine and alpine leases is obviously patchy both on a macro- and a micro-scale. On a macro-scale, the steep rocky areas, heath communities, and dense snowgum are largely neglected, whereas the bogs, fens, and snowpatch vegetation are preferentially visited both for the more palatable plants which grow there and for drinking water. On a micro-scale, there is a wide range of palatability in the species available for grazing. With standing crops of several tons per acre and removal by livestock (0·25–1 dry sheep equivalents per acre (0·6–2·5 per ha) for a 6-month growing season) of less than 0·5 ton, it is obvious that the grazing animal can exercise a wide range of choice. In this connection it is instructive to make an appraisal of grazing conditions about the turn of the century when the grazing lands were closer to their original condition. The recollections of old residents, botanical reports of early scientists, and evidence from long-term exclosure studies leave no doubt that many species have become much less common and in places have virtually disappeared, leaving grazing lands in which the unpalatable snowgrasses are almost entirely dominant. Such species include the grasses: *Agropyron velutinum*, *Agrostis* spp., *Deyeuxia* spp., *Danthonia frigida*, *Trisetum subspicatum*; the sedges: *Carex hebes*, *C. breviculmis* and *Luzula campestris*; and various forbs: *Ranunculus* spp., *Euphrasia* spp., *Aciphylla* spp., *Craspedia uniflora* and other composites. It is clear that the original herbaceous vegetation provided more palatable grazing than the present herbaceous vegetation dominated largely by the snowgrasses. From this it can also be inferred that early grazing was probably more uniform, and that effective stocking rates were not necessarily any higher than at present, even though there were more livestock.

The virtual disappearance of the more palatable herbaceous species, and the use of fire to promote palatable new growth from the otherwise unattractive snowgrass, have produced a general opening up of the herbaceous sward with numerous bare and semi-bare spaces between the snowgrass tussocks. The main species in the secondary successions on the bare spaces include several minor herbs which now provide the basis of most of the grazing. The most widespread and palatable (at early growth stages) of these minor species is *Rumex acetosella* (sorrel), an alien; *Hypochaeris radicata*, *Taraxacum officinale*, *Trifolium repens*, and *T. fragiferum* are also common introductions. Native minor herbs include *Geranium pilosum*, *G. sessiliflorum*; *Scaevola hookeri*; and composites such as *Cotula* spp., *Helichrysum* spp., *Leptorhynchos squamatus*, and *Senecio lautus*.

Livestock gain weight as long as there is an adequate supply of intertussock minor herbs which, despite the generally moist condition of the soils due to snowmelt, require frequent summer rains for good seasonal growth. When the cover of the intertussock species has been grazed so heavily that no more is available for grazing and the snowgrass inflorescences have been eaten, the snowgrass itself is grazed. At this stage a rapid loss in bodyweight begins. This is seen in the generalised graph of sheep weight changes in grazing trials in the Kosciusko area carried out since 1958 (Fig. 13 : 2).

TABLE 13 : 2 Crude protein and phosphorus contents, and digestibility, of main components in a snowgrass community

Component	Crude protein (%)	Phosphorus (%)	Digestibility *(in vitro)* (%)
Snowgrass leaves	5	0·1	19
Snowgrass inflorescences	10	0·2	64
Minor herbs	11	0·2	68

Since there is usually a sufficient quantity of dry matter available, the performance of livestock is related more to the quality of the available feed. Table 13 : 2, giving the analyses of minor herbs and snowgrass, shows the very low nutritive value of the latter species, except when in head.

The existence of the minor herbs in the intertussock species depends not only on discontinuities in the snowgrass sward but also on the micro-environment provided by the surrounding snowgrass tussocks, especially as regards shelter from wind and frost. This condition is difficult, if not impossible, to maintain permanently, since the snowgrass tussocks do not have an indefinite life and snowgrass seedlings are mostly destroyed by grazing; therefore, the snowgrass tussocks tend to thin out further. In relatively favourable sites the intertussock species extend accordingly, but in more severe situations there is an increase

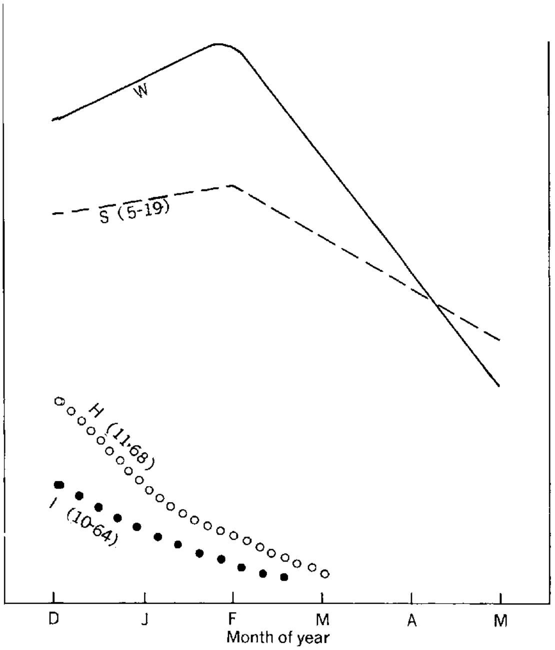


Fig. 13 : 2 Generalised changes during grazing season of sheep bodyweight (W) in relation to quantities of the main components of the community: snowgrass leaves (S), minor herbs (H), and snowgrass inflorescences (I). The average values for per cent crude protein and per cent digestibility respectively of S, H, and I are shown in brackets

in bare ground due to accelerated frost, wind and water erosion.

The effects of the above vegetation changes on grazing intensities may now be examined. If we consider a typical area of snowgrass country, we find, firstly, that disturbance by past bushfires producing areas of dense regrowth snowgum and invasion of herbaceous communities by shrubs has already produced a patchy distribution of livestock. In such a 3790-acre (1535 ha) grazing lease studied at Kosciusko, the level of stocking was 900 dry sheep equivalents. The northern and middle sections of this lease are too steep, rough and overgrown by shrubs to provide much grazing, and the stock spent most of their time on the more uniform southern portion of some 600 acres (243 ha). The approximate composition of the vegetation here is shown in Table 13 : 3. Most of the grazing was concentrated on the 'snowgrass with intertussock spaces' component; the composition of the intertussock spaces is shown in Table 13 : 4. Restricting consideration to the 'minor herbs' component, the area actually grazed for most of the time now becomes only about 87 acres (35 ha), giving an effective stocking rate of 10 sheep per acre (25 per ha). Similar high effective grazing pressures are also typical of other sub-alpine and alpine areas.

TABLE 13 : 3 Composition of typical snowgrass communities

Community	% Cover
Snowgum with continuous snowgrass	7
Snowgum with shrubs (heath)	11
Shrubs (heath)	14
Continuous snowgrass	30
Snowgrass with intertussock spaces	38

TABLE 13 : 4 Composition of 'intertussock spaces' component of Table 13 : 3

Cover type	% Cover
Bare ground	26
Litter	37
Minor herbs	37

GRAZING AND OTHER FORMS OF LANDUSE

Improvement of grazing efficiency in the context of the problems outlined above would require more uniform and complete utilisation of the total area of the grazing land. This in turn would necessitate either utilising the abundant snowgrasses or replacing them by sown pasture species. In view of the unpalatability and low nutrient value of the snowgrasses and the poor performance of livestock grazing them, fuller utilisation would be a difficult task. An alternative would be to establish sown pasture species (e.g. *T. repens*, *T. fragiferum*, *T. ambiguum*, *Poa pratensis*, *Agrostis* spp., *Anthoxanthum odoratum*, *Dactylis glomerata*, *Festuca rubra*, *Lolium perenne*, and *Phleum pratense*), using high rates of fertilisers and sowing techniques designed to minimise frost heave of the young seedlings.

It has been estimated that the establishment, maintenance, and fencing of sown pastures under sub-alpine and alpine conditions would cost considerably more than $4 per acre ($10 per ha) per annum. To justify this, stock carrying capacities would have to be increased up to 10-fold. Lower areas which can be grazed all the year round at present offer much greater potential for improvement and a higher return on capital invested.

Furthermore, some of the consequences of higher stocking rates are not in the interest of water catchment values—these include removal of plant cover and soil compaction with resultant surface runoff, prevention of regeneration of trees with their beneficial effect on the amount and timing of water yield, and drying-out of swamps which improve water quality and have a sustaining effect on streamflow in winter. Nor are the effects of grazing on vegetation compatible with the preservation of national park and nature conservation values, an important consideration in a country where sub-alpine and alpine areas are so few (Costin 1966, 1967).

For the above reasons the day of commercial grazing in the sub-alpine and alpine areas is probably ending. Most of the Snowy Mountains catchments above 4500 ft (1372 m) are now closed to grazing, and there has been a general scaling-down in Victoria, with total exclusion in some areas. The main grazing activity is now in the Central Plateau of Tasmania, but on a declining scale.

14

SOUTH-WESTERN TEMPERATE FORESTS, WOODLANDS, AND HEATHS

R. C. ROSSITER AND P. G. OZANNE

Temperate heaths, forests, and woodlands occur in the statistical subdivision of Western Australia designated the South-West Region, which covers about 110,000 sq miles (285,120 km²). This area is bounded to the south and to the west by the sea, and extends inland to the 11 in. (279 mm) isohyet or the 3-month isopleth for length of growing season (Fig. 14 : 1). The in-

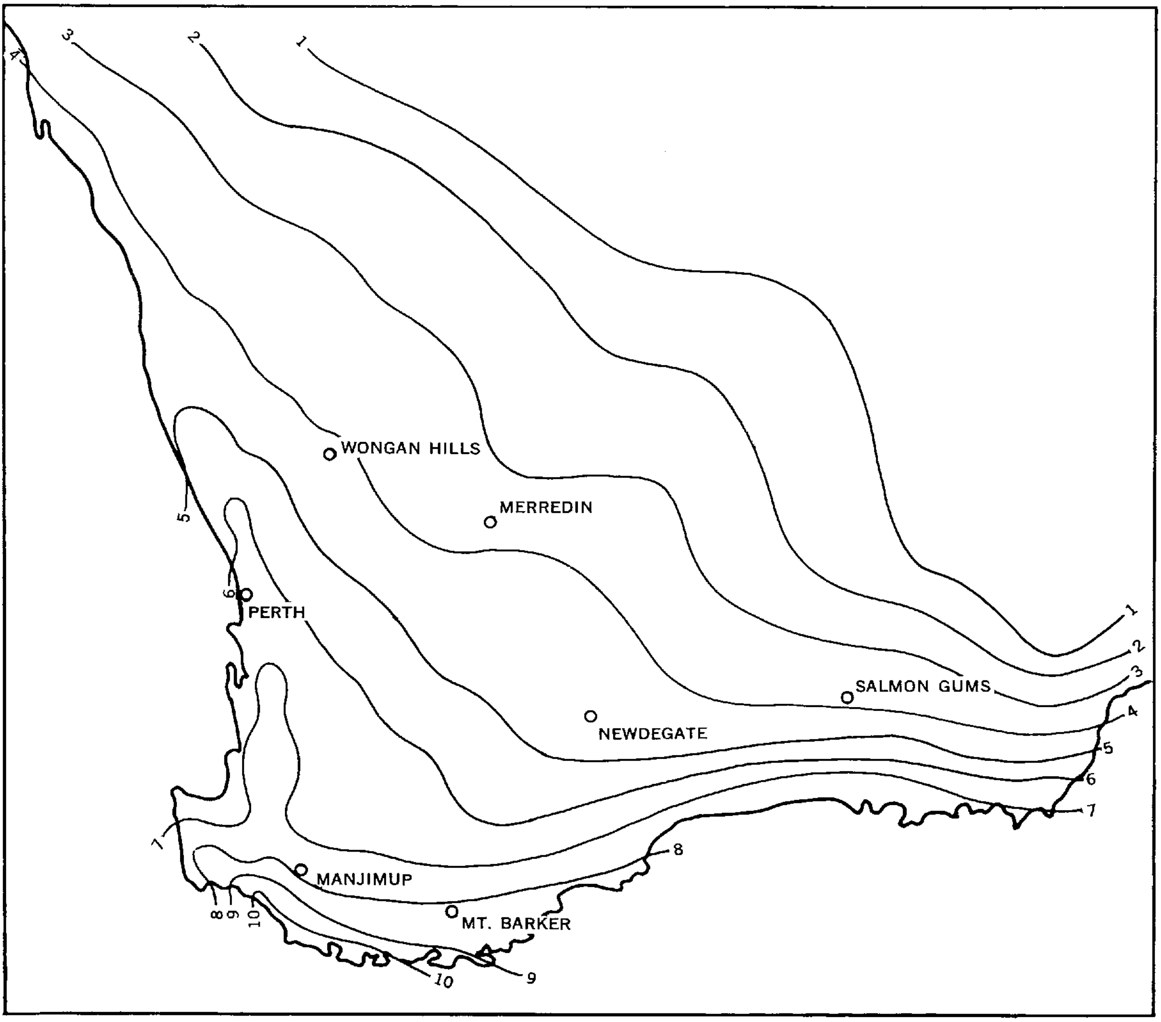


Fig. 14 : 1 Length of growing seasons (months) (*Source:* Commonwealth Bureau of Meteorology)

land boundary corresponds roughly to the inland limit of cereal-growing and to a sheep carrying capacity of greater than 0·1 sheep per acre (1 sheep to 4 ha). It is slightly east of the boundary, based on a mean rainfall of 175 mm for May to August used by Gardner (1944) to separate the South-West and Eremean vegetation provinces.

CLIMATE

The typically Mediterranean climate comprises fairly mild wet winters and warm dry summers, but compared with counterparts elsewhere, such as California, U.S.A., and parts of Israel, Western Australia has rather high winter temperatures and there is a slightly higher incidence of summer rainfall.

The mean annual rainfall ranges from more than 55 in. (1397 mm) to about 11 in. (279 mm). Slightly less than 20,000 sq miles (51,840 km^2), that is less than 20 per cent of the south-west, has an annual rainfall of less than 25 in. (635 mm) (see Fig. 1 : 8).

Although the rainfall distribution is highly seasonal, only the far western coastal areas have 85 per cent or more of the annual rainfall during the May–October period. Comparable areas in California and Israel are much larger (Naveh 1967). The proportion of winter rainfall declines inland from the coast, and also from north to south. The three inland centres, Mullewa, Merredin, and Salmon Gums, have about 12–13 in. (305–330 mm) annual rainfall, but the proportions of winter rainfall are 75, 69, and 55 per cent respectively. By Australian standards, rainfall variability, especially interseasonal variability, is low.

The length of effective rainfall season, or 'growing season', at least for pasture plants, is usually estimated from rainfall and evaporation data (Prescott 1949). Average values for annual evaporation from a free water surface range from about 40 in. (1016 mm) in the south to more than 80 in. (2032 mm) in the central and northern outer wheat belt. Moreover, length of growing season ranges from more than 10 months in the extreme south to only about 3 months at the eastern boundary. But the actual length of growing season in the latter case, especially for cereal crops, is probably nearer 3·5 months than 3.

Temperatures are moderate (Gentilli 1956). In the hottest month, February, mean daily temperatures range from about 65°F (18°C) to 80°F (27°C); lowest values occur close to the southern coastline. In the coldest month, July, the corresponding range is from about 45°F (7°C) to 60°F (15°C); lowest values are found in the north-western part of the Darling Plateau. For most of the six wettest months, mean daily temperatures exceed 50°F (10°C) and frosts are rare.

The differences between mean maximum and minimum temperatures for coastal areas, predictably less than those inland, also show much less variation throughout the year. Very broadly, the diurnal range for coastal areas is only 20°F (11°C) in summer and 16°F (9°C) in winter, while the corresponding inland values are 30°F (17°C) and 20°F (11°C).

Over the span of a growing season for crops and pastures, ambient temperatures generally come within the range of 21/16°C (day/night) to 12/7°C. Thus growth of temperate pasture species is restricted to some degree by low winter temperatures.

Computed values of solar (global) radiation for December range from more than 700 cal. cm^{-2} day^{-1} in the north-eastern wheat belt to less than 550 cal. cm^{-2} day^{-1} near Albany on the south coast. For June—the month of lowest radiation—mean values range from 275 cal. cm^{-2} day^{-1} to 170 cal. cm^{-2} day^{-1}. Over the period of the growing season radiation commences at 300–350 cal. cm^{-2} day^{-1}, falls to 200–250 cal. cm^{-2} day^{-1} in winter, and rises to 400–450 cal. cm^{-2} day^{-1} in spring.

Visible radiation almost certainly restricts plant growth rate during the winter months, even at moderately low values of leaf area index (L.A.I.). But the importance of the role of temperature relative to light energy for growth inhibition of pastures during winter is probably species-dependent (Black 1964).

SOILS

Laterite, predominant throughout the south-west, is the parent material for the majority of soils. Soil patterns are shown in Map 2. Mulcahy (1967) recently described the broad landscape patterns and soils for the areas to the east of the Darling Range, that is on the large expanse of the interior plateau. He distinguished four zones.

Salt Lakes and Sandplains

A large zone of internal drainage, lying mostly eastward of the 14 in. (350 mm) isohyet, represents an ancient, well-preserved landscape of subdued relief. Extensive sandplains of deep, yellow sandy material have originated from the weathering of laterite and subsequent colluvial transport downslope. Much of the original laterite profile has been destroyed, and sometimes rock outcrops on the divides.

Erosion on the steeper valley sides has given rise to colluvial and alluvial deposits derived mostly from fresh rock. The valley soils formed on this unweathered parent material are fine-textured, calcareous, and alkaline. These are the 'heavy' soils of the wheat belt, which originally carried woodlands of salmon gums (*Eucalyptus salmonophloia*) and gimlets (*E. salubris*). Wind action on the dry lake surfaces has produced 'lake parna'—a silty, saline, and calcareous material forming mallisols, locally called 'snuffy, morrel' soils.

Younger Laterites

These lie in a moister climate westward of the above zone, and represent the first stage of rejuvenation of the drainage system. More active westward drainage has resulted in a network of valleys and reduced the size of the old plateau residuals.

The main feature of the old valleys is the extensive preservation of lateritic profiles on the sides and floors, the valley-side laterites generally being devoid of a pallid zone. More recent dissection has given rise to pediments (exposures of pallid rock) and downslope, where the pediment is dissected and fresh rock exposed, to red-brown earths and sometimes yellow podzolics. Still further downslope, younger colluvial and alluvial deposits produce fine-textured, calcareous, solonised brown soils.

Laterite-free Area

This, the least extensive zone, occurs only where valleys of a few rivers are deeply entrenched. Perhaps the best example is the Avon Valley, which encompasses the towns of Northam and York. Lateritic materials are usually absent from the valley sides, and red-brown earths are formed from the fresh rock. At lower elevations, colluvial and alluvial material have produced solonised brown soils. In the south the best example is the valley of the Blackwood River where kraznozems are formed from the softer ferruginous parent material. In the Frankland River valley, which drains to the south coast, granites and gneiss have given rise to brown podzolic soils.

Detrital Laterites

The westernmost zone extends to the Darling Scarp. The inland margin coincides with the 25–30 in. (635–762 mm) annual rainfall belt. The entire area is occupied by jarrah (*Eucalyptus marginata*) forest. Remnants of the old Tertiary Plateau are generally small, but ironstone materials of detrital origin are abundant. Hence the dominant soils are lateritic podzolics. Only limited agricultural development has occurred in this zone.

Other Minor Zones

To these four zones outlined by Mulcahy (1967) must be added those underlain by Jurassic and Cretaceous sediments to the west of the Darling Range north of Perth (the Dandarragan Plateau) and those underlain by Miocene sediments along the south coast east of Albany. These sediments flank the Western Platform (Yilgarn Shield) (see Fig. 2 : 1). Because of the sandy nature of the parent material (in both areas), geomorphic and pedogenic processes have led to an even greater preponderance of sandy soils than on the Western Platform. On the Dandarragan Plateau the sandy soils are usually coarse-textured, but along the south coast they are almost always fine-textured. Modifications to the lateritised surfaces have followed the same general pattern as that described by Mulcahy for the zone of salt lakes and sandplains.

Finally, on the Swan Coastal Plain, bounded by the Darling Scarp south of Gingin and the Hill River Scarp north of it, there is a narrow belt of deep sands, together with smaller areas of alluvial soils of much heavier texture. The latter are used mainly for irrigation. Three zones of deep sands have been mapped (McArthur and Bettenay, 1960): the Quindalup system, the youngest and closest to the coast, is calcareous; the Spearwood system consists of yellow sands over limestone; and the Bassendean system, the oldest, is characterised by pale grey deep sands. These last soils are especially difficult to wet, and so seedling germination and emergence may be uneven. Addition of fine particle amendments helps to overcome the non-wetting problem (Roberts 1966).

VEGETATION

According to Gardner (1944), only in the south-west of Australia is the true Australian flora most richly developed. Sclerophyllous plants predominate in every formation, especially in the heaths, and herbaceous plants, especially grasses, are relatively rare. Major vegetation types (see Map 3) are described below.

Temperate Sclerophyll Forests

These occur in the higher-rainfall areas and, for the most part, do not extend inland beyond the 20 in. (508 mm) isohyet. However, heaths replace them on the narrow belt of deep sands forming the Swan Coastal Plain, on the sandy soils formed from Miocene sediments along the south coast east of Albany, and on the sandy soils of the Dandarragan Plateau, north of latitude 31°S.

Karri forest provides the only example of a wet sclerophyll forest in Western Australia. It is characterised by large trees, principally karri (*Eucalyptus diversicolor*), tingle tree (*E. jacksoni* and *E. guilfoylei*), and marri (*E. calophylla*), with mesophytic undergrowth. There is also a prominent understorey of mainly *Casuarina decussata*, *Agonis flexuosa*, and *Banksia* spp. This forest is limited edaphically to soils from granite and gneiss and climatically to annual rainfalls greater than 45 in. (1100 mm). It is found only in the extreme south-west corner of the State.

Jarrah forest, a temperate dry sclerophyll forest, covers most of the higher-rainfall areas inland to the 25 in. (635 mm) isohyet. The distribution of jarrah (*E. marginata*) corresponds closely to that of soils formed on detrital laterites. Other large trees are few, the main associates being *E. patens* (yate) and *E. calophylla* (marri or red gum). All three of these trees are rough-barked, an unusual characteristic among the trees of the south-west. The understorey includes species of Persoonia, Banksia, Casuarina, and Agonis. Sclerophyllous shrubs form a layer 2 to 3 m high and belong mainly to Myrtaceae, Proteaceae, and Leguminosae. There are few herbaceous species. Considerable areas of the jarrah forest are used for timber and for water catchment.

Wandoo (*E. redunca*, var. *elata*) often occurs in small communities within the jarrah forest, generally on valley floors where subsoils are clayey. But the main area of wandoo forest, in the 20 in. to 25 in. (508–635 mm) rainfall belt, occurs on lateritic soils. Small but dense areas of mallet (*E. astringens* and *E. gardneri*) occur on adjacent stony hillsides. Wandoo communities are often woodland rather than forest in form, but are nevertheless poor in herbaceous species.

Tuart (*E. gomphocephala*) is confined to calcareous limestone soils of the Swan Coastal Plain. In the southern part of the tuart forest, shrubs are comparatively scarce, but low trees, such as species of Agonis and Banksia, are common. The presence of a herbaceous ground cover gives this community a woodland appearance.

Temperate Woodlands

Lying for the most part inland of the 20 in. (508 mm) rainfall isohyet, these eventually merge with shrublands of mulga (*Acacia aneura*) to the north. However, as shown in Map 3, the temperate woodlands give way mainly to mallee in the south-eastern corner of the 11 in. to 20 in. rainfall belt. The reason for this is not clear. The woodlands are interspersed with numerous areas of heath (too small to be shown in Map 3). This is again a reflection of the predominating influence of soils on vegetation in the south-west of Western Australia.

York gum-jam woodland is most common on the western margin of the woodland zone. This community of York gum (*E. foecunda*, var. *loxophleba*) and jam (*Acacia acuminata*) occurs in dissected valleys on soils formed from fresh rock (mostly granites). There is an extensive area in the laterite-free zone of the Avon Valley. Jam tends to be associated with the lighter-textured granitic soils and York gum with the soils formed from more basic parent materials. In the vicinity of Wagin the species change and swamp yate (*E. occidentalis*) dominates the woodland, especially where the soils are low-lying and clayey. Wandoo (*E. redunca* var. *elata*) is sometimes associated with York gum and jam. This woodland is sometimes referred to as a temperate savannah woodland because in many cases the undergrowth is dominated by forbs, for example *Stypandra glauca* and *Pimelea* spp.

Salmon gum-gimlet woodland occupies more extensive areas than the York gum-jam. The salmon gum (*E. salmonophloia*) and gimlet (*E. salubris*), together with morrel (*E. oleosa*, var. *longicornis*), extend eastwards to Zanthus and northwards to the mulga shrublands. The woodland is comparatively rich in shrubs, especially in *Acacia* spp. and in Proteaceae in the western part of its range. Towards the eastern boundary, Myoporaceae and Chenopodiaceae predominate. The salmon gum-gimlet community is best developed on the brown solonised soils of the valley floors in the zone of salt lakes and sandplains. It is almost invariably associated with moderately heavy-textured soils, alkaline in reaction (at least in the subsoil). Another eucalypt, yorrel (*E. gracilis*), is common where surface soils are sandy. The salmon gum-gimlet country has been prized for wheat growing since the early days of settlement.

Eucalypt Shrubland (*Mallee*)

The mallee in the south-west comprises several species of Eucalyptus, including *E. incrassata* and *E. annulata*, all with the characteristic 'mallee' habit. Several stems arise from an underground rootstock, resulting in a coppiced habit and canopy top (Wood 1929) (Pl. 21). The predominantly mallee zone occurs as a southern and south-eastern extension of the temperate woodland zone.

There is no clear evidence of the mallee zone being associated with special soil characteristics (see Map 2). But, in general, the soils are sandy or light-textured at the surface and overlay clay subsoils, which are often alkaline.

The distribution of mallee suggests that summer rainfall is an important climatic factor.

Heath

This vegetation type is dominated by sclerophyllous shrubs, mostly about 1 m high, principally of the genera Acacia, Melaleuca, and Grevillea. Some plants are taller (e.g. Xylomelum, Lambertia, Banksia, and Nuytsia), especially on the deeper sands.

The distribution of heath is determined mainly by soils. All heaths occur on infertile lateritic soils that are predominantly sandy in the surface but may be gravelly as well. The so-called 'blackboy' (*Xanthorrhoea* spp.) is common on the more gravelly soils.

The largest areas of heath occur on lateritic soils flanking the Great Western Platform, that is on the Dandarragan Plateau and on the Miocene sediments east of Albany. In both areas the mean average rainfall ranges from about 16 in. (406 mm) to more than 20 in. (508 mm). However, in the southern area the heath is generally associated with *Eucalyptus tetragona*—thus giving rise to a mallee-heath, rather than heath proper. Common shrub genera are Dryandra, Hakea, Isopogon, and Verticordia. East of Esperance, *E. angulosa* replaces *E. tetragona*.

The Swan Coastal Plain, where annual rainfall is as high as 32 in. (813 mm), supports a community dominated by *Banksia* spp. There is an understorey of shrubs and the community has the appearance of a woodland, with an understorey of other shrubs. Outliers of the community extend to areas of relatively low rainfall, for example 15 in. (381 mm). The soils are characteristically grey or yellow deep sands of low inherent fertility.

Apart from these three areas, moderately large and numerous expanses of dry heaths occur interspersed throughout the temperate woodland zone. Here also the heaths occur on lateritic soils, associated with 'interfluves', namely the 'sandplain soils'. The interior and coastal heaths have the same genera, but different species. Grasses are rare in these heaths, and those that are present (Triodia and Plectrachne) have little grazing value.

LIVESTOCK INDUSTRIES

For the 5-year period 1961–2 to 1965–6 the average net value of primary production for Western Australia was $280 million, compared with $240 million for manufacturing industries. Despite the emphasis on secondary industries in recent years, agriculture, including animal production, still plays a dominant role in the State's economy.

Within the South-West Region, cereals—predominantly wheat—give the highest economic return. For example, in 1966, wheat returned $120 million (gross value) compared with $100 million for wool. However, the livestock industries continue to provide a major source of income, although not such a high proportion as in the early part of the decade.

Sheep

At the present time there are more than 23 million sheep in the south-west. The current rate of flock increase of 12 per cent per annum will raise the numbers to 59 million by 1975 (H. G. Neil, personal communication).

Most of the sheep are used for wool production, and the gross value of this product ($100 million) greatly exceeds that of meat production, including fat lambs (about $17 million). In 1966, 1,700,000 grown sheep and less than 900,000 lambs were slaughtered to produce 45,000 tons of meat. The strong emphasis on wool production is reflected in the breed structure of the sheep population: more than 20 million Merinos, and about 500,000 Corriedales. The residue comprises British breeds and, to a great extent, Merino × British breed crossbreds.

Approximately half the sheep in the south-west are carried in the 20 in. to 40 in. (508 mm to 1016 mm) rainfall zone. About 15 per cent of the properties are devoted to sheep grazing only, while 64 per cent combine cereal production with sheep. The average farm covers about 1500 acres (608 ha), and the average flock size is approximately 1700 sheep. Sheep cut about 9·5 lb (4·3 kg) wool per head and produce 10·9 lb per acre or 12·2 kg per ha. Lambing percentages average 70.

The other half of the south-west's sheep are carried in the larger wheat-sheep zone, where the annual rainfall is 11 in. to 20 in. (279–508 mm). Here, 96 per cent of the farms raise cereals as well as sheep. The average farm is 3500 acres (1418 ha) of which 17 per cent is used for wheat and 7 per cent for oats and an average flock is 1400 sheep. Wool production is lower than in the higher-rainfall zone and averages 8·2 lb (3·7 kg) per head. Lamb marking percentages (67) are also lower.

In recent years flock numbers have been increasing rapidly and it seems likely that the rate could be maintained for a number of years. However, with present wool prices it is difficult to predict future trends in sheep numbers. There could be a substantial swing to cattle.

Cattle

Western Australia carries slightly more than 1 million beef cattle, but only half of these are in the south-west. Meat production, mainly beef, is about 58,000 tons per year, and has a gross value of $28 million. Gross income from beef is considerably more than from mutton and lambs, but only about one-quarter as much as that from wool.

Substantial numbers of beef cattle are run throughout the extensive agricultural areas, but almost half of the total, which exceeds 500,000, are in areas receiving an annual rainfall greater than 35 in. (889 mm), where the average farm size is only about 560 acres (227 ha).

In the south-west, calving percentages average only about 75 (Wilkie 1966). However, some well-managed herds achieve values as high as 95 per cent. Calves kept for 'baby beef' are commonly sold at 8–10 months at dressed weights of 250–350 lb (113–158 kg). Animals for steer beef are sold at 1·5 to 2·5 years of age at weights of 550–750 lb (250–340 kg) dressed. The numbers of beasts sold in these two classes are approximately equal.

About 190,000 dairy cattle in the region (comprising most of those in Western Australia), produce 18 million lb (8×10^6 kg) butter, 3·7 million lb ($1{\cdot}7 \times 10^6$ kg) cheese, and almost 62 million gal. (282×10^6 litres) milk, with a gross value of slightly more than $16 million. The dairy herds consist mainly of Australian Illawarra Shorthorn, Jersey, Guernsey, and Friesian cattle. More than 80 per cent of them are in the higher-rainfall sclerophyll forest areas, where beef cattle are also plentiful. A substantial proportion of the milk products comes from the 30,000 acres (12,150 ha) of irrigated pasture.

GRAZING LANDS

Native herbaceous plants are relatively rare in the forests and heaths, and even the woodlands have little value as grazing lands.

Some evidence indicates that kangaroo grass (*Themeda australis*) occurred on a limited scale in forests and woodlands prior to European settlement, but disappeared rapidly following the introduction of domestic livestock. Several spear grass species (*Stipa semibarbata*, *S. variabilis*, and *S. juncifolia*), foxtail mulga grass

(*Neurachne alopecuroides*), and two wallaby grass species (*Danthonia caespitosa* and *D. penicillata*) were common in the original York gum-jam woodlands, and still persist to some extent in non-cultivated areas. Initially, grass density was greater in the southern part of the salmon gum-gimlet woodland because of the higher incidence of summer rain. Some areas, such as Grasspatch, were grass-dominant, probably with species of Danthonia and Stipa, but these have since disappeared.

There is little doubt that the grazing lands of the south-west of Western Australia, like the heaths, forest, and woodlands, have affinities with their counterparts in south-eastern Australia. But perennial grasses failed to persist under grazing, and this failure is a common phenomenon in areas with Mediterranean climates. Because of the impermanence of the native grass communities, it may be argued that south-western Australia has no native grazing lands (see Map 4).

At best, the grazing lands of the south-west have only very minor significance. The livestock industries depend almost entirely on sown pastures, the most important component of which is *Trifolium subterraneum* (subterranean clover).

SOWN PASTURES

About 13 million acres (5·26 million ha) of the South-West Region is under sown pastures. This constitutes 20 per cent of the total area, and the proportion is roughly constant throughout the region except in the northern agricultural area, where, because of extensive sandplains, it falls to only 10 per cent. However, the total cleared area in the south-west is a little less than 31 million acres (12·6 million ha), so sown pastures occupy more than 40 per cent of the cleared land surface.

Except for small areas of perennial pastures in the extreme south-western corner and of irrigated pastures of temperate perennials, the pastures of the south-western temperate forests, woodlands, and heaths are Mediterranean annual.

Land Preparation and Sowing Practices

In the sclerophyll forests, land is now cleared by pushing down the trees and stacking them in windrows with a bulldozer. Small trees and shrubs may be cleared by dragging either a long heavy log behind a bulldozer or a long heavy chain between two large tractors travelling abreast. These operations are normally carried out in the spring or early summer. By the end of summer the dead scrub and light timber is usually dry enough for burning, after which the land may be levelled by dragging harrows of heavy rails across it. Unburnt debris is gathered up by heavy-duty stick rakes.

After the first rains the land is ready for ploughing, with a stump jump disc plough, to a depth of 4–5 in. (10–13 cm). The soil is often left fallow for a year to encourage the decay of native vegetation, and then ploughed again the next autumn. The fallow period may be omitted, and the land cultivated immediately for sowing to wheat or oats. When the crop has been harvested the following summer, the stubble is burnt and the land ploughed again to control regrowth of trees, shrubs, and poison plants like York Road poison (*Gastrolobium calycinum*). After the opening rains a pasture is sown by a tyne seeder with a small seeds attachment.

A decade or more ago, seeding rates for subterranean clover were as low as 2–4 lb per acre (2·2–4·5 kg per ha). Since that time the rates have slowly increased, and figures of 8–12 lb per acre (9–13 kg per ha) are currently common. Rates in the wheat belt are predictably lower than those in the higher-rainfall areas. Barrel medic, usually sown at about 5 lb per acre (5·6 kg per ha), has smaller seeds than subterranean clover and is seldom used in the higher-rainfall areas. Wimmera ryegrass is usually sown under a cereal cover crop at low rates (2 lb per acre or 2·2 kg per ha).

Pasture Species

Sowing of pastures probably began about the turn of the present century with the use of lupins for fattening sheep during summer in the Geraldton area (Gladstones 1968). However, even in 1931–2 the total area sown to pasture was less than 400,000 acres (162,000 ha). The most common legume was the so-called 'mid-season' (Mt Barker) cultivar of subterranean clover (Dunne 1938) in the jarrah forest areas, where the rainfall is greater than 25 in. (635 mm). Since the early thirties, the sowing of pastures has proceeded at a rapid, indeed exponential, rate. By 1961–2 the sown pasture area had risen to 8·2 million acres (3·3 million ha) and now is about 13 million acres (5·25 million ha). This rapid increase is mostly attributable to subterranean clover, and specifically to early-maturing cultivars, chiefly Dwalganup, which have extended the range of annual pastures into the lower-rainfall areas. Virtually all the pastures in the south-west contain but one sown species (Table 14 : 1).

TABLE 14 : 1 Pasture species in south-west Western Australia: area sown and seed produced

Species	Seed production		Area of pasture
	1961–2	1966–7	1967
	tons	tons	Acres (ha) × 104
Trifolium subterraneum			
certified cultivars	2437	8780	1,200(486)
Geraldton		2417	300(121)
Dwalganup		124	400(162)
Yarloop		465	50(20)
Woogenellup		1249	300(121)
Mt Barker		161	50(20)
Trifolium hirtum			
(rose clover)	3	435	35(14)
Trifolium cherleri			
(cupped clover)	—	111	15(6)
Medicago tribuloides			
(barrel medic)	37	1093	100(40)
Medicago littoralis			
(strand medic)	—	73	12(5)
Lupinus spp.[a]			
(approx. 65% digitatus 30% angustifolius)	571	260	50(20)
Ornithopus compressus			
(W.A. or yellow flowered serradella)	5	110	20(8)
Lolium rigidum			
(Wimmera ryegrass)		131	
Perennial species including lucerne, white clover, and paspalum			55(22)

[a] Fall in production marked over the last few years because of the incidence of lupinosis and development of alternative pasture species.

1 long ton = 2240 lb = 1016 kg = 1 metric ton approx.

Source: Based on data published in *Western Australian Year Book* No. 6, 1967.

The pastures in the south-west may be classified as Mediterranean annual, perennial grass-annual legume, and temperate perennial.

Mediterranean Annual Pastures

Annual pastures, by far the most important, occupy virtually all of the total area of 13 million acres (5·25 million ha). They are all self-regenerating to a greater or lesser extent. The overriding influence of subterranean clover is shown by the fact that this species is growing on about 12 million acres (4·8 million ha).

The use of several cultivars of subterranean clover has overcome the wide climatic, and to a much lesser extent edaphic, range of the south-west. The early ones, Dwalganup and Geraldton, together occupy about 7 million acres (2·8 million ha) lying almost entirely inland of the jarrah forest, that is where the annual rainfall is less than 25 in. (635 mm). As mentioned earlier, this applies to 80 per cent of the south-west. These two early cultivars are well adapted to light-textured soils, even under an annual rainfall as low as 12 in. (305 mm), but they are not suited to the heavier and alkaline soils of the salmon gum-gimlet woodland (see below). Other early cultivars occupy much smaller areas. For example, Yarloop, which is particularly well adapted to waterlogged areas, and the newer Dinninup occupy 500,000 acres (202,500 ha) and 100,000 acres (40,500 ha) respectively. Unfortunately, all these cultivars in use in this zone of less than 25 in. (635 mm) annual rainfall are highly oestrogenic and likely to cause 'clover disease' in sheep (see Chapter 26). A great deal of research is being devoted to the development and production of safer cultivars. Those currently under field test include Daliak, Seaton Park, Northam A, and the bred cultivar, Uniwager.

Where the rainfall exceeds 25 in. (635 mm), that is in the jarrah forest zone, Mt Barker has been the common cultivar sown, but in recent years Woogenellup has volunteered within these areas. Mt Barker now occupies only 500,000 acres (202,500 ha), compared with almost 3 million acres (0·8 million ha) of Woogenellup (B. J. Quinlivan, personal communication). Fortunately, both these cultivars appear to be 'safe' with respect to clover disease. Other

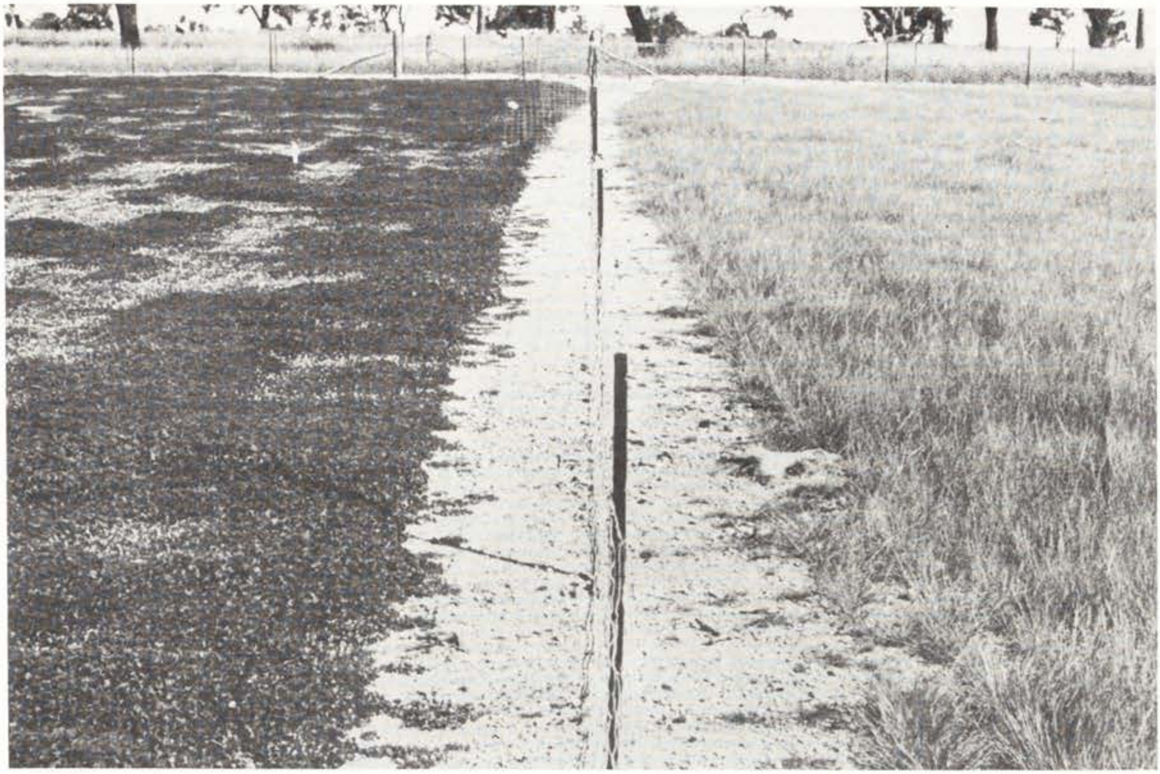


Plate 47 Mediterranean annual pastures: subterranean clover sown left; volunteer silver grass (*Vulpia myuros*) right, south-western Western Australia (CSIRO photo)

cultivars in this zone, e.g. Bacchus Marsh, Clare, and Tallarook, occupy only small areas.

Annual grasses, for example Wimmera ryegrass (*Lolium rigidum*) and to a very small extent soft bromegrass (*Serrafalcus mollis* syn. *Bromus mollis*), have sometimes been sown with subterranean clover. By and large these grasses have not been successful. However, a number of species usually enter clover pastures as volunteers after varying periods. These include silver grass (*Vulpia* spp.) (Pl. 47), ripgut brome (*Bromus rigidus*), and to some extent barley grass (*Hordeum leporinum*), and the two important forbs, capeweed (*Arctotheca calendula* formerly *Cryptostemma calendula*) (Pl. 48) and erodium (*Erodium botrys*). Under some conditions, especially at low stocking rates, these volunteers can dominate the sown pasture. At moderate to high stocking rates, however, the proportions of clover and of the two forbs are relatively high and grasses are subordinate. Rossiter (1966b) has discussed the factors that influence the botanical composition of annual pastures.

Annual medics (*Medicago* spp.) have been sown mostly in areas of less than 15 in. (381 mm) annual rainfall, and where soil conditions are too alkaline for *Trifolium* spp. The total area involved is over 1 million acres (0·4 million ha), of which barrel medic (*M. truncatula* syn. *M. tribuloides*) occupies about 85 per cent and strand medic (*M. littoralis*) the remainder.

Barrel medic, especially its early cultivar Cyprus, is well suited to the relatively heavy-textured wheat-belt soils. These are the valley soils that originally carried salmon gum-gimlet woodlands. Burr medic (*M. polymorpha*) also volunteers on these soils. The volunteer grasses and forbs already mentioned for subterranean clover pastures are found also in medic pastures, but here the most prominent volunteer is common barley grass. Strand medic has been more successful on the calcareous coastal sandy soils of the Quindalup system north of Perth. These

Plate 48 Mediterranean annual pasture dominated by capeweed (*Arctotheca calendula*), coastal plain, south-west Western Australia (CSIRO photo)

soils previously carried a coastal heath community which included some small trees, especially *Acacia* spp.

Lupins rank next in general importance, and occupy an area of at least 500,000 acres (202,500 ha). They are well adapted to the slightly acid, relatively infertile, deep sands of the 20–33 in. (508–838 mm) rainfall zone, where the native vegetation is mostly dry temperate or banksia heath. Of the two main species grown, the Western Australian common blue or sandplain lupin (*Lupinus cosentini*, variously known as *L. varius*, *L. digitatus*, and *L. pilosus*) is the more important, but the New Zealand blue or narrow-leaf lupin (*L. angustifolius*) has wider edaphic tolerance and grows successfully on the lateritic soils of the jarrah forest. The best common lupins grow in the Dandarragan heathlands and in the *E. calophylla* (marri) forests north of Perth on deep red-brown sands of moderate fertility derived from Jurassic sandstone. Lupins have restricted use, mainly as a special-purpose grain legume for the dry summer. Sheep grazing on lupins are sometimes prone to the disease 'lupinosis' (see Chapter 26).

The newer pasture legumes, rose clover (*Trifolium hirtum*), cupped clover (*T. cherleri*), and serradella (mainly *Ornithopus compressus*) are sown on a total area of about 700,000 acres (283,500 ha). Bailey (1966, 1967) selected early-maturing cultivars of the two clovers for use in the low-rainfall areas of the south-western wheat belt where subterranean clover is not well adapted. The deep-rooting, yellow serradella (*O. compressus*) is being used on moderately deep sandy soils of the high-rainfall coastal heaths as an alternative to subterranean clover. This plant seems better adapted than clovers to soils with incipient potassium deficiency (Cariss and Quinlivan 1967).

Perennial Grass-Annual Legume Pastures

The combination of a perennial grass (such as *Lolium perenne* or *Phalaris tuberosa*) with

Plate 49 Lucerne (cv. Hunter River) on former eucalypt shrubland (mallee), South Australia (Department of Agriculture, South Australia, photo)

subterranean clover, common in woodlands of south-eastern Australia, has not been satisfactory in the south-west of the continent. The general and widespread failure of perennial grasses in the south-west is probably due to unsuitable soils, dry summers, and the superimposed grazing factor (see Chapter 6). The warm-season species kikuyu grass (*Pennisetum clandestinum*) may well prove better adapted. Perennial grasses are presently restricted to small areas of wet and dry sclerophyll forests in the extreme south-west, where the annual rainfall exceeds 35 in. (889 mm).

The perennial legume lucerne (*Medicago sativa*) has been grown with moderate success on some deep sands of heaths and mallee heaths receiving more than 20–25 in. (508–635 mm) of rain annually (Pl. 49).

The total area occupied by perennial-annual pastures is only about 30,000 acres (12,150 ha).

Temperate Perennial Pastures

Pastures of perennial species are confined to the irrigation areas adjacent to the Darling Scarp on the Swan Coastal Plain, south of Perth. The total area involved is roughly 20,000 acres (8100 ha) and is used mainly for dairying. The original vegetation on the mostly alluvial soils was sclerophyll forest, dominated by either flooded gum (*Eucalyptus rudis*) or wandoo. White clover (*T. repens*) and perennial ryegrass are the principal sown species. Paspalum (*Paspalum dilatatum*) commonly volunteers and is an important constituent of irrigated pastures.

As well as the perennial pastures described above, several salt-tolerant plants are used in salt-affected areas. According to Lightfoot, Smith, and Malcolm (1964), there are about 1 million acres (0·4 million ha) of salt lands, largely within the 14–25 in. (356–635 mm) rain, fall belt. Roughly one-third of this land was previously cropped or sown to pasture. Several studies (Millington, Burvill, and Marsh 1951; Burvill and Marshall 1951; Smith and Malcolm 1959; Smith 1961; Rogers and Bailey 1963; and Malcolm and Smith 1965) have indicated the value of a number of perennials for salt lands. Seashore paspalum (*Paspalum vaginatum*) is best suited to seepage areas that remain moist through the summer. Puccinellia (*Puccinellia capillaris*) and *Agropyron elongatum*, especially the former, have been grown successfully on bare,

Plate 50 Response by subterranean clover (cv. Dwalganup) to levels of superphosphate on lateritic gravel, south-west Western Australia (CSIRO photo)

highly salty soils that experience periodic flooding. *P. capillaris* has good seed production and withstands intermittent grazing. In the drier areas of the wheat belt, the native bluebush (*Kochia brevifolia*) and some saltbushes (*Atriplex* spp.) are sown extensively on salted land. Malcolm (1961) has emphasised that areas sown to these perennial species can be productive and provide useful summer grazing.

Fertilisers

Most soils of the south-west of Western Australia are almost completely infertile in the absence of applied fertilisers. They have been formed from the products of weathering of highly siliceous rocks low in the organic nutrients that plants and animals need. The landscape is old and the land surfaces have been leached for long periods by rain concentrated into a few months of the year. More than 80 per cent of the 15 million sheep in the State are run on farms where pastures (sown or volunteer) would be poorly productive without regular use of superphosphate.

Phosphorus. Superphosphate is used throughout the areas sown to pasture and crops. Local manufacture of superphosphate commenced early in this century. Its use was intensified after 1920 when the subterranean clover and superphosphate era of pasture development began. Responses to the use of superphosphate on annual pastures have been described many times, for example by Teakle (1945), Cullity and Elliot (1949), and Ryan (1965).

Ground rock phosphate as a fertiliser has received some attention (Rossiter and Ozanne 1955; Fitzpatrick 1961), as have serpentine superphosphate and phosphatic guano (Teakle

TABLE 14 : 2 Fertiliser usage in Western Australia

PASTURES				CROPS			
Area fertilised acres × 10^6 (ha × 10^6)	Super used[a] (tons)	Other fertilisers[b] (tons)	Average lb per acre (kg per ha)	Area fertilised acres × 10^6 (ha × 10^6)	Super used[a] (tons)	Other fertilisers[b] (tons)	Average lb per acre (kg per ha)
12·6 (5·1)	677,000	17,500	123 (138)	8·9 (3·4)	472,000	53,600	134 (150)

[a] Single superphosphate

[b] Other artificial fertilisers.

1 long ton = 2240 lb = 1016 kg = 1 metric ton (approx.).

Source: Data for 1967–8 season from *Western Australian Pocket Year Book*, No. 51, Comm. Bureau Census and Statistics, Perth, 1969.

and Cariss 1944). However, on a majority of soil types, single superphosphate has proved superior to these and a number of other sources of phosphorus.

Soil type has been shown to have a marked effect on phosphorus requirement, as has also the phosphorus fertiliser history of an area. Residual availabilities of 20–80 per cent are common in the year after superphosphate application. Ozanne and Shaw (1967) showed that the phosphorus requirements of subterranean clover pastures are related to the phosphorus sorbing capacities of the soils, and so these measurements may form the basis of a soil test for predicting phosphate needs. The sandy soils widespread in Western Australia usually have a low capacity to bind applied phosphorus, which may be lost by leaching (Ozanne, Kirton, and Shaw 1961).

Gladstones *et al.* (1964) and Humphries (1962) have examined the phosphorus requirements of different pasture species. In a comparison between eight annual pasture species, Ozanne, Keay, and Biddiscombe (1969) found marked differences in phosphorus requirements—in general those of the clovers were high, of the forbs intermediate, and of the grasses low. Rossiter (1964) described changes in botanical composition that may occur with different rates of phosphorus supply.

The 10 million acres (4 million ha) of pasture fertilised in 1965–6 received an average of 116 lb of single superphosphate (10 per cent P) per acre (130 kg per ha). This rate is close to that used on cropped land. Cereals grown in the 12–20 in. (305–508 mm) rainfall belt on sands and sandy loams need an initial application of about 200 lb of superphosphate per acre (224 kg per ha) (Cox 1968). Annual applications may then be gradually reduced until, after some 2000 lb per acre (2240 kg per ha) have been applied, a maintenance application of only 30–60 lb per acre (34–67 kg per ha) is required. On clay loams and clays an initial dressing of about 160 lb per acre (179 kg per ha) is required, reducing to a maintenance application of about 25 lb per acre (28 kg per ha) after 2000 lb per acre (2240 kg per ha) have been applied.

On light-textured soils suitable for subterranean clover, about 200 lb of superphosphate per acre (224 kg per ha) drilled with the seed is adequate. This is about the same as for cereals. But in the second year, 250 lb per acre (280 kg per ha) broadcasts are required. Thereafter, the amount needed decreases to about 30 lb per acre (34 kg per ha), more than that for cereal crops.

In areas of high rainfall, the phosphorus requirements of pastures are higher. New land in the 20–30 in. (508–762 mm) annual rainfall areas requires 360 lb of superphosphate per acre (403 kg per ha)—half drilled with the seed and the other half broadcast. Lateritic gravels need initial amounts up to 600 lb per acre (672 kg per ha) and annual dressings of 180 lb per acre (200 kg per ha) until the total superphosphate applied reaches 2000 lb per acre (2240 kg per ha). Subsequently, annual maintenance applications of 90–150 lb per acre (101–168 kg per ha) seem adequate.

On land receiving more than 30 in. (762 mm) of rain annually that formerly carried dense forests, pastures require still greater amounts of phosphorus. Newly sown land in such areas needs 500–1000 lb of superphosphate per acre (560–1120 kg per ha) in the first year and annual applications of 200–350 lb per acre (224–392 kg per ha) until the total reaches about 4000 lb per acre (4480 kg per ha). Thereafter, the maintenance requirement is small.

Nitrogen. Traditionally, symbiotic nitrogen fixation by legumes has supplied the nitrogen requirements of pastures in south-western Australia. Where suitable legumes can be established, the method has proved cheap and effective. In an area receiving 22 in. (559 mm) of rain annually, Watson (1963) and Watson and Lapins (1964) found that subterranean clover fixed 42–72 lb of nitrogen per acre (47–81 kg per ha) per annum in the top 4 in. (10 cm) of the soil. Soil nitrogen has increased under annual clover pastures by as much as 150–250 lb per acre (168–280 kg per ha) in exceptional cases, and on many soils increases of the order of 50–60 lb nitrogen per acre (56–67 kg per ha) can be achieved at comparatively low levels of superphosphate (56 lb per acre or 63 kg per ha).

These increases in soil nitrogen are also reflected in higher yields when the land is cropped to cereals after a clover ley. At Kojonup, one year of clover increased wheat grain yields from 950 to 1630 lb per acre (1064–1826 kg per ha), and each additional year under clover increased wheat yields by 120 lb per acre (134 kg per ha).

Return of nutrients through the grazing animal did not give greater increases in soil nitrogen under clover pasture than did cutting and removal of herbage. This apparent anomaly can be explained by the large losses of nitrogen from urine in a Mediterranean environment in summer and the adverse effect of the nitrogen returned in the urine on the efficiency of nitrogen fixation by the nodule bacteria.

Clover dominant pastures give only small responses to applied nitrogen. But pastures originally sown with annual legumes have been invaded by bromegrass, capeweed, and other volunteer species and are no longer legume dominant. In some cases the yield of such pastures can be doubled by applying nitrogen at 50 lb per acre (56 kg per ha) (Ozanne 1968). Greenwood, Davies, and Watson (1967) found that, where nitrogen was applied in large quantities, annual grasses replaced subterranean clover, even at stocking rates of 5 sheep per acre (12 sheep per ha). In their experiment, ammonium sulphate initially increased winter growth, but the accumulation of large amounts of straw impeded regeneration of the pasture and reduced yields.

Nitrogen usage, particularly for cereals, is increasing rapidly because of recent price reductions and the profitable results demonstrated in many hundreds of field trials (Roberts *et al.* 1966).

Sulphur. Sulphur deficiency was discovered in Western Australia at about the same time as in the eastern States (Rossiter 1952a). However, it was thought to be of little practical importance, partly because of the widespread use of single superphosphate (about 11 per cent sulphur), and partly because the severity of the deficiency was at first underestimated. The mobility of sulphate in the environment of the south-west was not realised. Large areas of the agricultural soils are podzolics or solodised solonetz with coarse-textured surface horizons and fairly sharp transitions to fine-textured subsoils. On slopes vertical penetration is impeded, and causes water to move downslope within the profile. This causes considerable lateral movement of sulphate (Ozanne, unpublished), and sometimes obscures the results of field trials. Where lateral movement is not important, vertical leaching may remove fertiliser sulphate from the topsoil, so reducing its effectiveness. In some cases sulphate applied as gypsum in the autumn is completely removed from the topsoil before early spring (Barrow 1967b) and responses to further applications are then obtained.

Even where the rate of removal of sulphate is not rapid enough to produce a response to further applications in spring, the residual value of the sulphur in superphosphate is often lower than that of the phosphorus. Continued annual applications of superphosphate are changing many soils from an initial state in which phosphorus was the most deficient nutrient, to one in which sulphur is the more limiting.

Leaching is less important on soils that can adsorb sulphate. This property is well developed on soils derived from basic rocks or lateritic material and is most marked where the rainfall is high (Barrow, Spencer, and McArthur

1969). It can be related to the amount of extractable aluminium in the soil (Barrow 1967). Considerable areas of soils in the south-west have this property, and sulphur deficiency appears to be less important on them. On soils that are strongly leached, elemental sulphur is an effective source of sulphur for pastures.

There are indications that a sheep's requirement for sulphur may be higher than that of the pasture. Hence a pasture that is only marginally deficient in sulphur for plant growth may be severely deficient for grazing sheep.

In summary, sulphur deficiency is known to be important on light soils in the heavy rainfall areas (see Fig. 21 : 3a), but to be unimportant on some of the better soils. In the south-west, sulphur deficiency appears to be a consequence of the rapid loss of sulphate from the system. This can be contrasted with the Northern Tablelands of New South Wales, where an important cause of the widespread sulphur deficiency is low input of sulphur in rainfall (Spencer and Barrow 1963; Barrow, Spencer, and McArthur 1969) and where, in some years at least, leaching is unimportant.

Potassium. Pastures suffering from acute potassium deficiency in the higher rainfall areas (i.e. more than 25 in., 635 mm, annually) have been described by Rossiter (1947), Dunne (1955), and Fitzpatrick and Dunne (1956). Typically, the clover component of the sward disappears and is replaced by grasses of low productivity. In the dairying areas, frequent hay cutting has induced deficiencies on sandy loams. Re-seeding the pastures with clover on these soils is ineffective unless 200 lb potassium chloride per acre (224 kg per ha) is applied. Thereafter, 100 lb per acre (112 kg per ha) as a maintenance dressing for hay paddocks or 30 lb per acre (34 kg per ha) for pasture seems adequate.

More recently, potassium deficiency has shown up in extensive areas of sandy soils in the 15 to 25 in. (381 to 635 mm) rainfall zone (Toms and Fitzpatrick 1961). Most of the exchangeable potassium in these soils is associated with the organic matter in the surface 10 cm. Values of less than 0·2 m.e. of exchangeable potassium per 100 g of soil are commonly associated with potassium deficiency in clovers. Large areas of sandy soils adjoining the south and west coasts are low in potassium, and clover sown on new land in these areas may show deficiency symptoms at an early stage and before grazing. Clover has responded to as much as 224 lb of potassium chloride per acre (250 kg per ha), but in the drier areas 56 lb per acre (63 kg per ha) seems adequate.

Potassium fertilisers are not produced in Australia; the price of imported chloride is about $69 per ton and of sulphate about $90 per ton. Attempts are being made to overcome potassium deficiency in sandy soils by growing deep-rooted legumes such as serradella, lucerne, and lupins, which appear to grow satisfactorily without visible potassium deficiency (Toms and Fitzpatrick 1961; Gladstones *et al.* 1964).

Copper, zinc, molybdenum, and cobalt. Deficiencies of copper and zinc in pastures occur widely, especially on light land, and have been described by Dunne and Elliot (1950) and Rossiter (1951). Zinc deficiency primarily reduces the growth of the clover component of the pasture, but is overcome by an application of 1·5 lb of zinc oxide per acre (1·7 kg per ha). This dressing has an indefinite residual effect due to the 300 ppm or so of zinc present in the superphosphate applied annually (Ozanne, Shaw, and Kirton 1965).

Copper deficiency reduces seed-set in subterranean clover (Rossiter 1951), but is also important for its effects on sheep and cattle (Beck 1962). An application of 5 lb of bluestone ($CuSO_4.5H_{20}$) per acre (5·6 kg per ha) usually raises the level in herbage to the safe figure of 3 ppm copper.

Molybdenum deficiency occurs on a wide variety of soil types (Fitzpatrick 1957). The element appears to limit pasture growth primarily by reducing symbiotic nitrogen fixation in the legumes. However, a recent discovery of widespread molybdenum deficiency in cereals suggests that it may also be limiting grass production. An application of 2 oz of molybdenum trioxide per acre (140 g per ha) supplies the plant requirement indefinitely.

Cobalt deficiency has been recognised for some years in animals, particularly those grazing pastures near the south and west coasts (Bennetts 1955). More recently the response to cobalt was shown in the growth of subterranean clover (Ozanne, Greenwood, and Shaw 1963). However, the cobalt requirement for pasture growth is considerably less than that for healthy animals (Rossiter, Curnow, and Underwood

1948). Dressings of cobalt sulphate overcome deficiencies in some areas, but they often have only a short residual effect, and cobalt 'pellets' placed in the rumen of the sheep are sometimes more effective and economical, especially at low stocking rates.

Nodulation Problems

None of the indigenous strains of Rhizobium associated with the native legumes can effectively nodulate the introduced clovers, medics, peas, vetches, or most lupins. The exception is the Western Australian common blue lupin, which fixes nitrogen with several native strains (Lange and Parker 1960).

When the pasture legumes were introduced to the south-west, some effective *Rhizobium* spp. came in with them. These are slowly colonising the soils of their new environment and effective bacteria have been isolated from nodules on healthy plants in the field.

Pasture legumes sown on new land, especially if the soil is sandy and in an area receiving less than 20 in. (508 mm) of rain per year, often fail because of poor nodulation (see Chapter 22). Such soils appear to contain few or no effective Rhizobium.

The difficulty of clover establishment on virgin soils appears to be aggravated by antibiotic-producing fungi that multiply on the organic debris remaining after the original vegetation has been removed (Holland and Parker 1966). Leaving newly cleared land in fallow for 18 months helps to overcome this problem.

The inoculum now used in Western Australia for *Trifolium* spp. contains two strains of Rhizobium isolated locally. A successful strain must be able to grow and persist in problem soils as a saprophyte (Chatel, Greenwood, and Parker 1968). It must also be able to colonise the rhizophere, form nodules, and fix adequate nitrogen.

Weeds

Pastures on new land are usually weed-free, and most problems occur on land that has been developed for a long period.

The main weeds of old pastures are introduced plants, but native poison plants and eucalypt regrowth often present problems on newly developed land. The native poison plants (*Gastrolobium* spp. and *Oxylobium* spp.) regenerate from root fragments, and stock find the young growth palatable.

Sheep losses occur regularly and records of farmers losing many hundreds of sheep in a single night are common (see Chapters 23 and 26). However, cultivation and spraying with 2, 4, 5-T control both native poison plants and eucalypt regrowth.

Where cropping is important, the more serious pasture weeds are saffron thistle (*Carthamus lanatus*), double gee (*Emex australis*), Paterson's curse (*Echium lycopsis*, formerly *E. plantagineum*), Cape tulip (*Homeria* spp.), dock (*Rumex* spp.), sorrel (*R. acetosella*), and soursob (*Oxalis pes-caprae*).

In the higher-rainfall areas where cropping is less frequent, the important weeds are perennials, for example bracken (*Pteridium aquilinum*), dock, arum lily (*Zantedeschia aethiopica*), and blackberry (*Rubus fruticosus*). Annual weeds in these areas include Paterson's curse, double gee, sheep thistle (*Carduus pycnocephalus*), variegated thistle (*Silybum marianum*), and soursob.

Insect Pests

Several indigenous insects are now pests of pasture in the southern parts of Western Australia, where increased agricultural activities have allowed some native insects to increase enormously. Several introduced insect and mite species infest improved pastures wherever the absence of their native enemies has allowed them to build up to pest proportions (see Chapter 24).

The native insect pests include pasture webworms, other Lepidoptera, scarabs, grasshoppers, and crickets. The pasture webworm is the most important. It is a complex of species belonging to the genus Hednota (Lepidoptera: Crambidae) and is now considered one of the worst pests of pastures and cereal crops (oats excepted) of south-western Australia. This pest has increased with the change from fallow to ley pastures, and crops often have to be treated with insecticide or resown.

Introduced insects and mites include lucerne flea and red-legged earth mite. The introductions, blue oat mite, black beetle, and snails also infest south-western pastures.

Treatment with insecticides is usually carried out by boom spray or aircraft, which are now used extensively for treating pastures to control pasture webworm, red-legged earth mite, and lucerne flea, and also for caterpillar and grasshopper outbreaks. It is estimated that about 100,000 acres (40,500 ha) are sprayed each year for insect control.

ANIMAL PRODUCTION ON SOWN PASTURES

Management Methods

Clover pastures in the south-west have usually been grazed in a loose rotation system of grazing and spelling, dictated both by convenience and by the nutritional requirements of different classes of livestock. In recent years, however, the trend has moved towards set stocking, largely as an outcome of stocking rate experiments in which this simple management procedure has been used (see Chapter 27). By and large, set stocking is not deleterious, although there may be some advantage in autumn deferment in years where a 'false break' to the growing season occurs (Rossiter 1958).

'Strip' grazing was practised some years ago, particularly on irrigated pastures in dairying areas. This system, perhaps more appropriately called 'ration grazing', is sometimes used for grazing cereal crops.

In the wheat-sheep areas, the sheep commonly graze cereal stubbles during the summer period to supplement feed from dry pastures. At critical periods, such as late summer and early autumn, some sheep, especially weaners and breeding ewes, receive supplements of cereal hay or more commonly cereal grain. Oats may be sown to provide some winter grazing, but more particularly for use as a grain supplement and for sale as grain.

Conservation of pasture as hay or silage is now rarely practised in the sheep areas, largely due to the low production per acre and consequent high cost of the rather poor-quality feed obtained. Also, the practice of 'mowing and leaving' (Davenport 1957) for improving the quality of summer grazing is seldom used, probably for the same reason. In the dairying areas, on the other hand, hay and silage are still made.

Stocking Rates

The importance of stocking rate as a major determinant of animal productivity on pastures of Mediterranean annuals has become increasingly accepted in the past decade. Since the first stocking rate experiment at Kojonup in

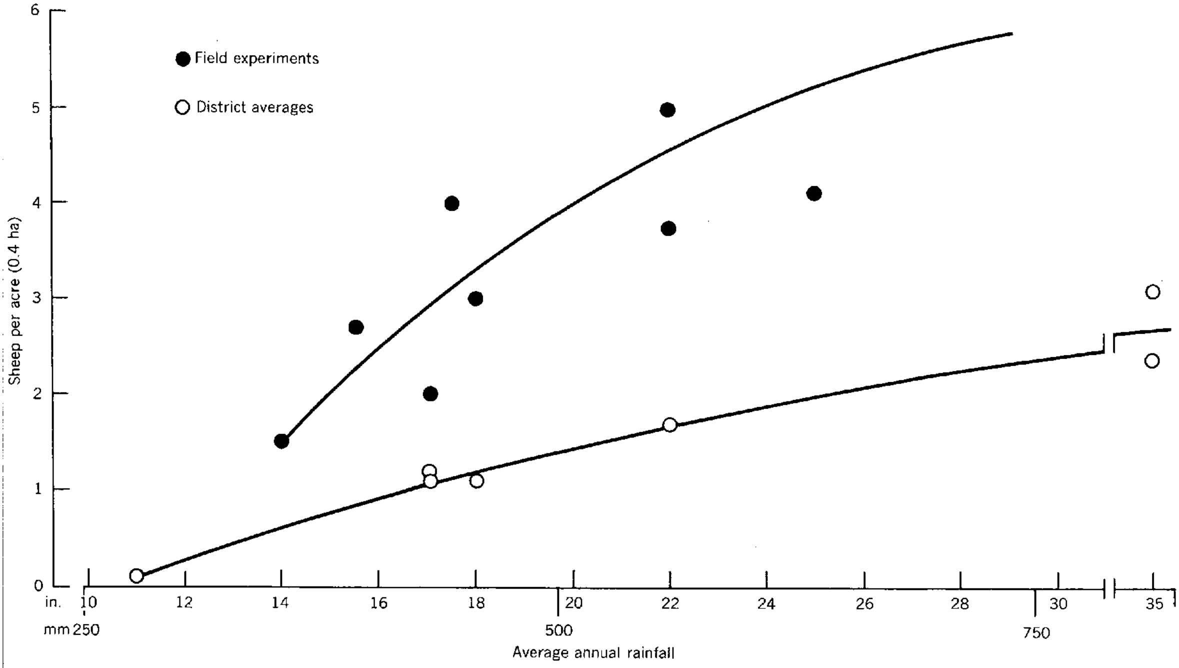


Fig. 14 : 2 Sheep per area on sown pastures. Field experiments compared with the district averages

TABLE 14 : 3 Stocking rates[a] and wool production

Location	Rainfall in. (mm)	Pasture species	Sheep per acre (Sheep per ha)	Greasy wool lb/acre (kg per ha)
Wongan Hills	14 (356)	Subterranean clover	1·5 (3·7) wethers	21 (24)
Beverley	15·5 (394)	Subterranean clover	2·7[a] (6·7) ewes	30 (34)
Northampton	17 (432)	Rose clover	2·0 (4·9) ewes	22 (25)
Esperance	17·5 (444)	Subterranean clover	4·0 (9·9) wethers	56 (63)
Chapman Valley	18 (457)	Subterranean clover	3·0 (7·4) wethers	38 (43)
Mingenew—Morawa	22 (559)	Cyprus barrel medic	4·0 (9·9) wethers	50 (56)
Kojonup	22 (559)	Sub. clover and soft brome	5·0 (12·3) wethers	44 (49)
Kojonup	22 (559)	Capeweed, sub. clover, and ripgut brome	5·0 (12·3) wethers	48 (54)
Mt Barker	30 (762)	Subterranean clover	6·0 (14·8) wethers	77 (86)

[a] Sheep carried for two years or more set stocked and not hand fed.

Source: Based largely on data published in *J. Agric. West. Aust.* (1966) 7 (10): 432–88.

1958 (Davies and Humphries 1965), a number of similar experiments have been undertaken.

In general terms, the available evidence suggests that on clover pastures throughout the zone receiving annual rainfalls of 14–25 in. (356–635 mm), stocking rates for sheep can be raised to twice the district average (see Fig. 14 : 2). This represents a dramatic improvement in animal production, especially of wool per acre. The Western Australian Department of Agriculture recommends operating at two-thirds to three-quarters of the maximum carrying capacity: this is usually close to the economic optimum.

Under high-rainfall conditions there is evidence, too, that increased cattle stocking rates can improve liveweight turn-off and income per acre. On an annual pasture near Mt Barker, in the 30–35 in. (762–889 mm) rainfall zone, Sprivulis (1966) found that the highest stocking rate, 1 yearling beast to 1·3 acres (0·5 ha), gave the highest net return per unit area. Cullity (1966) found that a stocking rate of 2 beasts per acre (0·4 ha), which was higher than commonly used, gave the greatest economic return from an irrigated perennial pasture at Wokalup.

Production per animal usually declines as stocking rates increase. For wool production this is well illustrated in the Kojonup experiment of Davies and Humphries (1965). A stocking rate and time-of-lambing experiment (Davies 1962) showed that growth of lambs born in autumn (April–May) was impaired at high stocking rates, but growth of lambs born in spring (August–September) was independent of stocking rate. The situation appeared to be intermediate for winter-born lambs. Effects on lamb growth rate were associated with differences in pasture availability and quality at different times of the year (see Fig. 14 : 3). At present, about one-half of the sheep flocks in the agricultural areas lamb in autumn, and the remainder in winter or early spring.

Unduly high stocking rates may reduce total animal performance through impaired reproduction and neo-natal mortality (Davies 1968). Lower conception rates in sheep may be due to 'clover disease', but poor body condition at mating time is a not uncommon cause. Lamb losses under farm conditions probably vary between 10 and 20 per cent (H. E. Fels, personal communication). In an experiment at Kojonup with Merino sheep, Davies (1964) showed that lamb losses increased from 20 per cent at 1·5 ewes per acre (0·4 ha) to 34 per cent at 5 ewes per acre (0·4 ha). Losses were higher among twins than singles, and among the lighter of the single lambs.

Pasture Quantity and Quality

Annual pasture yields of 10,000 lb dry matter per acre (11,200 kg per ha) or more can be achieved under European and New Zealand conditions, but rarely under the Mediterranean conditions of the south-west. This is almost certainly because of climatic, and to some extent edaphic, limitations to pasture growth.

For a 6-year period at Perth (35 in. or 889 mm

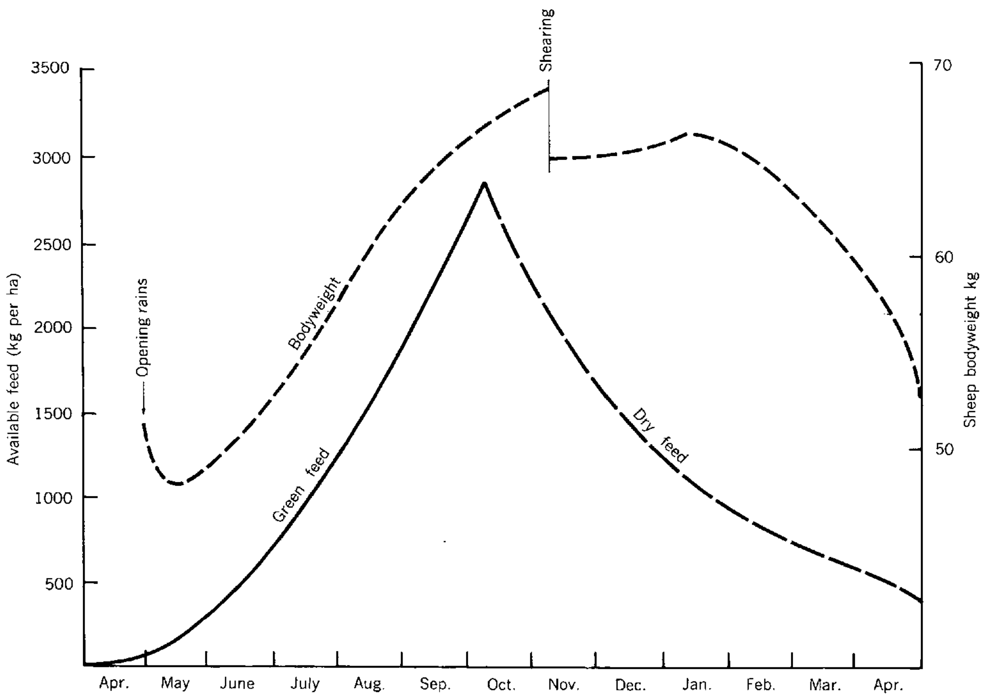


Fig. 14 : 3 Mediterranean annual pasture: seasonal pasture production and liveweight changes in sheep, south-west Western Australia

rainfall; 6·2 months growing season), the mean annual production of pasture was 3900 lb per acre (4368 kg per ha) under set-stocked conditions (Rossiter 1958). The pasture was mainly Dwalganup subterranean clover, capeweed, and ripgut brome grass. For a 2-year period at Kojonup (23 in. or 584 mm rainfall; 6·5 months growing season), the average annual production was 5300 lb per acre (5936 kg per ha) from a Dwalganup subterranean clover-dominant pasture and 7200 lb per acre (8064 kg per ha) from a soft brome-dominant pasture to which nitrogen had been applied (Greenwood *et al.* 1967). The higher pasture production at Kojonup is probably due to a slightly longer growing season and better soils.

Under drier conditions at Wongan Hills (14 in. or 356 mm rainfall), the mean annual yield of a Dwalganup subterranean clover-dominant pasture was 1700 lb per acre (1904 kg per ha) for a 6-year period. At the same time, non-legume pastures dominated by either capeweed or ripgut brome produced only 1000 lb per acre (1120 kg per ha).

Tall-growing legumes such as lupins and rose clover, when ungrazed during the growing season, can yield more than 10,000 lb per acre (11,200 kg per ha). But such high production is not sustained under grazing.

Figure 14 : 3 gives some indication of the amount of pasture available to grazing sheep in the Perth environment, and indicates changes in sheep liveweights. The shapes of these curves are similar for all the heaths, forests, and woodlands of the south-west. Marked losses of dry matter occur during maturation of the pasture at the end of the growing season independent of animal consumption. Rossiter (1966b) has discussed this question for Mediterranean environments in general. It will be noted that animal liveweights decline during the dry summer, and particularly in late summer. This is due partly to the lower amounts of feed on offer, especially at high stocking rates, and partly to its poorer quality. However, the greatest fall in liveweights occurs at the 'break' of the growing season, when the remaining dry residues are damaged by rain, and when new seedlings are emerging.

During the growing season—when grazing

animals almost invariably gain in weight—nitrogen contents, organic matter digestibility (OMD), and voluntary intake of pasture are usually satisfactory (Fels, Moir, and Rossiter 1959; Rossiter 1966b). In the dry summer period, on the other hand, OMD falls to about 50 per cent and sometimes to less than 45 per cent, even for subterranean clover (Fels, Moir, and Rossiter 1959). Dry clover and capeweed frequently contain about 1·5 per cent N, but dry annual grasses and *Erodium botrys* have less—0·5 to 0·8 per cent N. In a recent study with dry mature subterranean clover, Hume, Somers, and McKeown (1968) showed that although clover leaves contained a higher percentage of nitrogen than stems and petioles, *in vitro* dry matter digestibility was lowest for leaves. Differences between clover cultivars in dry matter intake and in digestibility were also found.

Sheep may select high-nitrogen feed in summer (Fels, Moir, and Rossiter 1959), and recent observations (Rossiter unpublished) have shown striking differences between subterranean clover cultivars in acceptability to sheep.

Increased stocking rates often increase the proportion of clover in annual pastures (Rossiter and Pack 1956) and decrease the proportion of annual grasses (Rossiter 1966b). These composition changes in turn influence pasture quality, especially for the summer period, and quality may be critical for weaner sheep on dry pastures.

Animal Production Problems

Two important animal husbandry problems on sown pastures in the south-west are low lambing percentages and sub-optimal livestock production, sometimes involving deaths of sheep. Deaths of lambs are responsible for 40 per cent of the reproductive wastage (Croker 1968).

One of the causes of low lambing percentages is undoubtedly the consumption of pastures with high oestrogenic activity (Bennetts, Underwood, and Shier 1946). The clinical signs of the so-called 'sub clover disease' are given in Chapter 26. The disease is associated particularly with the Dwalganup, Geraldton, Yarloop, and (probably) Dinninup cultivars of subterranean clover and is most likely due to the high isoflavone content, especially formononetin, of these strains. At present there is no known cure for ewes affected with this disorder. Its control is brought about by the use of less oestrogenic cultivars (Davies and Dudzinski 1965) or by restricting access of young female sheep to clover-dominant pastures.

Sub-optimal livestock production may be due to deficiencies of trace elements, particularly deficiencies of copper (Bennetts and Chapman 1937) and cobalt (Underwood and Filmer 1935), or to toxic substances in pastures. The areas of copper and cobalt deficiency are known, but there are others in which the response to copper and cobalt varies between seasons and between paddocks. More recently, selenium-responsive situations have been observed in the higher-rainfall regions, but the response to selenium has varied between seasons and within districts.

Two other problems of more restricted importance affect animal production. Lupinosis, first reported in 1948, is associated with sheep grazing the common bitter lupins (*L. cosentini* and *L. angustifolius*) during summer and especially after summer rains. The etiology of lupinosis is still not completely known (Gardiner 1967). The other problem, urinary calculi, is sometimes associated with clover disease and can lead to losses among sheep.

15

THE MALLEE AND MALLEE HEATHS

P. M. BARROW AND F. B. PEARSON

DISTRIBUTION

'Mallee' is used primarily to describe the shrub-like, multi-stemmed habit of growth of a number of species of the genus Eucalyptus in southern Australia (Pl. 21). It is also a descriptive term for the plant communities and for the areas in which these eucalypts occur.

Mallee vegetation gives way to low heath on certain soil types as rainfall increases. Eucalypts may be completely absent but where present retain the typical mallee habit of growth. Heath communities with mallee eucalypts are known as mallee heaths.

Mallee and mallee heath extend from south-western New South Wales (long. 145°E) through north-western Victoria, southern South Australia to the south-west of Western Australia (long. 118°E). The latitudinal range is from 30°S to 37°S (see Map 3).

The mallee and mallee heath areas of South Australia include practically the whole of Yorke Peninsula and Eyre Peninsula, the coastal plains north of Adelaide, most of the country east of the Mt Lofty Ranges to the Victorian border and south almost to Naracoorte, totalling some 32 million acres (13 million ha) out of the 40 million acres (16 million ha) in the State receiving 10 in. (254 mm) or more rainfall annually.

In Victoria mallee extends from the South Australian border as far east as Kerang, and from the River Murray southwards to Warracknabeal, giving way to mallee heaths and heaths in the Little and Big Deserts.

Adjoining the Victorian mallee there is a large area of mallee to the north of the River Murray in New South Wales. Isolated areas also occur further east in New South Wales.

In Western Australia mallee extends over a huge belt of country from near Esperance in the south to beyond Kalgoorlie. The Western Australian mallee is described in Chapter 14.

CLIMATE

Throughout the mallee and mallee heath the climate is of the Mediterranean type characterised by a predominantly winter rainfall (see Figs. 1 : 7, 1 : 8).

The inland limit of mallee vegetation corresponds reasonably closely with the 8 in. (203 mm) annual rainfall isohyet. The wetter limit is not so clearly defined but occurs at approximately the 18 in. (457 mm) annual isohyet, beyond which mallee gives way to mallee broombush and mallee heath. These extend approximately to the 22 in. (559 mm) annual isohyet.

Temperature and rainfall data for Lameroo, in the southern Murray Mallee in South Australia are given in Table 15 : 1.

SOILS

The topography of the mallee and associated

TABLE 15 : 1 Meteorological data for Lameroo, South Australia

Month	Average daily maximum temperatures (°C)	Average daily minimum temperatures (°C)	Average monthly and yearly rainfall (in.)	(mm)
January	30·6	12·7	0·63	16
February	30·1	13·0	0·95	24
March	27·6	10·9	0·65	17
April	22·6	8·5	0·94	24
May	18·5	6·7	1·71	43
June	15·2	4·8	1·69	43
July	14·7	4·1	1·52	39
August	16·1	4·3	1·86	46
September	19·5	5·7	1·86	46
October	22·4	7·6	1·31	33
November	26·2	9·7	0·92	23
December	29·3	11·8	0·97	25
Year	22·7	8·3	15·01	381

Source: Commonwealth Bureau of Meteorology.

areas is flat to gently undulating and characteristically without streams.

Soil type is the dominant factor determining vegetation, landuse, and pastures. Broadly speaking there are three main soil groups: solonised brown soils (mallee soils) in the lower rainfall areas (8–18 in., 203–457 mm), and solodised solonetz and deep siliceous sands in the wetter areas (15–22 in., 381–559 mm) (see Chapter 3).

Solonised Brown Soils

Solonised brown soils are alkaline throughout the profile and are characterised by an accumulation of lime, usually in nodular or travertine form. A typical profile described by French, Matheson, and Clarke (1968) for 'sandy mallee' soils is as follows:

0–30 in. (0–76 cm) brown, yellow-brown, or pale reddish brown sand with occasionally some fine lime;

30–40 in. (76–102 cm) brown or reddish brown loamy sand or clayey sand with slight to moderate fine lime;

40 in. (102 cm) + yellowish brown clayey sand with fine lime and/or nodular limestone.

However, there is great variation in profile characteristics within solonised brown soils. The surface may vary in texture from loam to sand, and in colour from reddish brown to grey. Free lime may occur right to the surface, although more commonly only in the subsoil. Depth also varies considerably. In the 'stony mallee' soils the topsoil is underlain by dense travertine limestone at very shallow depths, rendering cultivation impossible.

In areas of light textured soils there is frequently a parallel dune and swale topography with the better soils occurring in flat plains between the sandy rises.

Solodised Solonetz

Solodised solonetz soils occur most extensively in western Victoria, in the upper south-east of South Australia and on Eyre Peninsula under slightly higher rainfall conditions than solonised brown soils. They are generally slightly acid at the surface, although lime may occur deeper in the profile.

These soils have a light grey sandy surface and a sharp division between A and B horizons. The B horizon consists of yellow to brown clay with a hard capping and characteristic domed structure, at depths varying from about 6 to 24 in. (15–60 cm) (see Pl. 7).

Deep Siliceous Sands

Deep siliceous sandy soils generally occur in association with solodised solonetz, mainly but not entirely on sandhills. They are moderately acid (pH 5·5 to 6·5) and extremely low in nutrients and in water-holding capacity. Frequently the depth of clay is in excess of 10 ft (3 m).

VEGETATION

The vegetation of the South Australian mallee has been described by Wood (1937). An outstanding characteristic is the habit of growth of the dominant eucalypt species, which develop an enlarged underground lignotuber in place of a normal tree trunk. Several bare stems arise directly from the lignotuber and produce a canopy of leaves at their extremities. The appearance of the vegetation is illustrated in Pl. 21. The height of mallee trees varies from about 4 ft (1·2 m) to a maximum of about 40 ft (12 m).

Because of the multi-branched habit and low height of the dominants, mallee is classified as eucalypt shrubland (Chapter 4, Map 3).

Mallee communities vary with both soil and climate. Near its drier limits mallee has affinities with the shrub steppe and at the wetter end of its range it grades into mallee heaths, heaths, and dry sclerophyll forests. Where mallee adjoins woodland it is common for the dominant woodland eucalypt species in the transition zone to have the mallee habit.

Relationships between various classes of mallee vegetation and soil types are set out in Table 15 : 2.

TABLE 15 : 2 Relationship between soils and mallee communities

Soil type		Vegetation type
Solonised brown soil	< 11 in. (279 mm) rainfall	Arid mallee
	> 11 in. (279 mm) rainfall	Mallee
Solodised solonetz		Mallee broombush
Transition to deeper sands		Mallee heath
Deep sands		Heath

Arid Mallee

In low rainfall mallee eucalypts are frequently taller but more widely separated than in other mallee areas. Red mallee (*E. oleosa*) is the most common eucalypt but a number of other tree species occur, the most important being false sandalwood (*Myoporum platycarpum*). Both these species grow to a height of 20–30 ft (6–9 m). Common smaller shrub species are bullock bush (*Heterodendrum oleifolium*), two species of cassia (*C. sturtii* and *C. eremophila*), and bluebush (*Kochia sedifolia*). A number of annual species germinate after rain.

Arid mallee has affinities with the drier aspects of shrub woodlands (see Chapter 16). At the drier limit of its range saltbushes become predominant in the ground layer, the main species being mallee saltbush (*Atriplex stipitata*) and bladder saltbush (*A. vesicaria*).

Mallee

In areas of 11–18 in. (279–457 mm) annual rainfall, mallee is an almost closed community of eucalypts about 10–20 ft (3–6 m) high. The commonest of the eucalypts are white mallee (*E. dumosa*), *E. oleosa*, and *E. gracilis*. The shrub layer is only moderately dense but has a large number of species, the most common being tea tree (*Melaleuca parviflora*), *Dodonaea bursariifolia*, and *Acacia* spp. Annuals are rare except after rains when a number of species, especially composites, establish where the canopy is open.

On deep red sandy soil eucalypts are replaced by mallee pines (*Callitris columellaris* and *C. preissii* syn. *C. propinqua*) which form low woodlands.

Mallee Broombush

Mallee broombush communities occur on solodised solonetz soils where the sand is less than 1·5 ft (46 cm) deep (Coaldrake 1951) in the upper south-east of South Australia, the Big Desert of Victoria, and Eyre Peninsula.

E. incrassata is the main species although several other species occur. All have the typical mallee habit and grow to a height of 6–12 ft (2–4 m). The eucalypt canopy is underlain by a layer of shrub species, the most important of which is broombush (*Melaleuca uncinata*). Other shrubs include *Hakea rugosa*, *H. muelleriana*, *Acacia spinescens*, and *A. rigens*.

Mallee Heaths

Where the sand is deeper than 1·5 ft (50 cm) heath species become prominent. Mallee species, however, persist where there is no more than about 4 ft (1·2 m) of sand overlying clay.

Mallee heath is thus a transition between mallee broombush and true heath in areas where the underlying clay is at a depth of from 1·5 to 4 ft (46 to 122 cm). The dominant eucalypt species of mallee heath is *E. incrassata*, but in this community it grows to a height of only about 6 ft (2 m).

Heaths

The deep sands are extremely poor both chemically and physically, and heath vegetation is commonly only 1·5 ft (0·5 m) high and does not normally exceed 4 ft (1·2 m).

The species of the heath do not form a complete canopy and there is a high proportion of bare ground. A great profusion of plant species occurs, the dominants being *Banksia ornata*, *Casuarina pusilla*, and *Xanthorrhoea semiplana* (yacca). These communities have affinities with dry sclerophyll forests and are described in Chapter 11.

LIVESTOCK INDUSTRIES

The mallee and mallee heaths can be divided into three broad zones of livestock enterprise:

1. pastoral areas (low rainfall),
2. mixed cereal farming-livestock areas,
3. high rainfall sown pasture areas.

1. *Pastoral Areas*

These are not of great extent, comprising open arid mallee with an annual rainfall of approximately 8–11 in. (203–279 mm).

Station properties vary considerably in size and scale of operation. Part of this zone is former marginal cropping country, where properties are often as small as 10,000 acres (4050 ha). The remainder comprises old established sheep stations as large as 100 sq miles in area (25,920 ha). Wool production from Merino sheep grazing on native grazing lands is the principal enterprise.

2. *Mixed Cereal Farming Livestock Areas*

The drier limit of successful cereal production on mallee soils corresponds approximately with the 11 in. (279 mm) annual isohyet, and mixed livestock-cereal production enterprises extend from this limit to approximately the 17 in. (432 mm) annual rainfall line. This includes all of the mallee proper soils and some of the solodised solonetz.

Within this zone the degree and frequency of cropping vary considerably. Better class land is cropped in alternate years but towards the drier fringe crops are sown about one year in five. Average wheat yields vary from about 10 to 25 bushels per acre (672–1680 kg/ha).

Livestock are run on all properties and contribute considerably to farm income. By far the most important livestock enterprise is wool production from Merino sheep but in higher rainfall parts there is some prime lamb produced by mating British breeds with Merino ewes.

Recently beef cattle have been introduced to a number of properties in the mallee, and this trend seems likely to increase. Cattle are generally purchased in store condition from areas outside the mallee, although there is some local breeding. The main breeds are Hereford and Shorthorn.

3. *High Rainfall Sown Pasture Areas*

In the mallee broombush and mallee heath crops are not of great significance although there is increasing interest in periodically sowing crops to renovate pastures.

Wool production from Merino sheep is the main enterprise but there is some change to more profitable forms of animal production and prime lamb production is of more significance here than in the farming areas. In recent years, too, there has been a swing to beef cattle production, and a number of beef cattle studs have been established in the area. Hereford, Shorthorn, and Aberdeen Angus are the main breeds.

Dairying is a minor activity in this zone.

GRAZING LANDS

The native vegetation of mallee and mallee heaths in areas receiving more than 11 in. (279 mm) of rain annually has a low value for grazing and a low carrying capacity. It is classified as Mallee Grazing Land (Chapter 6, Map 4). In earlier days of settlement, however, these areas were occupied by very large station properties, and carrying capacities of about one sheep to 30 acres (12 ha) were maintained by periodic burning of the vegetation.

The low rainfall mallee beyond the accepted crop areas is still utilised as grazing land. Here the trees are more scattered, and densities of shrub and grass species are higher. These grazing lands are classified as Xerophytic Midgrass (Chapter 6). The plants of most grazing value are the shrub steppe species which intrude into the mallee in this region. On shallow soils there are almost pure stands of bluebush (*Kochia sedifolia*) and on very light sandy soils a fairly dense community of a harsh-leaved tussock grass known as porcupine grass (*Triodia irritans*). Species of Stipa and Danthonia also occur but are too infrequent to be important components.

At the lower limits of rainfall, saltbushes become important in mallee grazing lands. Firstly, mallee saltbush (*A. stipitata*), and then at the limit of the range of mallee species, bladder saltbush (*A. vesicaria*), are of importance.

These grazing lands are little altered from their original state, but in some parts attempts have been made to clear the sparse cover of eucalypts. This was done earlier for cropping which proved uneconomic and more recently has been done again to stimulate production from edible native species and exotic species such as barley grass (*Hordeum leporinum*), woolly burr medic (*Medicago minima*), and barrel medic (*M. truncatula*). Fertilisers are not used, and no attempt is made to sow pasture species, except to a very limited extent in conjunction with contour furrowing as an erosion control measure on land which has been made bare by cropping.

SOWN PASTURES

Mixed Cereal Farming-Livestock Areas

Approximately 75 per cent of the mallee in the 11–17 in. (279–432 mm) rainfall zone has been cleared of native vegetation and developed for arable farming. Farm sizes average about 1500 to 2500 acres (608–1010 ha).

Early attempts at agricultural development met with little success because of the great cost involved in removing the large underground lignotubers ('mallee roots') of the eucalypts. With the invention of the stump-jump plough by R. B. Smith of Maitland, Yorke Peninsula, in 1876, the way was opened for relatively cheap development of large areas of mallee country for wheat growing.

The mallee was first rolled and burnt, and the land then ploughed and sown to wheat. Mallee stumps were left in the ground, and posed no great mechanical problem. Regrowth of shoots from the stumps was controlled by burning wheat stubbles and by slashing.

The development of mallee lands for farming reached its peak in the years immediately before and after World War I but is still in progress.

Originally, mallee farms were used almost exclusively for wheat production, but because of the uncertain rainfall and continuous cropping there was widespread wind erosion and loss of soil fertility. This created a desperate financial situation for mallee farmers during the depression of the early thirties. During this period there were government schemes in all States to increase property sizes by aggregation in the lower rainfall and light-textured soil districts. This enabled a widening of crop rotations, a reduction of fallow periods, and the integration of livestock enterprises with wheat production. Since this time 'mixed farming' has been a universal practice in the mallee.

At first the pastures were entirely volunteer cool season annuals. In the higher rainfall areas, especially on loamy soils, naturalised burr medic (*M. polymorpha*), barley grass, and to a lesser extent barrel medic made important contributions to pasture production, especially where phosphate applications to crops had raised soil phosphorus levels. In the drier sandy farming areas there were then no volunteer legumes of great value and soil fertility levels continued to decline.

It was during the mid-1930s that the need for legume-based pastures to maintain soil fertility in crop lands began to be generally recognised (Callaghan 1939). Barrel medic was suggested as a pasture legume for mallee areas by Professor H. C. Trumble as early as 1931, and seed was first harvested commercially in 1938 by Mr Alf Hannaford who did much to popularise its use in South Australia and Victoria (Trumble 1939). As a tribute to this pioneering work the Australian commercial cultivar of barrel medic was renamed Hannaford in 1967.

Hannaford barrel medic and Wimmera ryegrass, a Mediterranean annual pasture, is still the most important pasture mixture for the mallee. Jemalong barrel medic was discovered naturalised near Forbes, N.S.W. in 1939 (Andrew and Hudson 1954) and is well adapted to the Victorian and South Australian mallee. Crawford (1962) showed that this cultivar is superior to Hannaford in practically all areas where Hannaford is established, and is gradually replacing it.

Until 1959 no annual legume had been found satisfactory for the drier sandy farming areas of the mallee. However, work by Mann (1959) at Walpeup Research Station on a range of introduced annual medics resulted in the release of the Harbinger cultivar of strand medic (*M. littoralis*). This medic is very early maturing and grows well right to the limit of areas used for crops.

Hannaford, Harbinger, and Jemalong medics either alone or in mixture have provided annual legume pastures for all the cereal farming areas of the mallee. Their use has resulted in more and better quality pasture, and has been followed by significant increases in soil fertility.

The place of lucerne as a pasture plant in mallee areas (Pl. 49) was investigated by Cook (1948) and later by Angove (1952). Since the publication of their findings the area sown to lucerne in the mallee has steadily increased. At the present time the area of lucerne in South Australian mallee areas is over a million acres (405,000 ha). The Hunter River cultivar is used almost exclusively, although a small area is being sown to African.

Sown grasses are not important in mallee pastures. Wimmera ryegrass has been sown in the higher rainfall parts and is well established on the heavier soils. In the drier areas pasture grasses are not sown but barley and oats are commonly drilled into wheat stubbles to provide early winter grazing.

Pasture establishment methods. The usual method of establishing both medic and lucerne pastures is to sow the seed, either mixed with the fertiliser or through a small-seeds box with wheat or with stubble sown crops of barley or oats. The normal sowing rate for annual medics is 2–5 lb per acre (2·2–5·6 kg per ha) and for lucerne 0·5–2 lb per acre (0·6 to 2·2 kg per ha).

Crop rotations and fertiliser practices. Once established, annual medics rarely require resowing if managed correctly, and crop rotations have been designed to ensure this. Rotations vary, but characteristically a single cereal crop alternates with one or more years in pasture. All medic cultivars set a high proportion of hard seeds, many of which germinate two seasons after setting, thus ensuring good stands of volunteer medic in the year following a wheat crop.

Where the period of pasture is extended beyond two years medic is replaced by grasses and weed species, and the tendency now is to shorten the pasture phase to utilise fully the nitrogen fixed by the medic, and to avoid both the fungus disease hay-die (*Ophiobolus graminis*), and attack by the cereal eel-worm (*Heterodera avenae*), both of which increase under grass-dominant pastures.

In much of the mallee, where flats of heavier-textured soils alternate with parallel rises of light sandy soils, it has become common to subdivide properties on the basis of soil type and topography so that Jemalong and Harbinger medics can be sown on the regularly cropped flats and lucerne on the sandy rises. Lucerne paddocks are cultivated for crops about once every five years, and under these conditions a population of about 5 lucerne plants per sq yd (0·8 m^2) can be maintained almost indefinitely.

Solonised brown soils are deficient in phosphorus for normal plant growth, and marginally deficient in copper for livestock health and wool quality. Superphosphate is sown with all cereal crops at rates ranging from 0·5 to 1·5 cwt per acre (62–187 kg per ha). Application directly to pastures is not universally practised but in the better mallee areas superphosphate may be applied as a top-dressing in autumn at the rate of about 1 cwt per acre (125 kg per ha).

Where poor quality of wool indicates copper deficiency it is usual to apply copper sulphate with superphosphate at the rate of 3·5 or 7 lb per acre (4 or 8 kg per ha).

High Rainfall Sown Pasture Areas

Where rainfall exceeds 17 in. (432 mm) per annum mallee broombush and mallee heath lands are used mainly for permanent pastures. Property sizes vary from 1000 acres to 50,000 acres (405 to 20,250 ha). At the present time approximately 50 per cent of the mallee broombush and mallee heaths have been sown.

Because of their low nutritional status the solodised solonetz and deep sands have been among the last extensive areas left undeveloped in South Australia and western Victoria. Early attempts at development were largely unsuccessful until research by Riceman (1945) and Anderson and Neal-Smith (1951) demonstrated the necessity of the trace elements copper and zinc for successful pasture establishment and growth. The effect of trace elements on clover growth is set out in Table 15 : 3.

TABLE 15 : 3 Effect of zinc and copper on the first year yields of subterranean clover. Oven dry weights; in lb per acre (approx. kg per ha)

Fertiliser		Zinc sulphate	
		Nil	7
Copper sulphate	Nil	148	280
	7	149	383

Source: Riceman 1945.

These discoveries paved the way for a tremendous boom in land clearing and pasture sowing immediately following World War II and particularly in the 1950s. Modern technology and equipment and relatively large amounts of investment capital have enabled the use of more sophisticated methods of land clearing and development than in the true mallee. Clearing methods vary with the equipment and capital available, but it is now possible to obtain a mowable pasture at the outset. Where cheaper and less thorough methods are employed mowing is not possible and shrub regrowth necessitates re-working the land after about six years (Tiver 1958a).

Most of the new development is being done by contractors and costs vary from about $20 to $40 per acre ($50–100 per ha) for clearing and sowing to pasture.

The acquisition of approximately 800,000 acres (324,000 ha) of mallee in Victoria and South Australia in 1950 by an insurance company, the Australian Mutual Provident Society, and the subsequent publicity, gave a tremendous impetus to land development in the mallee broombush and mallee heath areas. The subdivision of this land after development into smaller holdings has been one of the few successes achieved by massive corporate land development schemes in Australia.

Pasture species and fertiliser practices. In the mallee broombush subterranean clover has been the outstanding pasture species and the key to successful land development. Bacchus Marsh and Dwalganup were used mostly in early sowings, but now Woogenellup and Geraldton are the main cultivars.

Medics also have a role in mallee broombush country, especially along the drier fringes where some mixed farming is practised. In the higher rainfall parts medics have not been as successful as subterranean clover but Jemalong and Harbinger are usually included in pastures sown on new land.

Lucerne (cv. Hunter River) is grown extensively in the mallee broombush areas, where it makes an important contribution to feed in summer and autumn when annual species are dry.

Annual ryegrass (cv. Wimmera) is the main grass sown. It is supplemented by barley grass and several species of Bromus which volunteer in pastures soon after establishment.

Perennial grasses are utilised to some extent, and in particular *Phalaris tuberosa* (cv. Australian) is a valuable species. Other perennial grasses which are being used include perennial veldt grass (*Ehrharta calycina*) and cocksfoot (*Dactylis glomerata* cv. Currie).

In the mallee heath and heath areas, successful development was for long considered impossible because of the depth of sand, the low plant nutrient status, and associated pasture establishment problems.

The earliest use of the very deep sands relied on perennial veldt grass, evening primrose (*Oenothera odorata*) and Dwalganup subterranean clover. However, the vigorous veldt grass soon eliminated the shallow-rooted legume, and the subsequent nitrogen deficiency reduced carrying capacity to a level barely sufficient to compensate for development costs.

Because of the depth of sand, lucerne seemed the obvious pasture plant, but establishment proved difficult. The various causes of lucerne failure were eventually determined (Tiver 1958b), and thus paved the way for the utilisation of deep sands. Techniques now include the use of Rhizobium-inoculated and lime-pelleted seed, lime drilled with the seed to counteract the acidifying effect of superphosphate in poorly buffered acid soils, and the separate placement of seed and trace elements to prevent copper and zinc toxicity to the inoculant.

In addition to 3 lb per acre (3·3 kg per ha) of lucerne, pasture mixtures usually contain small quantities of phalaris or cocksfoot, clover, medic, annual ryegrasses, and oats.

The fertiliser mixture usually consists of 187 lb per acre (209 kg per ha) of lime sown with the seed, and 374 lb per acre (419 kg per ha) of superphosphate containing copper sulphate and zinc sulphate each at 7 lb per acre (8 kg per ha), molybdenum oxide at 1 oz per acre (70 g per ha), and cobalt sulphate at 4 oz per acre (280 g per ha), sown separately.

At least 187 lb per acre (209 kg per ha) of superphosphate is applied annually until a total of 0·5 ton per acre (1255 kg per ha) has been applied, after which applications may be reduced to 94 lb per acre (105 kg per ha). Applications of copper are made periodically but further amounts of the other trace elements are not usually required.

Periodic renovation of pastures is essential. This is done by cultivating with tyne implements. Frequently oats are sown and superphosphate is applied at the same time. The extra grazing obtained from the oats covers the cost of the operation.

Renovation is usually done during May or June when the soils are wet. This does much to overcome the problem of water repellance thought to be caused by a fungal exudate which sometimes forms a hydrophobic film on individual sand grains (Bond and Harris 1964). Water enters irregularly into such soils and pasture may die of drought in unwetted patches.

ANIMAL PRODUCTION

The kinds and intensity of livestock production in the mallee and associated areas vary according to rainfall and soil fertility. In the mallee as a whole, the principal livestock enterprise is wool production from Merino sheep. Interest in other forms of livestock production is quickening because of recent falls in wool prices. Of the alternatives beef production is the most important, especially in the higher rainfall pasture areas of the mallee broombush and mallee heath.

In Table 15 : 4 forms of livestock husbandry and production data from three type areas in the South Australian mallee are presented.

TABLE 15 : 4 Livestock husbandry and production in mallee areas of South Australia

	Co. Young arid mallee	Co. Alfred mallee mixed farming	Co. Buckingham mallee heath
Mean annual rainfall	203–254 mm 8–10 in.	254–305 mm 10–12 in.	432–508 mm 17–20 in.
Numbers of holdings	97	771	624
Area of holdings	443,182 ha 1,094,276 acres	383,274 ha 946,356 acres	403,371 ha 995,977 acres
Sheep numbers	34,503	145,477	930,754
Approx. carrying capacity in dry sheep equivalents	0·12 to 0·30 per ha 0·05 to 0·12 per acre	0·49 to 1·24 per ha 0·2 to 0·5 per acre	3·70 to 7·41 per ha 1·5 to 3·0 per acre
Percentages of ewes carried	56·2	60·3	51·3
Percentages of ewes mated to Merino rams	97·8	92·1	80·1
Lambing percentages	42·1	74·7	81·5
Wool yields	201,260 kg 443,694 lb	793,880 kg 1,750,177 lb	4,791,803 kg 10,563,940 lb
Wool per head of sheep and lambs shorn	5·13 kg (11·3 lb)	4·99 kg (11·0 lb)	5·90 kg (13·0 lb)
Numbers of cattle for meat production	69	1994	22,050
Numbers of cattle for milk production	117	1185	3935

Source: Commonwealth Bureau of Census and Statistics.

County Young, north of the River Murray, is fairly typical of the low rainfall mallee pastoral area. County Alfred, south of the Murray and adjoining the Victorian border, is a typical dry mallee mixed farming area, and County Buckingham in the upper south-east adjoining the Victorian border is mainly high rainfall mallee broombush and mallee heath pasture, although other areas of heavier alkaline soils do intrude.

Feed availability and grazing management. In the mixed farming areas animals are managed to fit in with cropping practices. The main growth of pasture occurs during the spring and an abundance of feed is usually available until stock are placed on cereal stubbles in January. From then until the opening rains of the winter stock depend on dry feed; this is the period of greatest feed shortage.

Pasture hay is made in the higher rainfall farming areas, but throughout much of the mallee the only reserve fodder is cereal grain. Lucerne, where sown, also plays an important part in overcoming the feed gap in autumn and early winter.

Except in the occasional high rainfall season the health of livestock poses no serious problems in mallee areas. Nutritional disorders associated with the normal seasonal fluctuation in feed supply are the biggest problems.

In the higher rainfall grazing country the seasonal pattern of pasture growth is similar, but the spring flush is longer. Except where lucerne is a major component of the pasture some fodder is conserved, usually as hay. Oats are frequently sown as part of the pasture renovation program, and although the crop is often grazed during the growing season, grain is harvested as a fodder reserve whenever possible.

There are no major livestock health problems in the higher rainfall grazing country. Phalaris staggers is prevented by the use of cobalt pellets (Dewey, Lee, and Marston 1958). Infertility and lambing disorders in ewes due to oestrogenic compounds in subterranean clover have been common in the past, but Dwalganup and Yarloop are now being replaced by less oestrogenic cultivars.

WEEDS AND PESTS OF PASTURES

There are weeds in annual pastures in all of the mallee and associated areas. These include saffron thistle (*Carthamus lanatus*), lincoln weed (*Diplotaxis tenuifolia*), yellow burr weed (*Amsinckia* spp.), horehound (*Marrubium vulgare*), wild mignonette (*Reseda luteola*), onion weed (*Asphodelus fistulosus*), and capeweed (*Cryptostemma calendula* syn. *Arctotheca calendula*).

By far the most serious weed in mallee crop lands is skeleton weed (*Chondrilla juncea*) which appeared in the Victorian and South Australian mallee prior to 1947, and since then despite every effort by landholders, government, and local government agencies, has spread throughout the cultivated mallee lands of Victoria, New South Wales and South Australia Murray Mallee and Murray Plains districts. In addition, outbreaks are occurring with increasing frequency in mallee farming lands on Yorke Peninsula and Eyre Peninsula, and in the high rainfall grazing lands in western Victoria and upper south-east of South Australia.

In other parts of Australia skeleton weed is essentially a weed of crop lands and has been successfully controlled by annual legumes (Moore and Robertson 1964). In the mallee annual legumes offer little effective competition against skeleton weed in the sandier soils (Wells 1967). Lucerne will suppress the weed on the better class mallee soils, but there is reason to believe that this may not be the case in the more infertile solonetzic soils. On these soils skeleton weed appears capable of preventing the establishment of lucerne.

There are few insect pests of mallee pastures, and these are mostly controlled by chemicals. Red-legged earth mite (*Halotydeus destructor*) attacks pastures throughout most of the mallee and causes greatest damage to young seedlings of annual medics and clovers. This insect is easily and cheaply controlled by spraying with organo-phosphorus compounds. Treatment must be applied 3–5 weeks after the opening seasonal rains for effective control. Little spraying for pest control is done in the drier portions of the mallee.

Another insect pest of major significance is pink cutworm (*Agrotis munda*), the larval stage of which attacks lucerne plants in the late spring period and may destroy newly established stands. Chemical control of pink cutworm is routine practice on all new lucerne sowings in the higher rainfall mallee areas.

Rabbits have been a continuing problem in mallee areas. Until the introduction of myxomatosis the rabbit problem had appeared almost insurmountable because of the light sandy soils and the partial state of development of the mallee. Rabbit populations have increased again in recent years but the sponsorship of contract control operations by local governments has done much to meet this situation. Modern control is based on the destruction of warrens and strategic poisoning with sodium fluoroacetate (1080). Myxomatosis is regarded as an erratic ally in rabbit control because its effectiveness varies so much with seasonal conditions.

CONCLUSION

The area of solonised brown soils in South Australia, Victoria, and New South Wales includes some of the poorest and most marginal cereal farming country in Australia. It also includes much that is productive and capable of a high level of agricultural development.

Annual medics have been unquestionably the key to successful crop and livestock production. The perennial medic, lucerne, is just now coming into its own as a means of adding stability to farming and increasing carrying capacities on the lighter sandy soils.

The solodised solonetz and deep sands are some of the most inherently infertile soils in Australia but land on which early attempts to sow pastures failed is now yielding to modern technology.

There are an estimated 3 million acres (1,215,000 ha) of mallee broombush and mallee heath land still undeveloped in Victoria and South Australia. The difficulties in the way of utilisation are skeleton weed, the high fertiliser requirements, and the poor physical characteristics of the deeper sands.

16

SEMI-ARID WOODLANDS

R. MILTON MOORE, R. W. CONDON, AND J. H. LEIGH

DISTRIBUTION

Between the mesophytic grazing lands of eastern and northern Australia where pastures of introduced species can be sown, and the arid communities of the interior where animal production depends almost entirely on native species, there is an elongated belt of shrub and low woodlands characterised by grasses belonging to the genera Aristida, Stipa, Eragrostis, and Danthonia. These semi-arid communities extend in a great crescent from the north-east of Western Australia across the Northern Territory (lat. 18°S) through Queensland to the junction of the Murray and Darling Rivers in the south-western corner of New South Wales, thence in a narrow strip along both sides of the Murray River for a short distance into South Australia (lat. 33°S).

South of the Gulf of Carpentaria in north Queensland the continuity of the semi-arid communities is broken by tropical and arid grasslands overlying the Great Artesian Basin (Map 3).

Boundaries of semi-arid woodlands with arid shrublands of *Acacia aneura* (mulga) are not distinct and, in the south, species of the shrub and herbaceous layers may extend from one community to the other. Nevertheless there are sharp discontinuities with some other communities as a result of soil and topographic changes; soil texture in particular may have a controlling effect on vegetation within a uniform climatic zone. This is exemplified by the occurrence of outliers of arid grasslands, shrub steppe, and brigalow within shrub woodlands (see Figs. 16 : 1 and 9 : 1).

CLIMATE

The climate of Northern Territory semi-arid woodlands is discussed by Slatyer (1960, in press), Fitzpatrick and Arnold (1964), Fitzpatrick (1967a and b), and analyses of the climatology of semi-arid Queensland are given by Farmer, Everist, and Moule (1947) and Slatyer (1964).

The annual rainfall pattern in the semi-arid woodland zone changes from complete summer dominance in the Northern Territory through decreasing summer dominance in Queensland, equal summer and winter incidence in central New South Wales, to a predominantly winter incidence in southern New South Wales. In the Northern Territory where the winters are virtually dry, semi-arid woodlands lie mainly between the 30 and 20 in. (762–508 mm) isohyets. Southwards as the proportion of winter rain increases shrub woodlands occur at increasingly lower annual rainfalls. For example, in southern Queensland where 37 per cent of the rainfall is recorded in winter, shrub woodlands occur between the 24 and 18 in. (610–457 mm) isohyets, whereas in southern New South Wales where 62 per cent of the annual rainfall falls between May and October they are found between the 10 and 16 in. (254–406 mm) annual isohyets.

The rainfall pattern for semi-arid woodlands in central and eastern Queensland is similar to that shown in Tables 9 : 2 and 9 : 3 and lengths of growing seasons in north-eastern woodlands are shown in Fig. 7 : 2. Droughts during which there is less than two-thirds of the mean annual rainfall occur more than once in ten years in southern areas and there are dry periods of 3–4 months' duration each year.

Temperatures are typical of an inland region of low relief; winters are mild and characterised by warm days in the south and warm to hot days in the north. Below the Tropic of Capricorn frosts are common in June, July, and August. Summers are hot and temperatures above 100°F (38°C) are not uncommon in both north and south. The mean annual temperature varies from 60°F (16°C) in the south to 80°F (27°C) in the north. At Deniliquin (lat. 33°S) in southern New South Wales an average of sixty days a year exceed 90°F (32°C) and the mean annual evaporation is approximately 65 in. (1651 mm).

SOILS

A pattern of skeletal soils, red and yellow earths, red-brown earths, solodised solonetz, grey and brown cracking clays, is repeated wholly or in part throughout the semi-arid woodlands (see Chapter 3).

In eastern Australia skeletal soils on steep hills, ranges, and low ridges support mulga in the west (see Chapter 17) and eucalypt sclerophyll forests and woodlands in the east where the rainfall is higher (see Chapters 8 and 12).

In the Northern Territory and northern parts of Western Australia the soils common in semi-arid woodlands are red and yellow earths which have gradational or uniform texture profiles (Stewart 1954, in press; Rutherford 1964). In central Queensland semi-arid woodlands are found on texture-contrast soils, many of which are solodic or solodised solonetz. These soils are described by Sleeman (1964), Sweeney (1968), and Gunn (1967).

Much of the topography of the semi-arid woodland zone in New South Wales consists of flats interspersed with low rises; even a slight difference in elevation may mean a change in soil type (Stannard 1962), and each soil type in the catena has characteristic vegetation. The soils of the flats are grey and brown clays frequently with gilgais and often self-mulching (see Chapter 3, Pls. 5 and 6). Above the flat areas soils have less clay, more silt in the surface, and are more compact. Typical red-brown earths and grey and brown clays (Stace *et al.* 1968) have been described in the Macquarie region of New South Wales by Downes and Sleeman (1953). At the tops of rises the soils may be sandy or gravelly.

Sandy brown acid soils similar to the Nyngara brown acid soils described by Downes and Sleeman (1953) occur in the summer rainfall zone of northern New South Wales known colloquially as 'soft red' country (James 1960a). These range from deep sands and sandy loams to shallow sandy loams and soils with a loam surface overlying loams and clay loams. Lighter-textured variants are frequently associated with sand hills. There is a gradual increase in texture with depth and many of these soils have a compacted zone of clay loam or clay at 18–24 in. (46–61 cm).

The soils of the gently undulating country of central and northern New South Wales called 'hard red' country are also brown acid but here they are red-brown loams and clay loams generally lacking calcium carbonate. Profile differentiation is variable, and is generally expressed as a heavier-textured and more compact sub-surface horizon. These are similar to the Giridale brown acid soils of Downes and Sleeman (1953).

The extensive riverine plain of southern New South Wales and northern Victoria (Butler 1950) was formed by outwash from mountains to the south and east of Deniliquin (see Chapter 2). The soils are clay and clay loams and are classified as grey or brown cracking clays.

Many of the southern soils have fairly high levels of salt and as in Queensland there are extensive areas of solodic and solodised solonetz soils.

In addition to these commonly occurring soils there are other brown soils in the winter rainfall zone of New South Wales that are light and medium textured at the surface, becoming slightly heavier with depth but with no marked profile differentiation. They are characterised by nodular limestone appearing at 12–18 in. (30–46 cm), becoming heavy at 24 in. (61 cm), and extending to 6 or 7 ft (1·8–2 m). These soils are akin to the solonised brown soils described by Stephens (1953) but, at least in the northern part of New South Wales, do not have the highly alkaline reaction considered typical of solonised brown soils, nor do they contain appreciable quantities of soluble salts.

VEGETATION

Shrub woodlands and low woodlands have been described in the Northern Territory by Perry and Christian (1954) and Perry (1960, in press); in northern Western Australia by Speck, Fitzgerald, and Perry (1964), Speck and Lazarides (1964); in Queensland by Blake (1938), Isbell (1957, 1962), Holland and C. W. E. Moore (1962), Perry and Lazarides (1964), Johnson (1964), Pedley (1967), and Story (1967); in New South Wales by Beadle (1948), C. W. E. Moore (1953a and b), O. B. Williams (1955, 1956, 1961), Stannard (1958, 1962, 1963), James

Plate 51 Semi-arid low woodland of *Eucalyptus dichromophloia* (bloodwood) with an understorey of *Aristida* spp.: Xerophytic Midgrass grazing lands (northern), Northern Territory (CSIRO photo)

(1960b), Condon (1961a and b), and Biddiscombe (1963); and for Victoria by Zimmer (1937) and Rowan and Downes (1963).

Shrub woodlands have one or more shrub layers, the taller being 10–20 ft (3–6 m) and the shorter 3–10 ft (1–3 m) (Pl. 17). In places the shrubs extend beyond the lower limits of the upper-storey trees and form extensive shrublands. In other places as, for example, in north Queensland and the Northern Territory, the overstorey trees including eucalypts may be reduced to shrub height and are classified as low woodlands. There are small patches of true grasslands: *Stipa aristiglumis* in temperate, *Dichanthium sericeum* and *Bothriochloa erianthoides* in sub-tropical, and *Dichanthium fecundum*, *D. tenuiculum*, and *Eulalia fulva* in tropical semi-arid zones. These grasslands are more extensive in higher rainfall areas and are briefly described in Chapters 6, 8, and 9. There are also outliers of arid grasslands, both tussock and hummock (see Chapter 17), within the semi-arid woodlands.

Although many species of eucalypts occur on both sides of the Great Artesian Basin several are restricted to one side or the other (Perry and Lazarides 1964). On the western side of the common eucalypts *E. brevifolia* (snappy gum), *E. pruinosa* (silver-leaf box), and *E. argillacea* (western box) are generally about 20 ft (6 m) high and form low woodlands with sparse herbaceous layers. To the south the dominant form is shrub woodland (see Map 3).

A *Eucalyptus brevifolia* low woodland, the Sparse Low Woodland of Perry and Lazarides (1964), extends from the Kimberleys in Western Australia to western Queensland on shallow stony or lateritic soils between the 15 and 27 in. (381–686 mm) mean annual rainfall isohyets. On soils derived from more basic rocks *E. brevifolia* may be replaced by *E. terminalis* (bloodwood) (Pl. 18) and *E. argillacea*. Parts

Plate 52 Semi-arid low woodland of *Bauhinia cunninghamii* (bean tree) with understorey of *Aristida* spp. and *Chrysopogon fallax*, Carpentaria, Queensland (CSIRO photo)

of this woodland are classed as arid and the drier southern half in which the dominant grass is *Triodia pungens* is described in Chapter 17. As rainfall increases *E. dichromophloia* (bloodwood), *E. pruinosa*, and *Ventilago viminalis* (supplejack) become more common. Other shrubs in this semi-arid low woodland include *Atalaya hemiglauca* (whitewood), *Grevillea striata* (beefwood), *Petalostigma banksii* (quinine bush), *Terminalia canescens*, as well as several species of Acacia and of Cassia. Species of Aristida have a high constancy and the common ones are *A. inaequiglumis* and *A. pruinosa*.

South of the Gulf of Carpentaria and interspersed with grasslands of *Dichanthium fecundum* (bluegrass) and *Eulalia fulva* (brown top) or *Astrebla* spp. (Mitchell grasses) there is a low woodland of *Eucalyptus pruinosa* which extends westwards, between the 17 and 25 in. (432–635 mm) mean annual rainfall isohyets, across northern Australia to the Kimberleys. It occurs mostly on red or yellow earths. Low trees or shrubs occurring sporadically include *Atalaya hemiglauca*, *Grevillea striata*, and *Eucalyptus terminalis*. There is a sparse low shrub cover of *Carissa lanceolata* (konkerberry). The grass layer is composed mainly of *Aristida pruinosa*, *A. inaequiglumis*, *Sehima nervosa*, and *Chrysopogon fallax*.

In the Victoria River district of the Northern Territory a silver-leaf box community occupies the lowlands of hilly volcanic country where the rainfall ranges from 30 to 17 in. (762–432 mm) per annum. Herbaceous species of tropical woodlands, *Themeda australis*, *Bothriochloa decipiens*, and *Chrysopogon pallidus*, occur in the higher rainfall parts of the community. The native couch grass, *Brachyachne convergens*, is common throughout.

Between latitudes 15° and 18°S and the 17–30 in. (432–762 mm) annual rainfall isohyets in the Northern Territory there are two other low

Plate 53 Semi-arid low woodland of *Melaleuca viridiflora* (tea tree) with understorey of *Aristida* spp. and *Chrysopogon fallax* (ribbon grass), Carpentaria, Queensland (CSIRO photo)

woodlands, one dominated by *Eucalyptus dichromophloia* (Pl. 15), a species common in tropical and sub-tropical woodlands in Queensland, and the other by *Acacia shirleyi* (lancewood). The commonest grass in both communities is *Aristida pruinosa*. Other species present are *Sehima nervosa* and, in the higher rainfall parts, *Themeda australis* and *Chrysopogon pallidus*. Towards the drier boundaries of these woodlands spinifex becomes more common and the communities merge with xerophytic hummock grasslands of Triodia and Plectrachne.

Between longitudes 143° and 141°E and latitudes 19° and 21°S there is a woodland of *Bauhinia cunninghamii* (bean tree) (Pl. 52) and *Melaleuca viridiflora* (tea tree) (Pl. 53). This is a drier expression of the *M. viridiflora* tropical woodland with which it intergrades to the north. Other tree and shrub species common in this community are *Atalaya hemiglauca*, *Owenia acidula* (emu apple), *Acacia excelsa*, *Albizzia basaltica*, *Terminalia aridicola*, *Grevillea striata*, *Erythrophleum chlorostachys* (ironwood), *Melaleuca nervosa* and *M. acacioides*. Smaller shrubs include *Carissa lanceolata*, *Acacia farnesiana* (mimosa), and species of Capparis. The grasses are mainly *Aristida* spp. and *Chrysopogon fallax*.

Further east there is a shrub woodland of *Eucalyptus microneura* (Georgetown box) on red and yellow earths, brown soils of light texture, solodised solonetz, and skeletal soils. *Erythrophleum chlorostachys* is a fairly constant associate of *E. microneura* in the tree layer which is commonly about 30 ft (9 m) high. There is a shrub layer about 10–15 ft (3–5 m) high in which the common species are *Petalostigma banksii*, *Terminalia ferdinandiana*, *T. aridicola*, *Ventilago viminalis*, *Bauhinia cunninghamii*, and *Alphitonia excelsa* (plum pine). Smaller shrubs include *Carissa lanceolata*, *Dodonaea filifolia* (hopbush), and *Acacia* spp. The grasses are principally three-awns: *Aristida armata*, *A.*

Plate 54 Semi-arid woodland: dense regeneration of *Callitris columellaris* (cypress pine) following thinning of original stand, western New South Wales (Soil Conservation Service, New South Wales, photo)

hygrometrica, *A. pruinosa*, *A. praealta*, and *A. ingrata*. To the north-west the *E. microneura* woodland intergrades with *Melaleuca viridiflora* tropical woodland.

Other woodlands within these latitudes and extending southwards are those of *Eucalyptus similis*, *E. microtheca* (coolibah), *E. normantonensis*, and *Acacia cambagei* (gidgee). North of latitude 22°S, *Eucalyptus brownii* (Reid River box) shrub woodlands form a mosaic with woodlands of *E. shirleyi*, *E. crebra* and *E. peltata*. *Eucalyptus brownii* occurs in monospecific tree communities on skeletal soils on the Einasleigh uplands (lat. approximately 19°S). *Eremophila mitchellii* (sandalwood or buddah) is a common associate shrub. Other shrubs that may be present include *Petalostigma* spp., *Erythroxylon australe*, and *Carissa lanceolata*. Common grasses are *Aristida* spp., *Bothriochloa decipiens*, *B. ewartiana*, and *Dichanthium fecundum*. Outliers of *E. brownii* occur just west of Townsville on solodic soils. Although the annual rainfall is relatively high (35 in., 889 mm), the soil environment other than at the surface is arid because of the impermeable nature of the soil. The shallower-rooted herbaceous community is dominated by *Heteropogon contortus* (bunch spear grass), a species characteristic of sub-tropical woodlands which occur at similar rainfalls but on more permeable soils (see Chapter 8).

Eucalyptus melanophloia (silver-leaved ironbark) which occurs as far south as 30°S latitude forms extensive woodlands between latitudes 25 and 20°S. The common grasses of this woodland are *Triodia mitchellii* (buck spinifex) and species of Aristida. This is the Eastern Spinifex of Perry and Lazarides (1964).

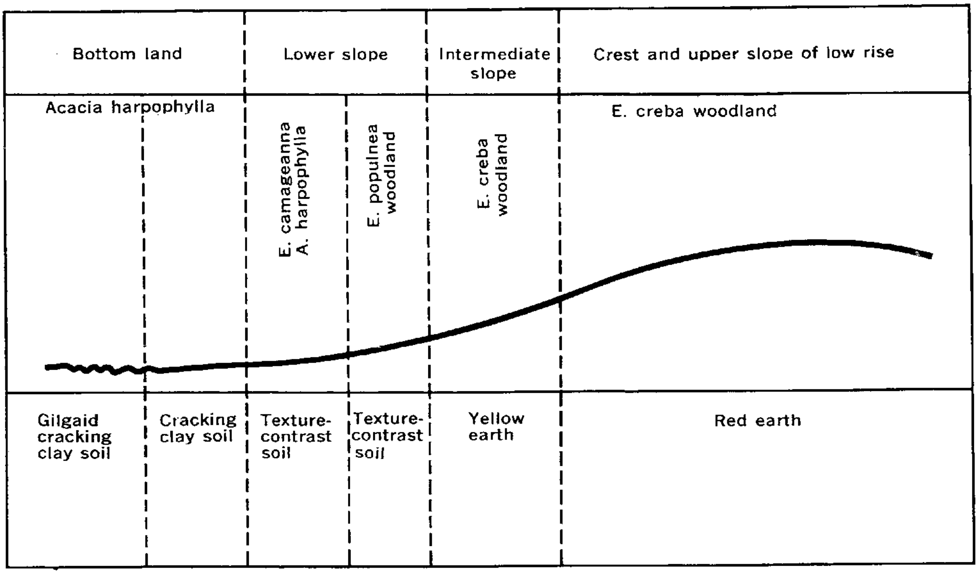


Fig. 16 : 1 Vegetation soil relationships of brigalow, sub-tropical woodlands, and semi-arid shrub woodlands at approx. 22°S lat. and 149°E long. (modified from Gunn 1967)

Near Clermont, Queensland (lat. approximately 23°S) *E. brownii* is replaced by a closely related species *E. populnea* (poplar, bimble or round-leaved box) (Pl. 17). *E. populnea* woodlands, classified as shrub woodlands by Beadle (1948), extend southwards to approximately 35°S latitude at longitude 144°E.

E. populnea grows on a wide variety of soils from grey and brown cracking clays to deep sands, but the soils most typical are red earths and solodised solonetz. There are extensive stands in which *E. populnea* is the only tree present but it is frequently associated with a number of other trees.

In central Queensland the *E. populnea* community is bounded to the east by *Acacia harpophylla* (brigalow), *Casuarina luehmannii* (buloke), or by sub-tropical woodlands of *Eucalyptus crebra*, *E. drepanophylla* (narrow-leaved ironbarks), and *E. dichromophloia*. Interrelationships of *E. populnea* with some other communities are shown in Fig. 16 : 1.

From Queensland *Eucalyptus populnea* in association with *Eremophila mitchellii* extends southwards on red earths into the Macquarie region of New South Wales. Common associates are *Eremophila glabra* (native fuschia), *E. sturtii* (turpentine bush), *Myoporum desertii* (poison bush), *Atalaya hemiglauca* (whitewood), *Geijera parviflora* (wilga), *Acacia homalophylla* (yarran), *A. excelsa* (ironwood), *A. deanei* (wattle), *A. oswaldii* (nelia), *Apophyllum anomalum* (warrior or currant bush), *Maytenis cunninghamii*, *Jasminum lineare* (jasmine), *Brachychiton populneum* (kurrajong), *Apophyllum anomalum*, *Canthium oleifolium* (myrtle), *Capparis mitchellii* (wild orange), *Cassia* spp. and *Dodonaea* spp. On sandy soils *E. populnea* is found with *Callitris columellaris* and *Eucalyptus dealbata* (tumbledown gum). On more clayey soils with gilgai, *E. populnea* usually grows with *Casuarina cristata*, *Geijera parviflora*, and *Eremocitrus glauca* (limebush). *Casuarina luehmannii* is a common associate on solodic soils in southern and central Queensland.

Herbaceous species characteristic of poplar box woodlands are *Stipa variabilis* and *Chloris truncata* in the southern, *Chloris acicularis*, *Bothriochloa decipiens*, and *Neurachne mitchelliana* in the central, and *Aristida pruinosa* and *A. inaequiglumis* in the northern parts of their distribution. *Aristida jerichoensis* and *A. contorta* are common throughout.

In southern and central Queensland and northern New South Wales, communities of *Acacia harpophylla* and *Casuarina cristata* (Pl. 54) occur within *E. populnea* woodlands usually on more fertile soils with higher clay contents.

Plate 55 Semi-arid shrub woodland of *Acacia pendula* (weeping myall) with *Rhagodia spinescens*, south-western New South Wales (CSIRO photo)

Further west within the same latitudinal range, *E. populnea* is increasingly confined to drainage lines and to 'run-on' areas between which *E. melanophloia* forms monospecific communities. Finally *E. populnea* intergrades with an arid shrubland of *Acacia aneura* on both alluvial 'soft-red' and hilly or undulating 'hard-red' country. On the 'hard-red' country typified by the Cobar peneplain, N.S.W., common shrubs are *Eremophila longifolia* (emu bush), *E. mitchellii*, *Cassia artemisioides*, *Geijera parviflora*, *Capparis mitchellii*, and *Acacia homalophylla*. The 'soft-red' country is characterised by *A. aneura* alone or in combinations with *E. populnea* and *Acacia excelsa* or *Heterodendrum*, *oleifolium* (rosewood or boonery). In higher rainfall areas and on sandier versions of the Nyngara brown acid soils, *Callitris columellaris* replaces *Acacia aneura*.

Between Cobar and the Darling River in New South Wales there is a shrubland or low woodland of many of the species that form the understorey of *E. populnea* woodlands. They are *Erythrophleum chlorostachys*, *Acacia homalo-*

Plate 56 Semi-arid low woodland of *Casuarina cristata* and *Heterodendrum oleifolium* on solonised brown soils, south-western New South Wales (CSIRO photo)

phylla, *Callitris columellaris*, *Eremophila mitchellii*, *Eremophila sturtii*, *Cassia artemisioides*, *C. eremophila* (birdseye), *Canthium oleifolium*, *Flindersia maculosa*, *Heterodendrum oleifolium* *Geijera parviflora*, and *Dodonaea* spp. Mulga too, is common, and the community is ecotonal with Acacia shrublands (see Chapter 17). *Aristida jerichoensis* is common on compact red loams and *A. contorta* and *Eragrostis eriopoda* on sandy loams.

Acacia pendula (weeping myall) forms woodlands (Pl. 55) on grey cracking clays in the north-western slopes and Macquarie Region of New South Wales and on the plains extending northward to the Barwon and Namoi Rivers and westward to the Bogan River. Small areas too are found near the Darling Downs and further north in Queensland. *Acacia pendula* grows on both red-brown earths and grey and brown cracking clays at latitude 35°S between longitudes 145 and 147°E in southern New South Wales, that is just beyond the southern limits of *E. populnea*. According to C. W. E. Moore (1953a) the original dominants of the community were *A. pendula* and *Atriplex nummularia* (oldman saltbush). Today there are no stands in which the original structure of the community can be seen. From observations of a few isolated ungrazed areas remaining it has been assumed that the community was a shrub woodland with trees up to 30 ft (9 m) high and a well-developed but probably discontinuous shrub stratum. It would appear from the evidence that the dominant species on the red-brown earths was *A. pendula* usually with a shrub stratum of *A. nummularia*, while on the grey and brown clays the dominant species was *A. nummularia*, with scattered *A. pendula*. Associated shrubs were *Rhagodia spinescens*, *Enchylaena tomentosa*, and *Kochia aphylla*. The species of the herbaceous layer vary according to soil texture. *Chloris truncata* and *Stipa variabilis* are common on light-textured soils with an A horizon more than 4 in. (10 cm) deep. *Danthonia caespitosa* and *Chloris truncata* are now the principal species on heavy-textured soils in the south but it seems likely that *Stipa aristiglumis* was formerly common if not dominant on these soils.

In southern New South Wales, the driest of the semi-arid communities is a low woodland of *Casuarina cristata* and *Heterodendrum oleifolium* (Pl. 56). This community occurs west of the 14 in. (356 mm) annual rainfall isohyet on solonised brown sandy soils overlying nodular limestone. Associated shrubs include *Acacia homalophylla*, *Acacia loderi*, *Eremophila sturtii*, *Lycium australe* (Australian boxthorn), and *Exocarpus aphylla* (native cherry). *Myoporum platycarpum*, a species associated with mallee and shrub steppe in South Australia, may be locally dominant. The community is related to the *Acacia sowdenii* (myall)-*M. platycarpum* arid shrubland west of the Flinders Range in South Australia. The common grasses are *Stipa variabilis*, *Enneapogon avenaceus*, *Chloris truncata*, *Eragrostis dielsii*, and *Sporobolus caroli*. Chenopod forbs, especially copperburrs (*Bassia* spp.) are abundant.

Within the semi-arid zone between Ivanhoe and Deniliquin, N.S.W., there is a large area of treeless shrub steppe (see Fig. 16 : 2). This is

Plate 57 Semi-arid woodland: frontage woodland of *Eucalyptus microtheca* (coolibah) with understorey of *Triodia* spp. (spinifex) on flood plains of heavy-textured grey cracking clays, western New South Wales. Note regeneration of tree from lignotuber following ringbarking of central trunk (right foreground) (Soil Conservation Service, New South Wales, photo)

an outlier of a much larger Atriplex community (Pl. 19) in the arid zone and is discussed with arid zone communities in Chapter 17. The most widespread woodland in the Riverine Plain of New South Wales is the *E. woollsiana* (grey box) community which occurs mainly in the eastern and southern higher rainfall sections (see Chapter 12).

The extensive floodplains along creeks, rivers, and areas subject to flooding in arid and semi-arid Australia, constitute the so-called frontage country and include the Channel Country of south-western Queensland. In New South Wales frontage woodlands extend in a broad belt between the Barwon and Culgoa Rivers and along the Darling River to its junction with the Murray River. Four tree species—*Eucalyptus camaldulensis* (river red gum), *E. ochrophloia* (napunyah), *E. largiflorens* (black box), and *E. microtheca* (coolibah) (Pl. 57)—occur in semi-arid frontage woodlands, frequently in pure stands.

In the semi-arid tropics, frontage woodlands are composed of *Eucalyptus microtheca*, *E. terminalis*, *E. pruinosa*, *E. papuana*, and *Bauhinia cunninghamii*. The common grasses are *Aristida inaequiglumis*, *A. browniana*, *Bothriochloa decipiens*, *B. ewartiana*, *Chrysopogon fallax*, and *Chloris acicularis*. Further south *E. microtheca* grows on grey and brown cracking clays subject to flooding. There is a wide range of herbs and forbs in the ground layer, the most frequent including *Chloris acicularis*, *C. truncata*, *Paspalidium jubiflorum*, *Centipeda cunninghamii*,

Plate 58 Semi-arid woodland of *Eucalyptus largiflorens* (black box), Riverina, New South Wales (CSIRO photo)

Sida corrugata, and species of Bassia and of Kochia.

Eucalyptus camaldulensis occurs throughout temperate and tropical Australia from areas of high rainfall to the beds of infrequent streams in deserts. In the western districts of Victoria and in the lower south-east of South Australia *E. camaldulensis* is the dominant in a large area of temperate woodland subject to seasonal waterlogging (see Chapter 12). *E. camaldulensis* has no soil preferences and is found on a wide variety of soils from sands to heavy clays. In arid and semi-arid zones it is common on grey and brown cracking clays along rivers and streams and is sometimes associated with *E. ochrophloia* as well as with *E. largiflorens* and *E. microtheca*. Herbaceous species under red gum vary with the climate in which it is growing, but in southern semi-arid areas they are commonly *Eleocharis pallens*, *Poa caespitosa* sens. lat., *Marsilea drummondii*, *Amphibromus neesii*, *Pseudoraphis spinescens*, and species of Cyperus, Juncus, and Paspalidium.

E. largiflorens is restricted to the southern part of the continent and to the west of the 20 in. (508 mm) annual isohyet in New South Wales. It is generally found on poorly drained floodplain soils. Common species in the ground layer are *Bassia quinquecuspis* (roly poly), *Atriplex* spp., and the grasses, *Sporobolus caroli*, *Chloris truncata*, *Eragrostis setifolia*, and *Panicum decompositum*. There is evidence that *Atriplex nummularia* and *A. vesicaria* (bladder saltbush) may formerly have been prominent in this community. In addition to *E. microtheca* and *E. camaldulensis*, *Acacia stenophylla* and *A. salicina* may be associated with *E. largiflorens*. There are extensive *E. largiflorens* woodlands

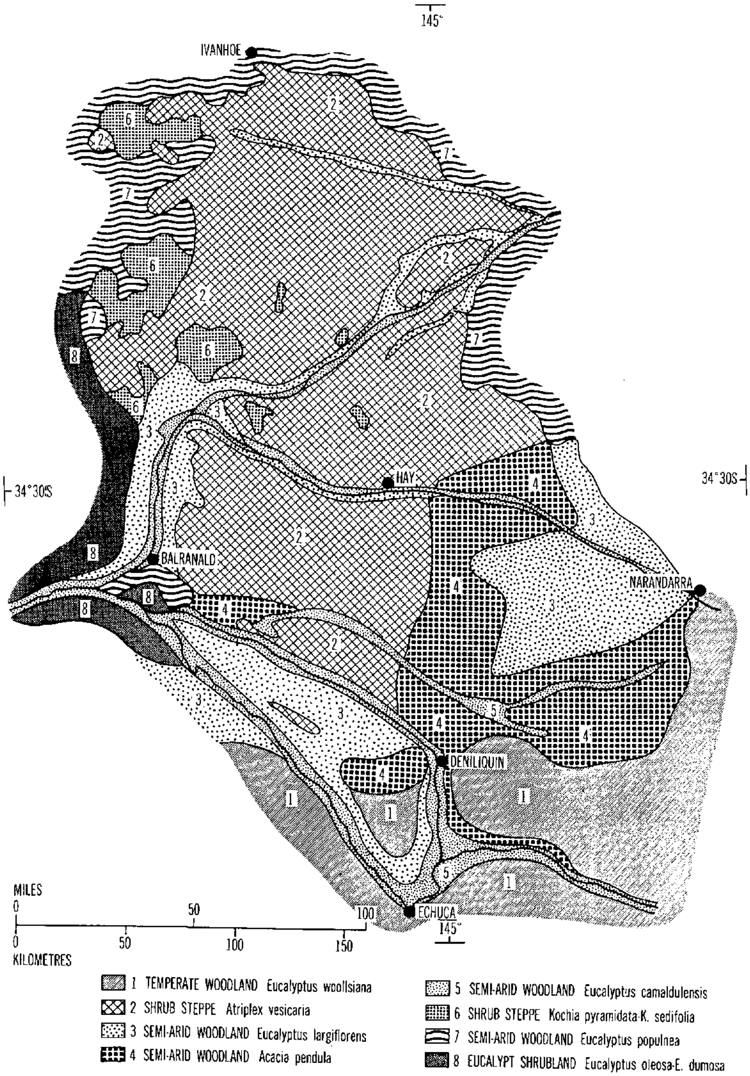


Fig. 16 : 2 Vegetation of the eastern Riverina (lat. 35°S) showing outliers of arid shrublands in semi-arid woodlands (J. H. Leigh)

(Pl. 58) west of Narrandera between the Edward and Murray Rivers and in north-western New South Wales (lat. 33°S).

The distribution of the plant communities of the eastern Riverina is shown in Fig. 16 : 2.

THE AGRICULTURAL INDUSTRIES

Beef production is the sole grazing industry in the semi-arid woodlands of the Northern Territory. In Queensland, too, beef is the principal product of semi-arid grazing lands. Sheep are increasingly confined to arid communities north of the N.S.W. border and there are few sheep north of latitude 21°S in the semi-arid zone although they are numerous in the adjacent arid shrublands (see Fig. 6 : 1).

Hereford and Beef Shorthorn are the popular breeds in Queensland but in the more tropical north Droughtmaster, Santa Gertrudis, and other Brahman crosses are being used increasingly because of their tolerance to heat and resistance to cattle ticks (*Boophilus microplus*).

In the southern semi-arid woodlands the principal industry is wool production. On most types of country graziers breed their own replacements and sell aged sheep. Usually the more productive country is used for breeding ewes and the poorer lands for wethers. Most properties carry some beef cattle but the numbers are small in relation to sheep. The ratio of sheep to cattle is about 25 to 1. Cattle are frequently bought following good rains to utilise excess grass and herbage. Merino is the predominant sheep breed and there are many well-known Merino studs throughout the semi-arid woodlands.

Prime lamb is produced on irrigated pastures along the principal rivers of the south and in association with crop production in the eastern and higher rainfall parts. Commonly, cross-bred Merino ewes are mated with British Down breeds.

In the higher rainfall (16–20 in., 406–508 mm) areas of the eastern Riverina plain, N.S.W., grazing enterprises are more varied, but still mostly based on sheep grazing. Beef production is more or less a sideline enterprise but of increasing importance because of low wool prices in recent years. The wool produced is mainly strong Merino (60–64's) with some Comeback, primarily Corriedale (58–60's). In recent years, significant changes have occurred in the interrelationship of enterprises within properties engaged in mixed farming in this area. With the fall in wool prices, there has been an increase in the area sown to wheat and in the eastern and higher rainfall parts wheat was a major source of rural income in 1968–69.

In the low rainfall (14–16 in., 356–406 mm) area of the Riverina the main grazing enterprise is production of strong to medium Merino wool with some beef cattle fattening in the better seasons. Normally not much wheat is grown because of the limitations imposed on arable farming by unsuitable soils and low rainfall. Recently, however, there has been a substantial increase in wheat growing, with large areas, for example 6000 acres (2430 ha), being farmed on individual properties. The low yields usually obtained and the not infrequent crop failures suggest that this country is marginal if not sub-marginal for wheat farming.

Below 14 in. (356 mm) annual rainfall the grazing industries are basically similar to those described for the 14–16 in. (356–406 mm) rainfall areas but there is virtually no cropping. Many of the old-established Merino studs are found in these low-rainfall areas and are responsible for the high quality of the Merino wool for which the western Riverina is noted.

Periodically flooded sites along the major streams of the Riverina carry extensive forests and woodlands of *E. camaldulensis*. These are administered by the State Forestry Commissions and the timber is sold for building purposes and for railway sleepers. These lands are leased for grazing which is generally controlled to allow trees to regenerate. This entails the restriction of certain sites to cattle alone and after flooding grazing of any kind may be prohibited (Dexter 1967).

Cypress pine produces millable timber where the average rainfall is above 14 in. (356 mm).

THE GRAZING LANDS

The grazing lands of semi-arid woodlands are characterised by a high constancy of species of Aristida, the three-awn, wire and kerosine grasses. They are classified as Xerophytic Mid-grass (see Map 4, Pl. 51). Another characteristic particularly of sub-tropical grazing lands of semi-arid woodlands is the high density of edible and inedible shrubs belonging to Myoporaceae, Capparidaceae, Rutaceae, and Sapindaceae. Edible species are commonly lopped during droughts. Others not only have no grazing value but reduce the growth of grasses and other herbaceous species and make mustering difficult.

Aristida spp. are generally high in fibre and low in nutritive value, and where the densities of more palatable species are low, as in the *E. brevifolia* and *E. pruinosa* low woodlands of the Northern Territory, the productivity of the grazing lands is poor (Perry 1960) and carrying capacities are as low as 4 or fewer beasts per square mile (1 to 65 ha).

The dominant perennial grass in the *E. dichomophloia* low woodlands of the Northern Territory is *Aristida pruinosa* (three-awn spear grass). Between the perennial tussocks there is a sparse cover of annuals including *Sporobolus australasicus* and a number of other species of Aristida. The growing period of these grazing lands is from 15 to 20 weeks and the carrying capacity is about 12 beasts to a square mile (1 to 22 ha). *E. argillacea* woodlands and *E.*

microneura woodlands have carrying capacities similar to those of the *E. dichromophloia* woodlands. *Acacia shirleyi* (lancewood) communities also have herbaceous understories of *Aristida* species but towards their drier margins spinifex, *Triodia pungens* (soft spinifex) or *T. mitchellii* (buck spinifex), becomes more common. *Ventilago viminalis* is fairly common and provides useful top-feed. These grazing lands respond quickly to rain but the quality of the feed is poor and even in the wet season the carrying capacity is only about 5 beasts to a square mile (1 to 52 ha) (Perry 1964).

Floodplains or frontage woodlands are valued in the semi-arid zone and because of their proximity to water have been subjected to heavy grazing. Their composition varies according to climate but generally their carrying capacity is of the order of 50 beasts to a square mile (1 to 5 ha).

In the Leichhardt-Gilbert area of the Gulf of Carpentaria the rainfall in the semi-arid part is from 20 to 30 in. (508 to 762 mm) annually. The growing period for the dominant *Aristida* spp. and herbs is about 20 weeks. Carrying capacity is 12 cattle per square mile (1 to 22 ha).

The principal understorey species of semi-arid woodlands of *Eucalyptus melanophloia*, *E. populnea*, and of *E. similis* near the Tropic of Capricorn are *Bothriochloa ewartiana*, *B. decipiens* (pitted bluegrass), *Eriachne* spp., and *Aristida* spp. The ratio of cattle to sheep is about 3 to 1. Average carrying capacities are 1 wether to 6–15 acres (2·5–6·5 ha) and 1 cattle beast to 40–70 acres (16–28 ha). To the west *Triodia mitchellii* increases in density and carrying capacities average about a cattle beast to the square mile (1 to 260 ha).

The most frequent grasses in the *E. populnea* woodlands of southern Queensland are *Bothriochloa decipiens*, *Chloris acicularis* (windmill grass), *Neurachne mitchelliana* (mulga grass), *Paspalidium constrictum*, *Enneapogon polyphyllus*, *Eragrostis* spp. and *Aristida* spp. There are more sheep than cattle in these woodlands and despite an annual rainfall of 21 in. (533 mm) carrying capacities are only of the order of 1 sheep to 4–8 acres (1 to 1·6–3·3 ha) on the best land and 1 to 12–15 acres (5–6 ha) on both the drier and more densely timbered country. High density of trees and shrubs, particularly of *E. populnea* and *Eremophila mitchellii*, is a major factor in reducing grass growth and in limiting carrying capacities.

Studies at Wycanna, near Talwood, southern Queensland (lat. 28°S), show that the density of *E. populnea* alone may be as high as 400 trees per acre (960 per ha) and is commonly 140 per acre (360 per ha). At such densities grass production and stock carrying capacities are very low. Reducing tree and shrub densities without soil disturbance increases dry matter production of grasses and herbs several fold (R. M. Moore and J. Walker, unpublished data).

Most of the shrubs of *E. populnea* woodlands regarded as unpalatable and even poisonous when mature, seemingly are eaten and without ill effects when resprouting or in the seedling stages of growth. Species that commonly regenerate when sheep are excluded include *Cassia eremophila*, *Acacia deanei*, *Dodonaea viscosa*, *Myoporum desertii*, *Jasminium lineare*, *Maytenis cunninghamii*, and *Canthium oleifolium*. Except in the early stages of regeneration many of the shrubs of *E. populnea* woodlands are inaccessible to livestock and scrub-cutting with power saws or scrub pushing with bulldozers are established practices during droughts. Most trees and shrubs of semi-arid woodlands and shrublands sprout from roots or swollen stem bases and are able to regenerate following cutting or other forms of felling. Palatability varies with locality and even among individuals of the same species but some that are relatively palatable and withstand lopping well are *Brachychiton populnea*, *Ventilago viminalis*, *Heterodendrum oleifolium*, *Flindersia maculosa*, *Canthium oleifolium*, and *Casuarina cristata*.

Trees and shrubs are generally high in protein (10–15 per cent) but low in digestibility and in phosphorus (Everist and Young 1967). Unfortunately many unpalatable species including *E. populnea*, *Eremophila* spp., and *Melaleuca* spp. (tea trees) also regenerate following ringbarking and other land clearing operations and are a major impediment to animal production, particularly in northern New South Wales, southern and central Queensland (Pls. 54, 57).

In southern and central Queensland cracking clays carry *Acacia harpophylla* forests (see Chapter 9) or frontage woodlands. Grazing lands of *E. largiflorens*, *E. microtheca*, or *E. ochrophloia* frontage woodlands at latitude 28°S carry about 1 sheep to 5 acres (1 to 2 ha).

The species of the more compact clays of the Channel Country further west are *Muehlenbeckia cunninghamii* (lignum), *Eragrostis australasica* (canegrass), *Atriplex inflata* (flat-topped saltbush), *A. spongiosum* (pop saltbush), *A. leptocarpa* (annual saltbush), *Bassia uniflora*, *B. brachyptera* (copperburrs), *Dactyloctenium radulans* (button grass), and *Tragus australianus* (small burr grass). Except after flooding the carrying capacity of the Channel Country is low.

To the south *Bothriochloa decipiens* declines and as the densities of temperate species *Stipa falcata*, *S. variabilis*, *Chloris truncata*, and *Danthonia caespitosa* increase, so do carrying capacities.

Effects of grazing on botanical composition of southern *E. populnea* grazing lands have been studied at Trangie, N.S.W., by Biddiscombe (1953) and in the Riverina, N.S.W. by C. W. E. Moore (1953b). The autecology of some of the principal grasses of *E. populnea* woodlands has been studied by Biddiscombe, Cuthbertson, and Hutchings (1954).

Sheep and wool production on the more productive grazing lands of southern *E. populnea* woodlands were studied experimentally by Biddiscombe *et al.* (1956) at Trangie, N.S.W., where the annual rainfall averages 17 in. (432 mm). The principal species were the native perennial grasses, *Stipa falcata* (*S. variabilis*?), *Chloris acicularis*, and *Digitaria coenicola*. Three rates of stocking with 2-year-old Merino wethers, 1 sheep to 1 acre (1 to 0·4 ha), 1 sheep to 1·5 acres (1 to 0·6 ha), and 1 sheep to 2 acres (1 to 0·8 ha) were combined with three management systems, continuous grazing, autumn deferment, and spring deferment. In the two latter treatments sheep were removed following the first effective autumn and spring rains respectively. Rainfall during the five years of the experiment was above average and there was only one period in which sheep at the highest stocking rate lost much more weight and produced less wool than those at lower rates of stocking. Deferred grazing was no better than continuous grazing, for either the grazing land or the sheep. Densities of the perennial grasses were higher at the heavier stocking rates following wet autumns and winters but showed least decline at low stocking rates in dry winters. The higher densities of perennials at high stocking rates in wet autumns and winters were thought to be due to lesser competition from cool season annual species. Basal areas of the perennial grasses were highest at the lowest stocking rate and differences between high and low stocking rates increased as the March–April rainfall decreased.

Where *E. populnea* is associated with *Callitris columellaris* on sandy soils the herbaceous layer is composed principally of *Aristida jerichoensis*, *A. calycina* (wiregrass), *A. contorta* (kerosine grass), *Eragrostis lacunaria* (love grass), *Ptilotus* spp., and *Vittadinia triloba*. The carrying capacity of the driest of these communities is similar to that of the *Casuarina-Heterodendrum* low woodland and may be as low as 1 sheep to 15–20 acres (1 to 6–8 ha).

The characteristic grasses of 'soft red' country in western New South Wales are *Eragrostis eriopoda* (woolly butt), *Enneapogon* spp., and *Aristida jerichoensis* and *A. arenaria*. Carrying capacities vary between 8 and 12 acres (3·2 and 4·8 ha) per sheep, depending on rainfall. *Eragrostis eriopoda* grazing lands respond quickly to light falls of rain. Overgrazed areas carry *Aristida contorta*, *Helipterum* spp. (paper daisies), *Calotis* spp. (bindii), and *Blennodia lasiocarpa*. The grazing lands of 'hard red' country are composed principally of *Aristida jerichoensis*, *A. contorta*, *Enneapogon* spp., *Neurachne mitchelliana*, *Eragrostis dielsii*, and *Bassia uniflora* and *B. convexula*. Carrying capacities range from 10 to 15 acres (4 to 6 ha) a sheep. Towards the western boundary of the semi-arid zone *Triodia mitchellii* may be associated with woolly butt and with *Aristida* spp. on both 'hard' and 'soft' red country. These grazing lands have low carrying capacities and are normally burnt every two years to promote growth of summer herbage.

In the south, *Stipa falcata* (spear grass), *Chloris truncata* (windmill grass), and *Danthonia caespitosa* (wallaby grass), species characteristic of adjacent mesophytic woodlands, occur in the eastern and higher rainfall parts of the area mapped as shrub woodlands. Densities of tall shrubs are low in some of these woodlands, particularly in those of the Riverina, New South Wales, which resemble temperate woodlands in structure. However, *Atriplex* spp. (saltbushes), *Bassia* spp. (copperburrs), and *Kochia* spp. (bluebush and cotton bush) are more common in semi-arid than in temperate woodlands and provide much of the summer grazing. A study of sheep grazing on a Stipa-Danthonia-Kochia community in the Riverina is reported by Leigh, Wilson, and Mulham (1968).

On the heavy-textured soils of southern *Acacia pendula-Atriplex nummularia* woodlands, *Stipa aristiglumis* and *Danthonia caespitosa* have declined in density under grazing and have been replaced wholly or in part by *Chloris truncata, Calocephalus sonderi, Bassia quinquecuspis* (roly poly) and the introduced annuals, *Carthamus lanatus* (saffron thistle), and *Medicago polymorpha.* In the north other common genera are *Astrebla* and *Eriochloa.* Carrying capacities are 1 sheep to 2–5 acres (0·8–2 ha). Southern frontage woodlands of *E. camaldulensis* and *E. largiflorens* carry about 1 sheep to 6 acres (2·4 ha).

In the Western Division of New South Wales a relationship between grazing capacity of arid and semi-arid grazing lands and average annual rainfall was established by Condon (1968). The relationship is exponential, ranging from 5 sheep per 100 acres (40 ha) at 7 in. (178 mm) rainfall, 10 per 100 acres at 11 in. (279 mm), to 30 per 100 acres at 18 in. (457 mm). Factors by which rating scales have been weighted for the estimation of grazing capacities of semi-arid grazing lands are tree and shrub densities, soils, topography, presence of palatable shrubs, condition as influenced by erosion, weeds, and rainfall. Each factor has a scale of values used as multipliers to give bonus ratings for those factors that increase and penalty ratings for those that decrease grazing capacities. To apply rating scales it is necessary to establish standard land classes for which grazing capacities at given rainfall levels are known.

THE PASTURES

The area sown to pastures in semi-arid woodlands is small. Perennial grasses are not grown to any extent although *Sorghum almum* and the American and Molopo cultivars of *Cenchrus ciliaris* (buffel grass) are being sown in small but increasing quantities in semi-arid woodlands in southern and central Queensland. Both species are sown more extensively on the more fertile soils of the adjacent brigalow lands (see Chapter 9), and individual properties are sowing large areas to *Cenchrus ciliaris* following the pulling of *Acacia cambagei* (gidgee) shrublands (Chapter 17). Excepting superphosphate on small areas of lucerne and barrel medic in the southern and eastern parts, fertilisers are not used in semi-arid woodlands.

Pastures of buffel grass, bambatsi grass (*Panicum coloratum* var. *makarikariensis*), *Sorghum almum*, lucerne, and annual medics are of potential value for increasing productivity in the eastern parts of the shrub woodlands from central Queensland to just south of the N.S.W. border. Lucerne and annual medics have already shown their value in south-eastern woodlands.

There is already some lucerne (*Medicago sativa*) in the higher rainfall parts of the semi-arid woodlands from central Queensland to the Riverina in New South Wales. It is sown at 0·5 to 2 lb per acre (0·6 to 2·24 kg per ha) and is grazed rather than cut for hay. The potential of lucerne in *E. populnea* woodlands is indicated by experiments at Trangie, N.S.W., where Robards and Peart (1967) found that in a year in which the rainfall was 14·4 in. (366 mm) Hunter River lucerne grazed for 1 week and rested for 9 carried 4 ewes per acre (10 per ha) year long and an additional 2·5 per acre (6·25 per ha) for 14 weeks during the spring. When set stocked lucerne carried only 1 ewe per acre (2·5 per ha). Sheep on rotationally grazed lucerne produced 52 lb wool per acre (58 kg per ha) in comparison with 11·8 lb per acre (13·2 kg per ha) on grazing lands of native species.

Where winter rains are experienced introduced cool season annuals have become naturalised. Their density varies widely and is generally greatest where all the native perennial species have been eliminated. If enough rain falls in autumn or early winter to germinate annuals, both production and nutritive value of the resultant pasture may be higher than that of native species in the same environment. In the absence of germinating rains the only feed available to sheep may be the seed in medic pods (burrs) produced the previous season. The common naturalised burr medics are *M. polymorpha*, *M. laciniata*, *M. minima*, and *M. praecox.* Burr medics are naturalised as far north as Gayndah in Queensland (approximate lat. 25°S) and when winter rainfall is high they contribute high protein feed when most needed. Medic burrs, however, are troublesome in wool and are responsible for a large measure of the vegetable fault in Australian wools.

Species common in volunteer pastures of cool season annuals are one or more species of Medicago, *Hordeum leporinum*, *Erodium cygnorum*, and *Carthamus lanatus* (saffron thistle). Pastures of medics and barley grass have a carrying capacity of about 1 sheep to 2 acres (1·25 per ha). More productive species *M. truncatula* (barrel medic), cultivars Jemalong (173) and Cyprus, and *M. littoralis* (strand medic), cultivar Harbinger, are sown in the higher rainfall parts of the mallee (see Chapter 15) and to some extent in eastern semi-arid woodlands. These species have straight spines and their pods do not adhere to wool. Snail clover (*M. scutellata*) a species with a non-spiny pod is being sown in the higher rainfall (28–19 in., 711–483 mm) woodlands, particularly in land cultivated for growing wheat.

In the eastern semi-arid woodlands, medic pastures are commonly established under cover crops of wheat, usually the last crop before the pasture ley phase of the rotation (Dann 1960). Initially annual ryegrass (*Lolium rigidum* cv. Wimmera) was sown as well but this species is now naturalised over a wide area and can be a serious weed in winter-growing cereal crops. In these areas there may be some potential for perennial grasses such as phalaris (*Phalaris tuberosa* cv. Sirocco) and Mediterranean cultivars of cocksfoot (*Dactylis glomerata*) (Oram 1965; Hoen and Oram 1967).

Species tests in southern New South Wales are described by Leigh and Mulham (1964), Kleinig (1965), and Jones and Muirhead (1966). The advantages of row cultivated pastures in a semi-arid environment are discussed by O. B. Williams (1963).

ANIMAL PRODUCTION

Pastoral production in the semi-arid woodlands of the Northern Territory is limited to low quality beef from semi-wild 'scrub' Shorthorns. Cattle are mustered only for branding and for selecting individuals to be sold. In north Queensland, too, cattle are raised with a minimum of husbandry. Breeding is largely uncontrolled and females are rarely sold. Males are sold when 4 to 5 years old.

Phosphorus deficiency in cattle is common and botulism is prevalent as a result of bone-chewing. Cattle ticks and tick fever are major impediments to animal production in northern areas and the scarcity of fenced paddocks makes control by dipping difficult. Bovine contagious pleuropneumonia is present in Queensland, Northern Territory, and Western Australia, and movement of cattle from affected areas is restricted.

In central Queensland where sheep are more common, lambing percentages are 30–60 and calving percentages 70–80. There is a pronounced feed shortage in winter and young cattle are usually sold after weaning at 9–15 months. Wool yields are 6–8 lb (2·7–3·6 kg) per ewe and 8–10 lb (3·6–4·5 kg) per wether.

In southern Queensland and New South Wales where the proportion of winter rain is higher, oats are commonly grown to carry cattle through the winter and spring period. Males and surplus females are sold at 800–900 lb (324–364 kg) at two and a half years. There is some phosphorus deficiency in cattle and losses due to St George's disease (*Bartonella bovis*) are common among cattle in the vicinity of St George. Blackleg (*Clostridium feseri*), leptospirosis (*Leptospira* spp.), vibriosis (*Vibrio foetus*), and brucellosis (*Brucella abortus*) are the most frequent diseases of cattle. Common sheep ectoparasites are lice (*Damalinia ovis*), itch mites (*Psorergates ovis*), and blowfly larva (*Lucilia cuprina* and *Calliphora* spp.).

In southern temperate woodlands where wool is the principal enterprise, feed shortages are usual in autumn and early winter, that is before the advent of winter rains, but here as in other parts of the semi-arid zone feed shortages may occur at any time of the year. Lambing percentages are of the order of 70–75. Wethers cut an average of 11 lb (4·5 kg) and ewes 9 lb (3·6 kg) per head. Cattle are bred on properties and sold at 20–24 months of age, usually at 900 lb (364 kg) liveweight. Calving percentages average 85.

The principal diseases of sheep are pulpy kidney or enterotoxaemia (*Clostridium perfringens*), black disease (*Clostridium novyi*), and toxaemic jaundice. The latter disease, particularly prevalent in crossbred sheep, is a complex of disease conditions of which poisoning through the ingestion of *Heliotropium europaeum* is one aspect and chronic copper poisoning (either separately or in combination with the liver damage resulting from heliotrope poisoning) is another (Albiston *et al.* 1940) (see Chapter 26). *Heliotropium europaeum* is believed to be introduced and is widely distributed throughout the southern shrub woodlands and drier temperate woodlands (C. W. E. Moore 1956).

Other weeds common in temperate semi-arid woodlands are *Xanthium spinosum* (Bathurst burr), *Carthamus lanatus* (saffron thistle), *Xanthium pungens* (Noogoora burr), and *Echium lycopsis* (Paterson's curse). Following good winter or spring rains the density of the native coloniser *Bassia birchii* (galvanised burr) increases in *E. populnea* woodlands on surfaces bared by drought or overuse. Mintweed (*Salvia reflexa*), a nitrate accumulator, is also common, particularly on clay soils in southern Queensland and northern New South Wales.

Photosensitisation is frequent among sheep grazing stands of *Medicago polymorpha*, *M. minima*, and *Erodium* spp. (crowfoot) in southern semi-arid woodlands. *Tribulus terrestris* (cathead or caltrops) may also be responsible for this condition in late summer and autumn when sheep have little alternative green feed.

The major source of feed for livestock in semi-arid woodlands will continue to be native grasses and herbs, and since grass-forb and tree-shrub densities appear to be negatively correlated, the control of woody plants is a factor of economic importance in all but the most southern areas. Of the woody species of importance limiting grass production in shrub woodlands *Eremophila mitchellii* has been controlled by basal stem spraying with 2, 4, 5-T in diesel fuel (Robertson 1965) and mature trees of *E. populnea* by injection with Tordon 50D or 2, 4, 5-T in water (Robertson 1966).

LAND TENURE

Land is generally leasehold in the Northern Territory and Queensland although much of the latter is being converted to freehold. In southern Queensland annual rents on leasehold land in the drier parts of *E. populnea* woodlands are 3 to 4 cents per acre (7–10 cents per ha) and property sizes range from 20,000 to 70,000 acres (8100–28,350 ha). Further east the properties are smaller—9000 to 25,000 acres (3645–10,000 ha)—and rents are about 20 cents an acre (50 cents per ha). Excepting the Western Division most land in New South Wales semi-arid woodlands is freehold. Rents of Western Lands leases in New South Wales are fixed by statute and range from 5 to 15 cents per sheep area. This means that if country is rated at one sheep to 5 acres (1 per 2 ha) and rent is 15 cents per sheep area, rent per acre is 3 cents (7 cents per ha). The rent varies according to factors such as proximity to rail, whether the country is suitable or not for breeding, and perhaps because of problems associated with a particular holding. Western Lands leases are leases in perpetuity but contain conditions restricting stock numbers, timber clearing, and other practices that may accelerate erosion. The Crown can require land in poor condition through overstocking to be rested for a stipulated period. The area of individual leases is graduated so that landholders remote from rail terminals or in lower rainfall areas are able to carry more stock.

Values have risen in the Riverina of New South Wales by almost 100 per cent from 1965 to 1968 in the higher rainfall woodlands to the east. These high values have been attributable largely to the influx of interstate buyers from South Australia and Victoria as well as proximity to the irrigation districts and assured river flows (see Chapter 18). Here non-irrigable land with a river frontage may be valued up to $75 per acre ($183 per ha) but throughout the temperate semi-arid woodlands values generally range from $2 to $30 per acre ($5–$74 per ha).

17

ARID SHRUBLANDS AND GRASSLANDS

R. A. PERRY

Australia is a dry continent. A vast area, certainly more than 60 per cent of the land surface, stretching from the west coast across the interior to within 300–400 miles of the east coast, is arid by any definition.

While the term 'arid' is relative, most agriculturalists and biologists accept Meigs's (1953) definition that 'arid areas are those in which rainfall on a given piece of land is not adequate for crop production'. This definition has a land-use connotation and it follows that, with the exception of areas where irrigation water is available, agricultural enterprises on arid lands are limited to the grazing of animals on native vegetation.

The definition further implies that aridity is determined not by total rainfall but by all the complex of factors associated with rainfall effectiveness. Such factors as the seasonal distribution of rain, its reliability, the level of evaporation during the rainy season, and the need for a reliable sequence of falls to provide a minimum unbroken growing season are important in determining whether crop production (or sown pastures) will succeed. In southern Australia, where rainfall is concentrated in the cool winter months with low evaporation, crops and sown pastures can extend to areas where the mean annual rainfall is as low as 10 in. (254 mm), but in northern Australia, where rainfall is restricted to the summer months when evaporation is high, a mean annual rainfall of 25 to 30 in. (635–762 mm) is required. Thus it is not possible to delimit arid areas, at least in an agricultural or biological context, on the basis of any single rainfall isohyet.

DISTRIBUTION

Delimiting the boundaries of the Australian arid zone is a simple matter in the south where long agricultural experience has defined the boundary for economic cropping and sown pastures but it is more difficult in the north where agricultural experience is limited. Meigs places the northern boundary at about the 15 in. (381 mm) isohyet but this is far too low. Experience with Townsville lucerne (*Stylosanthes humilis*), the sown pasture species capable of extending furthest into the dry margins of the summer rainfall cropping areas, indicates that it requires a growing season of about 12 weeks. Using length of growing season estimates determined from soil water balance models in which the inputs were weekly rainfall and weekly evaporation, and assuming that sown Townsville lucerne pastures would be economic if the growing season exceeded 12 weeks in 4 years out of 5, Perry (1967, 1968) placed the boundary at about the 30 in. (762 mm) mean annual isohyet in the Northern Territory. From agricultural experience in the south and east and agroclimatic analyses in the north Perry concluded that the boundary of the Australian arid zone approximates

1. the 10 in. (254 mm) isohyet in southern Western Australia and South Australia;
2. the 15 in. (381 mm) isohyet in New South Wales;
3. the 20 in. (508 mm) isohyet in southern Queensland;
4. the 25 in. (635 mm) isohyet in central Queensland; and
5. the 30 in. (762 mm) isohyet in north-western Queensland, Northern Territory, and northern Western Australia.

This boundary is similar to that accepted by the Australian Standing Committee on Agriculture in 1954. The area delimited is 2·2 million sq miles (5·7 million km^2) or 75 per cent of the land surface of Australia. Such a boundary is adequate for a broad Australia-wide circumscription but obviously Meigs's definition with its biological and economic implications cannot be applied on the basis of climate alone—changes in the economics of cropping and sown pastures will affect the boundary, as will local factors such as topography and soils. For example good stands of *Cenchrus ciliaris* have been established on particularly fertile soils near Blackall and Cloncurry in Queensland.

The boundary of the arid zone used in this book is based as far as possible on boundaries of natural vegetation, and the result is a somewhat different outline. It is closely similar in the south and differs most in the north where it approximates the 20 in. (508 mm) rather than the 30 in. (762 mm) mean annual rainfall isohyet.

However it is delimited, the Australian arid zone comprises a single vast expanse of land occupying all the central part of the continent and extending to the western and southern coasts. In fact, only a small corner in the south-west and a relatively narrow arc along the northern, eastern, and south-eastern coasts are not arid. The Australian arid zone is second in size only to the vast North African-Middle Eastern arid area. It is more than 2000 miles (3200 km) from east to west and 1250 miles (2000 km) from north to south extending from latitude 17°S to 35°S and from longitude 113°E to 148°E.

CLIMATE

In such a large area it is not surprising that there is a wide climatic range. This is illustrated in Fig. 17 : 1 on which some climatic parameters are listed for a number of arid localities.

Rainfall varies in amount, seasonality, and reliability. The area near Lake Eyre in South Australia has the lowest mean annual rainfall—about 5 in. (127 mm)—and rainfall isohyets tend to be concentric around this area, with the 10 in. (254 mm) isohyet meeting the coast at the Great Australian Bight and in the west. Apart from a small area in the south-west, and possibly a very narrow strip along the southern boundary, the whole zone receives more rain in the six summer months (October to March) than in the six winter months. Broadly speaking, the southern half of the arid shrublands and grasslands receives 50 to 70 per cent of its rainfall in summer, but over most of this area winter rainfall is more reliable and more effective than summer rain. In the northern half the proportion of summer rainfall increases from about 70 per cent in the south to over 90 per cent in the north. The number of wet days per year is least on the north-west coast where Mandora has 20, Port Hedland 21, Onslow 22, and Pardoo station only 15, whereas stations in the lowest rainfall area near Lake Eyre have between 25 and 30. The highest number of wet days per year occur in the south-east where Hay has 65, Wentworth 61, and Port Augusta 69.

Few attempts have been made to analyse rainfall data or to study rainfall/soil water/plant growth relationships in arid Australia. Most climatic studies in Australia have concentrated on the more humid areas and have been concerned more with delimiting the arid area than with studying it. Descriptions of the climate, and some analyses of rainfall in terms of duration of growing seasons or of frequency of effective falls of rain, are available for those parts of the zone surveyed by the CSIRO Division of Land Research (Slatyer and Christian 1954; Slatyer 1962, 1964, in press; Arnold 1963; Fitzpatrick and Arnold 1964).

In Queensland, Farmer, Everist, and Moule (1947), using precipitation/evaporation ratios to assess effective rainfall, produced a map of isolines showing the difference between summer and winter P/E ratios. The zero isoline runs east–west through central western Queensland and roughly approximates the northern limits of mulga (*Acacia aneura*) and myall (*A. pendula*) from which they postulated that these species need some winter rain. Davies's (1968) observations that mulga flowers after summer rain but requires rain in the following winter to mature fruits support this.

Arid shrublands and grasslands are characterised by erratic, as well as low, rainfall. Farmer, Everist, and Moule (1947) divided Queensland into zones on the basis of 0, 2, 4, and 6 months of effective rainfall in summer and winter in 50, 66, and 75 per cent of years. Their maps indicate that about half of arid Queensland has 0 months of effective rain in summer or winter in either 50, 66, or 75 per cent of years. Most of the rest has either 2 months of effective rain in summer, or 2 in winter and 2 in summer. For Alice Springs (central Australia), Fitzpatrick, Slatyer, and Krishnan (1967), using unpublished rainfall/soil moisture/plant growth data collected by Winkworth, have developed a model which simulates growth periods from inputs of

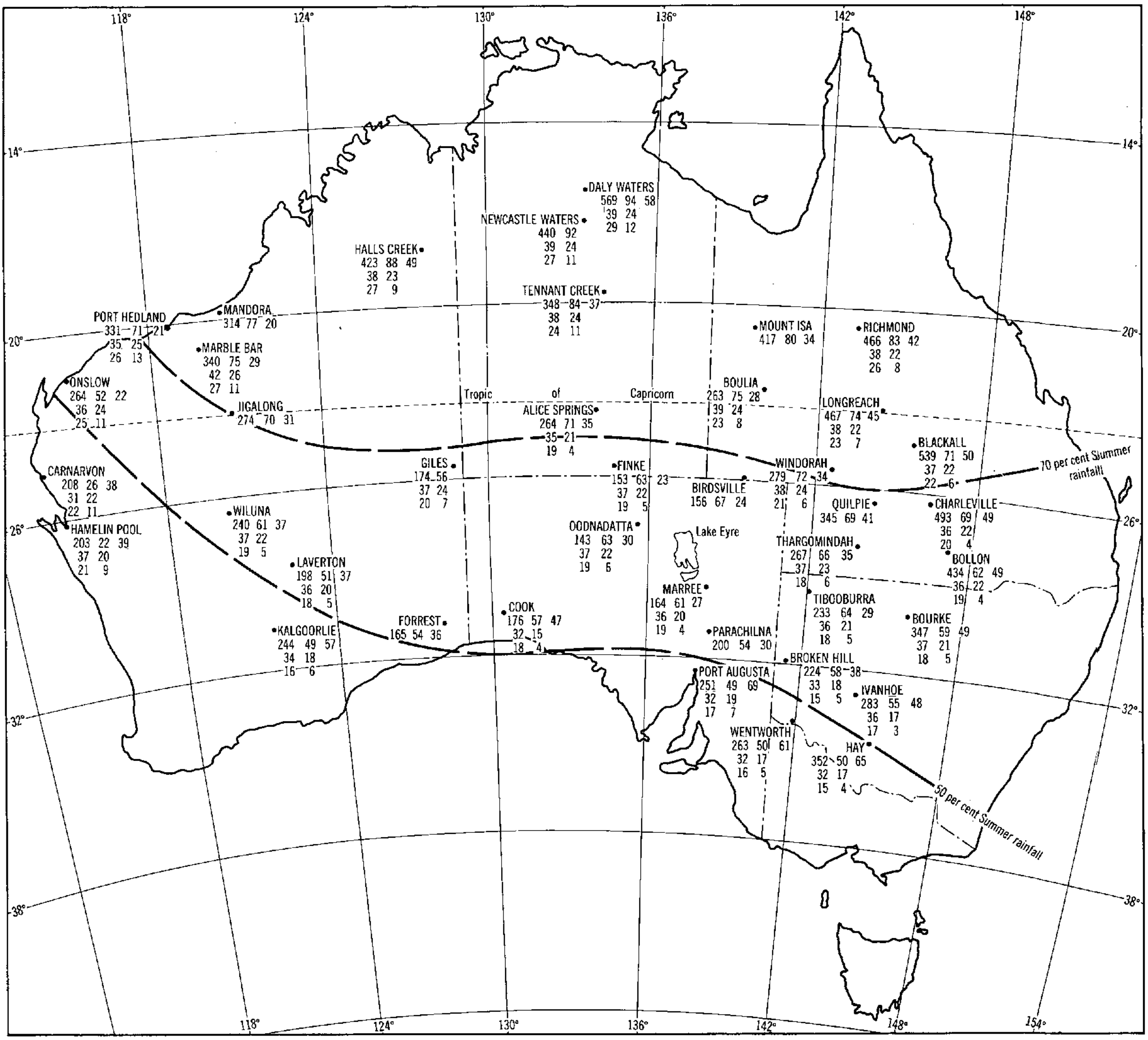


Fig. 17 : 1 Climatic data for selected localities. For each locality the data provided are:

Line 1 Mean annual rainfall (mm), percentage of rain received in the six summer months (October to March), and mean number rainy days

Line 2 Mean monthly maximum and minimum temperature (°C) for the hottest month

Line 3 Mean monthly maximum and minimum temperature (°C) for the coldest month

rainfall and evaporation. From the same data Perry and McAlpine (unpublished) have validated a simpler model from which durations of available soil moisture can be estimated from rainfall and evaporation. From a further assumption that, in the Alice Springs area, adequate forage production will result from 4 or more consecutive weeks of available soil moisture (validated from reports of pastoral conditions over the last twenty years) they have calculated that a single isolated dry summer can be expected 1 year in 4, 2 consecutive dry summers once in 19 years, 3 consecutive dry summers once in 71 years, and 4 consecutive dry summers once in 249 years. The probabilities of 1, 2, 3, or 4 dry winters are similar although winter rain is only about one-third of summer rain. Such figures are useful for evaluating the long-term economic implications of drought stocking strategies.

Rainfall in arid areas is spatially, as well as temporally variable. Much of the summer rainfall, in particular, comes from convectional storms which may yield rain over an area of, say, 10–15 sq miles (25–39 km^2). In any year one area may receive several downpours from overlapping storms whereas a nearby area may receive few or none. This phenomenon is poorly documented but is familiar to anyone who has flown over arid areas during rainstorms and is well known to pastoralists who frequently speak of receiving rain on one part of their property but not on others or of their neighbours receiving rain which they did not. Rainfall records at Alice Springs aerodrome and Alice Springs post office, 7 miles (11 km) apart, show many examples of one receiving heavy falls and the other little or none. The records of the Water Resources Branch of the Northern Territory Administration contain other examples—during 1968 most of the small Todd River catchment near Alice Springs received nearly double its mean annual rainfall but rainfall over the tributary Charles River catchment was well below average.

The northern parts of the Australian arid zone are characterised by hot summers and warm winters and the southern parts by hot summers and cool winters. Mean monthly maximum temperatures in the hottest month are highest in the Marble Bar (42°C) area and lowest in the south and south-west (31°C or 32°C at Hay, Wentworth, Port Augusta, Cook, and Carnarvon). Mean monthly minimum temperatures in the hottest month are also highest at Marble Bar (26°C) and are lowest in the south (Cook 15°C) and south-east (Hay, Ivanhoe, Wentworth 17°C). The hottest month over most of the zone is February and over a lesser area is January but near the northern margins the onset of the summer rainy season depresses temperatures and the hottest month is December (e.g. Richmond and Tennant Creek) or even November (e.g. Daly Waters and Halls Creek).

The coldest month is invariably July. The highest mean monthly maximum and minimum temperatures in the coldest month are in the far north (e.g. Daly Waters maximum 29°C; minimum 12°C) and the lowest in the south-east (e.g. Broken Hill, Hay maximum 15°C; Ivanhoe minimum 3°C). Frosts occur every year in the southern half, but the north is frost free.

In most places the mean diurnal range is 14–15°C during the hottest month and 13–14°C during the coldest month. Mean diurnal range is highest in the south-east in the hottest month (Ivanhoe 19°C) and in the north in the coldest month (Halls Creek and Richmond 18°C). It is lowest in summer in coastal Western Australia (Port Hedland 10°C and Carnarvon 9°C) and in winter in the south-east (Port Augusta, Kalgoorlie, and Broken Hill 10°C).

Few studies of temperature in arid Australia have been made. Farmer, Everist, and Moule (1947) produced a map of Queensland showing the number of months with a mean maximum temperature in excess of 35°C. In most of arid Queensland mean monthly maxima exceed 35°C for 2 months each year and in an area near Richmond, Winton, and Cloncurry they exceed 35°C in 6 months each year.

TOPOGRAPHY AND SOILS

Topographically the most characteristic feature of arid Australia is its monotonous flatness. Vast areas consist of gently undulating plains varying in altitude from about −30 ft (−10 m) at Lake Eyre to about 2000 ft (600 m) near Alice Springs. These plains are broken here and there by isolated low mountain ranges, the largest of which are the Macdonnell Ranges in central Australia which rise to 4995 ft (1500 m) at their highest point and extend in an east-west direction for about 400 miles (640 km). Nowhere are the mountains high enough to have more than a marginal effect on climate (see Chapter 2).

Much of arid Australia has a wide, shallow basin-and-range topography with the following characteristic sequence of landscapes:

1. low stony ranges;
2. narrow alluvial fans and floodplains at their foot;
3. broad, gently undulating erosional, lateritic, or 'old' alluvial plains;
4. broad sand plains or dune fields; and
5. a central area of salt pans or alluvial plains.

The large areas in Queensland of gently undulating plains formed on Mesozoic shales are the main exception to this generalised topographic sequence.

No large river systems comparable with the Nile, Indus, or Colorado cross Australia's arid areas. By comparison the Murray-Darling system which rises in the humid eastern highlands and crosses the south-eastern part of the zone is small and has little influence on the zone as a whole. Vast areas, particularly in Western Australia, have no organised drainage system and over much of the rest small ephemeral streams rising in hilly areas terminate on the footslopes. Much of the north-east of the zone drains by way of broad, shallow, often braided rivers towards Lake Eyre but they flow intermittently, and only in exceptional years does water actually reach Lake Eyre. Over the whole zone the mean annual runoff is less than 0·5 in. (12·7 mm).

Plant growth in arid areas is dependent commonly on local redistribution and concentration of rain water. Water from slopes is concentrated on run-on areas where plants grow after falls of rain as low as 0·5 in. (12·7 mm). Microtopographic features such as gilgais, wanderrie banks, and mulga groves are important for the same reason.

Most of the landscapes are formed on, or from the products of, an ancient deeply weathered land surface, and most of the soils are highly leached and infertile. Little detailed information on soils is available. Soil descriptions and broad-scale maps have been published for those areas surveyed by the CSIRO Division of Land Research (Stewart 1954, in press; Litchfield 1962, 1963; Sleeman 1964; Rutherford 1964). Other areas have been covered by Jessup (1951), Butler (1950), and Jackson (1962) and recently the existing information on soil distribution has been compiled into the *Atlas of Australian Soils* (Isbell *et al.* 1967, 1968; Northcote 1960, 1962, 1966, 1968; Northcote *et al.* 1967, 1968).

Many different soils and variants occur but broadly speaking there are six main groups.

Red Sands and Red Clayey Sands

These are the soils of the sand plains and dune fields which cover about a third of the area (siliceous sands and earthy sands—Map 2, Chapter 3). They are extensive in Western Australia, north-western South Australia, and southern Northern Territory and are characteristic of the Great Sandy Desert, the Gibson Desert, the Great Victoria Desert, and the Simpson Desert.

The soils have uniform profiles, are massive in structure, and freely drained. The red sands, characteristic of dune fields, contain almost no clay or silt and the red clayey sands of the sand plains contain less than 10 per cent of clay plus silt. They are weakly acid to neutral and highly infertile, with nitrogen and phosphorus levels less than 0·02 and 0·01 per cent respectively.

Most sand plains and dune fields lack organised drainage, indicating that rain infiltrates where it falls.

Red and Yellow Earths

These soils are second only in extent to the red sands and also cover nearly a third of the area (see Map 2). They are the common soils of the ancient deeply weathered plains and of 'old' alluvium derived from them and are also developed on erosional surfaces on many rocks. They have a gradational profile with coarse to medium-textured surfaces grading into finer-textured lower horizons and a massive structure. Their reaction is acid to neutral and they are highly infertile.

Some of these soils contain ferruginous nodules and in some a siliceous hardpan occurs in the profile (Litchfield and Mabbutt 1962).

Cracking Clays

The biggest area of these soils is in an arc stretching around the north and east of the arid zone, that is across the Northern Territory and in Queensland (grey, brown, and red clays—Map 2, Chapter 3). They are also the most common soils of the riverine plain in the south-east. They are developed on fine-textured alluvium (e.g. the Barkly Tableland and the riverine plain) and on basic rocks (e.g. basalt in the Victoria River district of the Northern Territory and shales and limestones on the rolling downs of Queensland).

They are mostly grey or brown, have uniform profiles with a high clay content, are alkaline in reaction, and exhibit strong swelling and shrinking characteristics with wetting and drying. Normally those on alluvium are infertile but residual soils are moderately fertile.

Texture Contrast Soils

This group includes solonetz, solodised solonetz, and solodic soils, soloths, and solonised brown soils (see Map 2, Chapter 3). These soils have an abrupt transition in their profile from a coarse- or medium-textured surface to a finer-textured subsoil which is commonly hard and impermeable (Pl. 7). The surface horizon is neutral and the subsoil alkaline with low to high salt levels. In some areas, such as the stony tablelands, the surface is covered by a pavement of siliceous stones.

Texture contrast soils are most common in the southern half of the zone. Because of an impermeable subsoil they are susceptible to erosion and 'scalding' and in many areas landscapes with these soils are in poor condition.

Calcareous Earths

These soils (the grey-brown and red calcareous soils of Map 2, Chapter 3) are widespread, occurring wherever highly calcareous substrates occur. They are of coarse to medium texture, contain fine carbonate throughout the profiles, and are strongly alkaline.

Landscapes with these soils are mostly erosional in origin with moderate slopes. They are susceptible to erosion and, in many areas, are in poor condition. A deep variant in the Ord River catchment provides the worst example of erosion in the Australian arid zone.

Skeletal and Stony Soils

These (the lithosols of Map 2, Chapter 3) occur on hills and mountains.

Soil Microtopography

An important feature of the Australian arid zone is the pronounced microtopography on many landscapes. Many areas with cracking clays or texture-contrast soils are gilgaid, a microtopographic phenomenon believed due to shrinking and swelling of the soils. Gilgais may be circular or linear in outline. On gentle to moderate stone-covered slopes in the southern arid zone they are commonly contour-aligned.

On such areas and on the stony tablelands vegetation is restricted largely to the gilgais and the intermediate pavement areas are practically bare. On many gently sloping areas with red earth soils in central and Western Australia the slopes are not uniform but consist of a contour-aligned succession of steeper and flatter areas believed to be a sheet-flow phenomenon. The flatter areas carry groves of mulga and grass and the steeper (intergrove) areas are largely bare. In Western Australia a pattern of grassed wanderrie banks interspersed with bare areas is of alluvial origin (Mabbutt 1963).

VEGETATION

Little detailed information on the distribution of plant communities or species, or the factors influencing it, is available for any part of arid Australia. However, at a broad level the general structure and composition of the major communities is known and published descriptions, mostly accompanied by maps of various kinds, are available for about half the area (Blake 1938; Crocker 1946b; Beadle 1948; Jessup 1951; Perry and Christian 1954; Condon and Stannard 1956; Stannard 1958, 1963; James 1960b; Perry and Lazarides 1962, 1964; Speck 1963; Speck and Lazarides 1964; Perry in press).

Apart from large trees along the major stream lines the vegetation is low, the highest components rarely exceeding 30 ft (10 m). The communities are simple structurally and ground cover is sparse. The communities are composed of one or more distinct layers, these being short grass-forb, tussock or hummock grass, low shrub, and tall shrub-low tree. Within each layer one or a few species tend to comprise most of the biomass on each site and, by considering these prominent species, reasonably discrete layer-communities (synusiae) can be recognised. Individual species and synusia appear to react independently to environmental influences and their distributions commonly overlap. It is common, for example, for shrub steppe or grassland communities to occur as understoreys in tall shrub-low tree communities.

The arid shrublands and grasslands are poor floristically, the number of species being only a few thousand, a high proportion of which are endemic. The Poaceae is by far the largest family, other prominent families being Asteraceae, Mimosaceae, Fabaceae, Caesalpinaceae, Chenopodiaceae, Malvaceae, Goodeniaceae, Myrtaceae, Myoporaceae, Amarantaceae, Boraginaceae, Solonaceae, Proteaceae, Zygophyllaceae, Brassicaceae, and Portulacaceae. These families comprise over half the total flora. Large genera include Aristida, Eragrostis, Triodia, Eriachne, Helichrysum, Helipterum, Calotis, Acacia, Swainsona, Indigofera, Crotalaria, Cassia, Atriplex, Kochia, Bassia, Sida, Goodenia, Eucalyptus, Eremophila, Ptilotus, Heliotropium, Solanum, Hakea, Grevillea, and Zygophyllum.

Compared with other arid areas in the world the vegetation is remarkably benign, the plants, with a few notable exceptions, lacking spines or thorns. Large succulents of the Cactaceae and Asclepiadaceae do not occur although many of the Portulacaceae and Chenopodiaceae are succulent or semi-succulent. The acacias, unlike those of other parts of the world, are almost all phyllodineous. Two prominent grass genera (Triodia and Plectrachne—commonly called spinifex) are unusual in that they grow as large evergreen tussocks or hummocks and, in many respects, resemble shrubs.

There are many plant communities but the vegetation can be described broadly in five main categories shown in Map 3.

Shrub Steppe (Saltbush)

These are communities characterised by chenopodiaceous shrubs normally 3 ft (1 m) or less in height. Shrub density varies from scattered isolated plants to dense stands with only 1 or 2 ft (0·5 m) between individuals and containing up to 200 shrubs per acre (500 per ha) (Pl. 19).

The saltbush shrubs commonly occur in mono-specific stands but mixtures of two or more species occur on some sites. The most common and constant species are *Atriplex vesicaria*, *A. rhagodioides*, *Kochia sedifolia*, *K. pyramidata*, and *K. astrotricha*.

The shrub steppes are restricted to the southern half of the zone where 30 to 50 per cent of rain falls in winter. Mean annual rainfall is less than 10 in. (254 mm) except for the area of *Atriplex vesicaria* on the riverine plain of southern New South Wales where rainfall is as high as 14 in. (356 mm).

Shrub steppes occur on a variety of soils. On the riverine plain *A. vesicaria* grows only on clays but elsewhere it is found also on medium- and coarse-textured soils, generally calcareous or alkaline in reaction. Kochia communities mostly occur on texture-contrast soils and calcareous earths and not on fine-textured soils.

In long dry periods the spaces between shrubs are bare but following rains short grasses and forbs grow, grasses being more common after summer rains and forbs after winter rains. In many areas shrub steppe communities occur as understoreys to Acacia shrublands (Pl. 55).

Atriplex vesicaria communities commonly exhibit contagious distributions. On the cracking clay soils of the riverine plain the patterns are not immediately obvious but on stony slopes in western New South Wales and in northern South Australia they are very distinct. Here the shrubs grow in and around linear, contour-aligned gilgais (in which stones are rare) separated by stony almost bare areas.

Acacia Shrublands

These are characterised by a layer of tall shrubs (or low trees) normally 10–20 ft (3–7 m) high but in some areas as low as 6 ft (2 m) or as high as 30 ft (10 m). The density of the tall shrub layer varies from only 2–3 per acre (1 per ha) to over 3000 per acre (8000 per ha) in some mulga stands in central western Queensland.

Acacia shrublands are widespread and occupy nearly a third of Australia's arid lands, occurring in all parts except the far north. They mainly occur on red earth soils but are common on most soils except cracking clays, and gidgees (*Acacia cambagei* and *A. georginae*) are found even on these in some areas.

Acacia shrublands are commonly found in almost monospecific stands (Pl. 20). Mulga (*Acacia aneura*) is the most widespread community and occupies the largest area. It is prominent on red earths, common on stony hillslopes (mainly on acid rocks), and also occurs on clayey sands. Everist (1949) has described mulga in Queensland in considerable detail. Myall (*A. sowdenii*) is common in South Australia, wichetty bush (*A. kempeana*) in central Australia, and *A. georginae* and *A. cambagei* in Queensland, all on calareous soils. On coarse-textured alluvial soils a mixed community of ironwood (*A. estrophiolata* or *A. excelsa*), *A. kempeana*, whitewood (*Atalaya hemiglauca*), corkwood (*Hakea intermedia*), rosewood (*Heterodendrum oleifolium*), and several other species occur. Associated communities are cypress pine (*Callitris columellaris*) on sand ridges in western New South Wales and false sandalwood (*Myoporum platycarpum*) and belah (*Casuarina cristata*) in south-western New South Wales and in South Australia. Large areas in central New South Wales carry a low woodland of rosewood and belah (Pl. 56).

Along the southern boundary of the arid zone Acacia shrublands give way fairly sharply to

Plate 59 Arid low woodland of *Eucalyptus brevifolia* (snappy gum) with understorey of *Triodia* spp. (spinifex), Northern Territory (CSIRO photo)

semi-arid woodlands but in the east they grade imperceptibly into them.

Apart from areas in the south, where shrub steppe communities form an understorey, low shrubs are not prominent but several species of Eremophila and Cassia occur scattered through most stands of mulga. The common ground layer is comprised of annual or short-lived perennial grasses and forbs with scattered plants or patches of perennial tussock grasses such as *Eragrostis eriopoda*, *Danthonia bipartita*, and *Aristida* spp.

In central and Western Australia mulga communities on gentle slopes exhibit a grove pattern in which contour-aligned groves of dense mulga alternate with almost bare intergroves.

Arid Low Woodlands

Lateritic plains and stony hills in the far north are characterised by open stands of low eucalypts about 20 ft (6 m) high. The common species are *Eucalyptus brevifolia*, *E. pruinosa*, *E. terminalis*, and *E. argillacea*, and the common ground layer is xerophytic hummock grass (Pl. 59). The communities grade into the semi-arid woodlands to the north.

Arid Tussock Grassland (*Mitchell Grass*)

Communities characterised by perennial tussock grasses 1·5 to 3 ft (0·5 to 1 m) high extend in a great arc on cracking clay soils across the northern and north-eastern margins of the arid zone. They also occur on smaller areas of cracking clays in central Australia and western New South Wales but not on similar soils of the riverine plain of New South Wales which carry shrub steppe.

The characteristic grasses occur as discrete tussocks 2 ft (0·6 m) or more apart. Individual tussocks may be circular in outline and 6–9 in. (15–23 cm) in diameter but commonly have an elongated outline about 6 in. by 18 in. (15 × 45 cm) (Pl. 22). Spaces between tussocks are bare in long dry periods but support a variable cover of short annual grasses and forbs following good rains. A Mitchell grass community and its response to a particular season has been described by Everist (1935).

Most of the grasslands are characterised by one or more of the Mitchell grasses (*Astrebla* spp.). Barley Mitchell grass (*A. pectinata*) is the commonest species in the low to moderate rainfall areas, particularly in the Northern Territory and northern Western Australia. Curly Mitchell grass (*A. lappacea*) is prominent on the vast areas of rolling downs in Queensland, bull Mitchell grass (*A. squarrosa*) near the higher rainfall margins of the grassland area and on run-on areas in drier parts, and weeping Mitchell grass (*A. elymoides*) in wetter environments over most of the grassland area. In most of the tussock grasslands the perennial component is almost entirely Mitchell grass with a scattering of other species, but occasionally other species are important constituents. Feathertop (*Aristida latifolia*) is the most common of these; it appears to increase under grazing but is also favoured by particular seasonal conditions. Bluegrass (*Dichanthium fecundum*) and panic (*Panicum whitei*) are common near the higher rainfall margins and also on the basalt areas of the north-western part of the Northern Territory. In the low rainfall areas of central Australia neverfails (*Eragrostis setifolia* and *E. xerophila*) are common associates of Mitchell grass and on some sites occur without Mitchell grass.

In aerial photographs the tussocks appear to be arranged in a pattern. In flat areas the pattern appears to be small-scale and possibly reflects a common alignment of the linear tussocks, but some of the rolling downs country in Queensland shows larger-scale, contour-aligned patterns.

Large areas of the grasslands are entirely treeless and shrubless but scattered shrubs or low trees occur in some areas. Mimosa (*Acacia farnesiana*) is widespread, boree (*Acacia cana*) grows on some of the rolling downs in Queensland, in some areas near the Northern Territory-Queensland border gidgees occur as an overstorey, and on the basalt country in the Northern Territory rosewood (*Terminalia volucris*) and nutwood (*T. arostrata*) are common. Creeks are usually lined with coolibah (*E. microtheca*) and bore drains with Parkinsonia or Myoporum.

Boundaries between grasslands and other communities are mostly sharp and coincide with abrupt changes in soil texture, but where fine-textured soils continue into semi-arid areas there is a gradual transition to bluegrass-browntop grasslands (Chapters 6, 8, 9).

Arid Hummock Grasslands (*Spinifex*)

These are the most widespread and extensive communities of arid Australia, occupying about one-third of the area, and occurring everywhere, except in the extreme south, on the red sands and red clayey sands of the great sand plains and dune fields and also on many rocky hillslopes (Pl. 24).

The communities are characterised by spinifex (*Triodia* spp. and *Plectrachne* spp.) which are perennial evergreen grasses mostly forming large tussocks or hummocks. The normal hummock is 3–5 ft (1–1·5 m) in diameter and 1·5–2 ft (0·5–0·6 m) high but in some species (e.g. *T. longiceps*) the hummocks grow as large as 20 ft (6 m) in diameter and 6 ft (1·8 m) high and in others (e.g. *T. basedowii*) the centre of the hummock dies and mature plants form annuli 5–15 ft (2–5 m) in diameter, about 1·5 ft (0·5 m) wide and 1·5 ft (0·5 m) high (Pl. 26). The hummocks occur as discrete plants generally with bare interspaces. Of the many species, *T. basedowii* is the most extensive, being the common species on sandy soils up to about 12–14 in. (305–356 mm) mean annual rainfall. Further north *T. pungens* is the common species on sands, red earths, and rocky areas. *Plectrachne schinzii* is common on sands where rainfall is about 12–14 in. (305–356 mm), *T. clelandii* and *T. hubbardii* grow on rocky areas in central Australia, *T. longiceps* is particularly common in calcareous environment, and many other species (e.g. *T. secunda*, *T. wiseana*, *T. brizoides*, *T. intermedia*, *T. roscida*) grow in the north-west. *T. irritans* extends further south than other species but is found more as scattered tussocks in Acacia shrublands and mallee communities than in hummock grasslands.

The morphology of the leaves of spinifex has been described by Burbidge (1946). They are all highly lignified and are folded about the midrib to appear cylindrical. The stomates are in grooves on the undersurface which normally occurs as a slit in the cylinder.

Other grasses and forbs are abundant only in exceptionally good years or in the first few years after fires. The commonest are the three-awns (*Aristida pruinosa*, *A. browniana*, *A. contorta*), woollybutt (*Eragrostis eriopoda*), and parakeelya (*Calandrinia balonensis*) but there are many others. In the far north other grasses are more common with three-awn (*Aristida pruinosa*) being the most widespread and ribbon grass (*Chrysopogon fallax*) being particularly common in the 'pindan' country of Western Australia.

In very few areas are the hummock grasslands true grasslands. While spinifex is the characteristic feature of the vegetation, scattered trees and shrubs occur almost everywhere. Mostly these are only 3–6 ft (1–2 m) high but in some areas of central Australia there are majestic stands of desert oak (*Casuarina decaisneana*) up to 60 ft (18 m) high. Along the northern margin the eucalypts of the eucalypt low woodlands become more common and there is a gradual transition between the communities.

GRAZING LANDS

In non-arid parts of Australia grazing lands consist largely or entirely of the understoreys of the vegetation communities, but in arid areas most of the characteristic shrubs and low trees are browsed by stock and the whole vegetation —grasses, forbs, shrubs, and low trees—comprise the grazing lands. Thus for arid areas vegetation communities and grazing lands (the rangelands of Perry 1968) are virtually synonymous. The browse (or top-feed as it is called in Australia) species is mostly evergreen and is important particularly in drought periods when the grasses and forbs are absent.

Published descriptions and maps of grazing lands were available for only half the arid zone (Blake 1938; Beadle 1948; Jessup 1951; Christian and Stewart 1954; Perry 1960, 1962, 1964, in press; Wilcox and Speck 1963; Speck, Fitzgerald, and Perry 1964) but all the main types are included.

There are many types of grazing lands but like the vegetation they can be grouped into five main classes (see Table 6 : 1).

Saltbush-Xerophytic Midgrass

The grazing lands of the shrub steppe (saltbush) vegetation has been classified as saltbush-xerophytic midgrass (see Chapter 6). Following rains many species of short-lived grasses and forbs grow between and under the shrubs. These are more palatable than the shrubs and are preferentially grazed. In long dry periods the less palatable shrubs provide at least part of the diet of the animals which continue to scavenge remnants of the grasses and forbs.

Most of the saltbush-xerophytic midgrass grazing lands are used for wool production but beef is produced in the far north of South Australia. Stocking rates vary from about 1 sheep to 3 acres (1·2 ha) on the riverine plain of New South Wales to 1 sheep to 30 or 40 acres (12–16 ha) in drier areas.

Bushes are susceptible to heavy grazing and in many areas stands have been reduced greatly or even eliminated. Even on the flat riverine plain with its comparatively high rainfall considerable areas of bush have deteriorated and some areas are 'scalded'. Jones (1966) estimated that here over 50 per cent of the scalds regenerated naturally to annual vegetation during the 1950s when rainfall was above average (Pl. 60). However, in drier areas where much of the shrubland occurs on sloping sites with erodible soils, destruction of the bush can be disastrous as regeneration of vegetation is poor and landscapes erode rapidly to a bare 'scalded' condition. A considerable proportion of the shrubland landscapes in western New South Wales, north-eastern South Australia, and Western Australia is in poor condition and requires special management, and possibly mechanical treatment, for regeneration to take place.

Acacia Shrub–Shortgrass

These are the grazing lands of the Acacia shrublands. The ground storey consists of scattered tussocks or patches of perennial tussock grasses (*Eragrostis eriopoda*, *Danthonia bipartita*, *Aristida* spp., *Eriachne* spp., and others) and, in favourable periods, a wealth of short-lived grasses and forbs of which *Aristida contorta*, *Enneapogon* spp., *Helipterum floribundum*, and *Calotis hispidula* are the most common and widespread. Beadle (1948) considers that perennial tussock grasses were once more abundant in western New South Wales and that they have decreased greatly under grazing. This is not true for central Australia where perennial tussock grasses are scarce in

Plate 60 Shrub steppe: degraded *Atriplex vesicaria* community now dominated by annual composites, western New South Wales (CSIRO photo)

both grazed and ungrazed stands.

In favourable periods stock prefer the short grasses and forbs but most of the prominent shrubs and low trees are moderately palatable and are grazed in long droughts when grasses and forbs are lacking. In many areas mulga, particularly, is cut or 'pushed' during long droughts to keep stock alive.

Acacia shrublands are used for wool sheep grazing in the south and in much of Queensland and for beef cattle in the north. Stocking rates vary from about a sheep to 5 acres (2 ha) in the higher rainfall parts to a sheep to 20 or 30 acres (8–12 ha) under more arid conditions. Cattle are grazed at 5 to 8 per sq mile (2 to 3 per km^2).

In the West Darling district of New South Wales and some parts of South and Western Australia the shrub and low tree cover has been reduced or eliminated under grazing and many sites have eroded. Depletion of the stands appears to be due to destruction of seedlings and young plants by stock and rabbits combined with the natural death of mature plants. In central Australia natural regeneration appears adequate to maintain mulga density but many stands of witchetty bush have been depleted. In central Queensland mulga regenerates freely producing dense stands up to 3000 plants per acre (8000 per ha) under which very little grass is produced. Here mulga is a weed and mechanical control is attempted—some dense stands have been treated two or three times in the hundred or so years of grazing occupation.

Georgina gidgee, prominent on both sides of the Queensland-Northern Territory border, is poisonous to ruminants and is responsible for heavy losses of both sheep and cattle in long dry periods.

Xerophytic Tussock Grass

The grazing lands of the arid tussock grasslands are the most productive in arid Australia and although they occupy less than 10 per cent of the total area they probably carry half the stock. In most areas they have a regular summer wet season which produces a dense growth of short grasses and forbs in the spaces between the perennial tussocks. The perennials also grow rapidly following rains.

Stock preferentially graze the annuals but the perennials provide most of the forage in the late dry season. During this period the dry mature grasses are low in nutritive value and stock lose weight.

Wool sheep are grazed on all except the northernmost parts of these grasslands in Queensland, at stocking rates of a sheep to 5–10 acres (2–4 ha). In north Queensland and in the Northern Territory beef cattle are grazed at 15–20 per sq mile (6–8 per km^2).

Mitchell grass is well adapted to arid conditions. Following light rains axillary tillers shoot from the lower 3–5 nodes of the old stem. They flower within 17 days and set seed within a further 10 days. Heavier rains will produce new basal tillers which grow and develop more slowly. Mature plants grow and seeds germinate under a wide range of temperatures (15°C–42°C). The plants are susceptible to heavy grazing; removal of the lower nodes prevents response to light rains, and grazing to a short stubble kills many plants. In many places the density of perennial grasses has been reduced and in some they have been eliminated. Fortunately most landscapes are not erodible and reduction or elimination of the perennial species merely reduces late dry season carrying capacity. The headwaters of the Ord River are an exception—land there has eroded severely and costly remedial measures have had to be employed to ensure longevity of the projected downstream dam (Fitzgerald 1967, 1968).

Xerophytic Hummock Grass

In their natural states most of the grazing lands of the arid hummock grasslands and the arid low woodlands will not support stock and vast areas are unoccupied Crown land. Areas along the northern margins are grazed at low stocking rates, particularly in the Pilbara and Kimberley districts of Western Australia where softer grasses are associated with the spinifex. In the Pilbara district grazing has eliminated these better grasses and Nunn and Suijdendorp (1954) have shown that their regeneration is possible by a system of burning plus deferred grazing.

The grazing lands of eucalypt low woodlands are also xerophytic hummock grass although they grade into xerophytic midgrass in the northern and higher rainfall parts of the woodlands.

THE LIVESTOCK INDUSTRIES

About half of Australia's arid lands, the sand plains, dune fields, rocky hills, and salt lakes are considered unsuitable for grazing and a large proportion of them remain as an unalienated Crown land. The remainder is used for grazing wool sheep (south) or beef cattle (north) under very extensive management conditions. Stocking rates are low but the area supports nearly 48 million wool sheep and 4·5 million beef cattle, nearly a third of Australia's sheep and beef cattle population.

Apart from a very small proportion held as freehold or perpetual lease most of the productive area is held by individuals or companies under long-term (30 or 50 year) leasehold from the various State governments (in the Northern Territory the Commonwealth) (Heathcote 1969). The size of the properties varies with the type of lease and among States. In the Northern Territory the average size is about 1000 sq miles (2600 km^2) and the largest exceed 5000 sq miles (13,000 km^2) whereas in western New South Wales few properties exceed 50,000 acres (22,000 ha). As well as controlling size of properties the governments impose different conditions as regards capital improvements, stocking rates, agistment, etc. These have been detailed by Heathcote (1969).

Although there are variations in detail the husbanding system is simple—year-long set-stocking. The lack of topographic variation does not provide opportunities for seasonal grazing and the alienation of the land on an individual property basis precludes nomadic grazing. Nowadays most properties are boundary-fenced and subdivided to a greater or less extent but stock are controlled largely by watering points. Most of the watering points are man-made and are either surface catchment tanks or drilled wells. In large areas of Queensland the wells are artesian and shallow channels (bore drains), often many miles long, distribute water across the land.

Although returns per unit area are very low, the large size of the holdings, the minimal degree of husbandry with the concomitant high efficiency per unit of labour (on average only one unit of labour is required for 1800 sheep), and the relatively low level of capitalisation, yield a high return to capital. In fact, on the basis of return to capital invested, the Australian pastoral industries rank among the most efficient agricultural industries of the world. In the last decade falling wool prices and rising costs of materials and labour have depressed the profitability of the wool sheep industry and are causing increasing concern for the future.

Another cause for concern is that in the past the grazing industries have been exploitative—they have been steadily mining the vegetation and land resources on which they depend for their future viability. This has not been documented by vegetation measurement but can be implied from areas in poor condition and from the trends in stock numbers. For all areas investigated stock numbers show a rapid rise following settlement, followed by a spectacularly sudden crash (generally associated with a drought period) and then a recovery to a fairly steady level at about a third of peak figures (Perry 1967). Relative stability is maintained only with continuing improvements, particularly extra watering points, which in effect bring more land within reach of stock.

IMPEDIMENTS TO ANIMAL PRODUCTION

A major reason for the efficiency and profitability of the animal industries in arid Australia is freedom from pests and diseases. Stock are left virtually to roam the ranges from year to year. Cattle are mustered (rounded up) for calf branding and drafting (cutting out) of animals for market and sheep for lamb marking and shearing; few other operations are necessary.

Both ecto- and endo-parasites are minor problems. Cattle ticks are only along the tropical margins and sheep lice occur occasionally in some areas. In the past, the sheep blowfly (*Lucilia cuprina*) was a major pest but the Mule's operation and other management practices have minimised this problem.

Bovine tuberculosis and contagious bovine pleuropneumonia, widespread in the past, have now been eradicated. Vibriosis is prevalent in cattle in tropical areas but its effect on reproduction is not known.

Phosphorus deficiency is common in cattle on the Mitchell grass areas of the Barkly Tableland and is associated with bone chewing and botulism. In many of the shrub steppe areas water supplies are saline and in dry periods when a proportion of the diet is composed of chenopod shrubs with a high salt content sheep are exposed to an excessive salt load, but the effect on production is not known.

Many plants in arid Australia are poisonous to stock but only two are of economic significance. Georgina gidgee, which contains sodium fluoroacetate, causes severe losses in cattle and sheep and indigo (*Indigofera dominii*) causes a chronic disease (Birdsville disease) in horses. Other plant poisons cause occasional losses or severe losses under particular circumstances such as when hungry travelling animals are allowed to graze an area where a poison plant is plentiful.

Everywhere in the arid zone reproductive rates of stock are lower than in the more developed higher-rainfall country. However, it is only in the far north, and particularly on the Mitchell grass areas, that reproductive rates are very low. Here lambing percentages on some properties are so low (30 per cent or less) that flock numbers can be maintained only by buying sheep. Cattle reproductive rates are low also in these northern areas. The most likely reason is the poor nutritive value of the grasslands in the dry season. In an experiment in the Kimberley area supplementation with whole cotton seed for four months of the dry season had dramatic effects on calf drop and cow survival (Armstrong *et al.* 1968). Vibriosis in cattle and the effect of high temperatures on the fertility of rams probably also contribute to low reproduction rates in these areas.

THE FUTURE OF AUSTRALIA'S ARID GRAZING LANDS

Most Australians blame avaricious pastoralists for the exploitation of arid grazing lands but it is more accurate to ascribe it to lack of knowledge, not only on the part of pastoralists but also of governments (who after all are the owners), of financial institutions, and of scientists. Administrative policies are determined, or not determined when they should be, by governments lacking the basic facts. Generally management decisions are made by pastoralists, not on the basis of their knowledge of the biological environment, but because of financial exigencies determined by institutions also ignorant of the special needs of arid areas.

At present most of the grazing lands occupied in arid Australia are in fair to good condition largely because of three factors:

1. The perennial species of the major grazing lands are less palatable than the short-lived plants which appear after rains. The perennials therefore receive a period of natural deferment after each rain.
2. Most of the landscapes are flat and relatively stable to erosion.
3. Grazing by stock commenced only about 100 years ago and many areas have been stocked for a much shorter period.

Australia is fortunate on these three counts but they are no cause for complacency. They merely explain why Australia's arid grazing lands are not dustbowls already. If these lands are to be maintained in a productive state, management practices and financial arrangements specially adapted to arid conditions must be devised. This requires factual data from biologic and economic research. At present little is known of the climate, land, plants, or animals let alone the operation of the whole complex of interacting factors which constitute the grazing ecosystem. Finances and stock are managed, the vegetation and resources are not.

18

WATER AND IRRIGATED PASTURES

L. F. MYERS

The low and variable rainfall of most of the continent is the dominant factor in livestock production in Australia and droughts have frequently caused heavy stock losses. In the course of the last hundred years, Australia experienced seven major droughts which affected most of the continent as well as other local droughts of varying extent and duration. 'One of the most severe was that of 1895–1903, when the sheep population fell from approximately 106 m. down to 53 m. It took thirty years to build it up again to the 106 m. of the early nineties and a further ten years to reach a new peak of 125 m. in 1942. Then followed the disastrous drought of the middle forties when sheep numbers declined to 96 m.' (Franklin 1962 : 267). Since then, extensive areas of New South Wales and Queensland have had severe droughts in 1966–7.

The droughts and the importance of animal products in the economy generated considerable public enthusiasm for irrigation development in the early 1900s. It seemed obvious in those days that animal losses could be avoided if the country had plenty of irrigated pastures and that the economic benefits would be substantial. The low labour and capital costs of pastures were an added attraction. The result is that although Australia has only 3 million acres (1,215,000 ha) of irrigated land (about half that of California) over 60 per cent is permanently under pasture and a further 20 per cent is devoted to fodder crops and lucerne.

The area irrigated in each State of the Commonwealth and the crops grown are given in Table 18 : 1. The emphasis on pastures rather than high return crops has led to a commitment of water resources in a way which could create problems in the future. For pasture development, land was chosen on the basis of topography to ensure low development costs. The suitability of the soils was often a secondary consideration though what constituted a good irrigation soil was not well known or understood at that time. The result is that irrigation water is committed to soils that are not capable of supporting crops demanding permeable well-drained soils. Versatility in landuse has been lost: and with it, a major advantage of irrigation agriculture.

An early realisation of the importance of water to Australia led to government action to control the major water resources. State governments have virtually complete control of rivers

TABLE 18 : 1 Area irrigated, by States, 1965–6
'000 acres ('000 ha)

Crop	N.S.W.	Vic.	Qld	S.A.	W.A.	Others[a]	Australia	
Pastures	742	1022	35	42	30	18	1889	(765)
Orchards and vineyards	52	90	9	60	12	7	230	(93)
Rice	64	—	—	—	—	—	64	(26)
Sugar cane	—	—	141	—	—	—	141	(57)
Vegetables	17	28	51	10	10	13	129	(52)
Other crops, incl. lucerne, fodder crops, and fallow	443	123	96	17	15	10	694	(281)
	1318	1263	332	129	67	48	3147	(1274)

[a] Tasmania, Australian Capital Territory, Northern Territory.
Source: Adapted from *Year Book of the Commonwealth of Australia.*

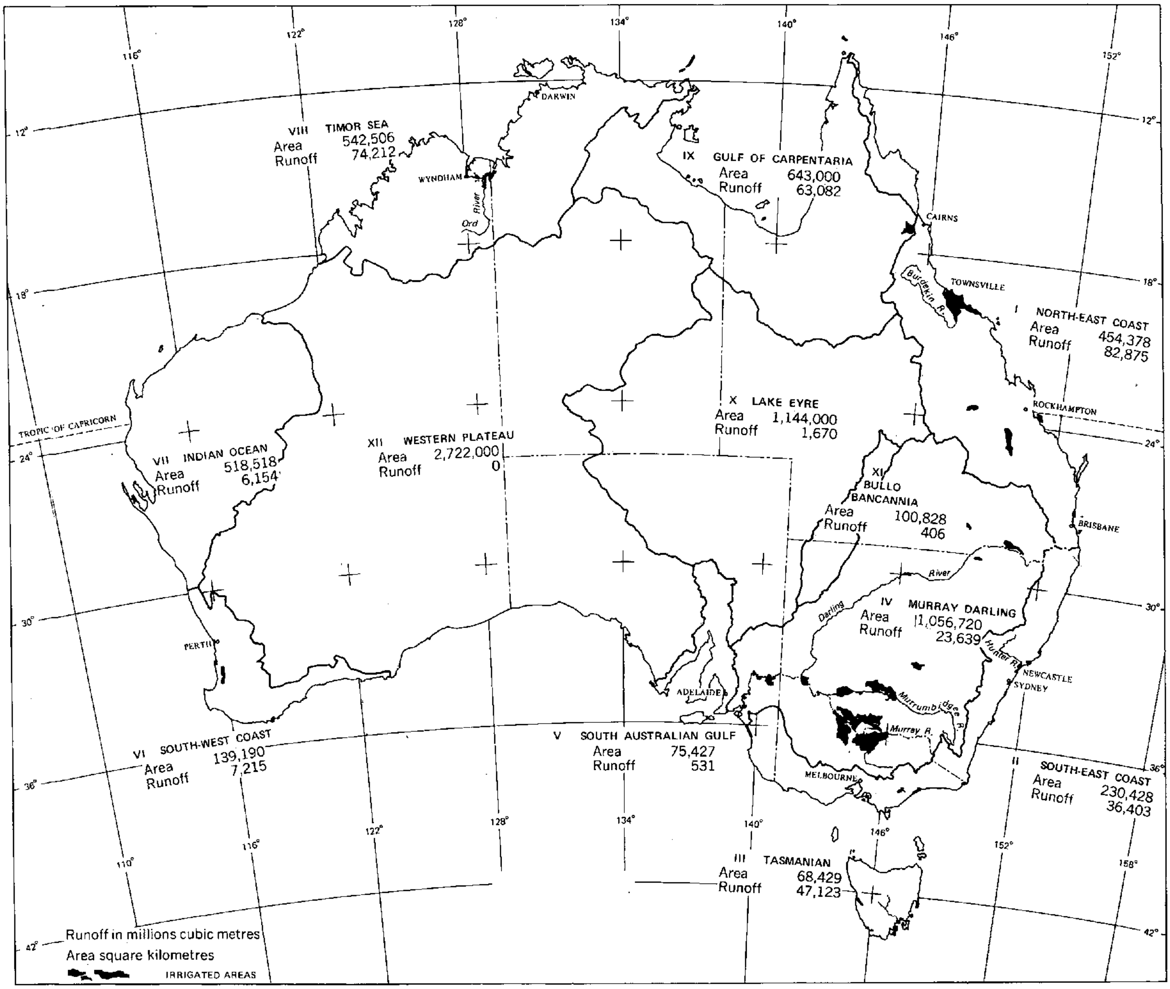


Fig. 18 : 1 Australian water resources: principal catchments and their runoff (*Source*: *Review of Australia's Resources 1963*. Canberra, Department of National Development for Australian Water Resources Council, 1965)

and underground waters. In the major irrigation states, Queensland, New South Wales, and Victoria, the water Acts are administered through commissions responsible to a minister of state.

In all that follows it is important to keep these points in mind, namely the frequent long droughts, the importance of the animal industries, the small water resources, and the control of water by government authorities. Another factor is beginning to operate: as the population rises agriculture must compete with urban and industrial needs, especially in New South Wales and Victoria. At present, industrial use of water is only about one-tenth of the amount used for irrigation but in some places competition is increasing.

AUSTRALIA'S WATER RESOURCES

The total surface runoff from the continent is about 280 million acre feet (345,170 million m^3) per year which is equivalent to less than 2 in. (51 mm) per year. Even when the 1 million square miles (2·6 million km^2) of the Western Plateau, which has no runoff, is excluded, the runoff is less than 3 in. (76 mm). The world average is 9 in. (230 mm).

The irrigation areas are mapped in Fig. 18 : 1

which also shows the drainage basins and their mean annual runoff.

Almost half of the runoff flows to the Gulf of Carpentaria and to the far north-east coast, but the amount used for irrigation in these areas is not significant. The Murray-Darling basin, on the other hand, has only about 8 per cent of the total runoff but supports 90 per cent of Australia's irrigated land. The apparent anomaly of water resources 'running to waste' where the greatest flow is concentrated highlights one of the problems of irrigation development in Australia. The flow from the major basins in northern Australia is barely exploited. Haigh (1964) discussed the irrigation potential of the North-east Coast Division of Queensland. He pointed out that this division has nearly 40 per cent of our mainland water resources and that areas within the division are suitable for irrigation. For example, the irrigated areas of the Burdekin delta, where the rainfall is 49 in. (1245 mm) annually, produce a third more sugar per area than adjacent non-irrigated areas with 80 in. annual rainfall. The Fitzroy and Burdekin Rivers have a catchment area greater than the area of the State of Victoria and a runoff equal to 70 per cent of the Murray Basin. In the Gulf of Carpentaria problems of suitable soils, topography and variable flow may be formidable but large-scale irrigation development would be possible. These areas could be used for irrigated pasture if suitable tropical pasture species are available but there are many, e.g. Campbell (1964), who would question the assumptions of Haigh (1964) and Tisdall (1961) that irrigation is the best way to use capital resources for agricultural development. The argument is refuted that such development is desirable simply on the basis that water is the ultimate limit to development in Australia.

A dominant factor in future irrigation development is the large variation from year to year of runoff water available. This is so even in the Murray-Darling Basin. The Murray River itself is partly snow fed but its tributaries are not. For example, the Goulburn River has annual flows varying from half a million acre feet to 6 million acre feet (616–7396 million m^3) and the Darling River from 1000 to 11 million acre feet (1·2–13,560 million m^3). The present capacity of storage dams on the Murray system exceeds the mean annual flow (12 million acre feet, 14,793 million m^3) and further storages are planned mainly to improve reliability of water supply and only partly to supply a modest increase in irrigated area (Australian Water Resources Council 1965).

The important areas in New South Wales, Victoria, and South Australia are served by the Murray River and its tributaries (Fig. 18 : 1). Because they constitute 90 per cent of all irrigated land and include most of the 2 million acres (0·81 million ha) of irrigated pastures these areas will be described in most detail.

MURRAY-DARLING BASIN

Soils

Soils of the Murray-Darling Basin are mainly heavy textured. The surface varies from loam to clay loam with clay subsoils. Topography is flat. The riverine plain which extends on both sides of the Murray River is a flood plain of heavy soils from clay loam to clay formed by efferent streams (prior streams) originating in the eastern and southern highlands at the end of the Pleistocene (Butler 1958).

The present permanent streams are less numerous than the clearly defined prior streams of the past. The most recent prior streams are seen as strips of light-textured soils, becoming smaller as they extend to the west. The light-textured soils are the levees of the prior streams and are reinforced to a varying degree by wind-blown sand from the original stream bed. The difference in height of the levees and the plain is often less than 3 ft (91 cm) but sand hills associated with the large streams may be up to 50 ft (15 m) high and extending up to 1 mile (2 km) from the stream bed. There is a wide margin around the edge of the plain where a layer of wind-blown calcareous clay, called 'parna' by Butler (1956), overlays the original landscape in a thin layer. Cockcroft (1965) also describes 'parna' and its influence on the properties of Victorian soils.

Apart from the sand hills, all soils including the levees have rather heavy subsoils that are salty at depth. Soils of all of the irrigation areas have been surveyed by CSIRO, State Departments of Agriculture, or the State Water Commissions, often in considerable detail.

More general accounts of the geomorphology and soils are available in Butler (1958) and

Langford-Smith (1960) for the area north of the Murray and in Cockcroft (1965) for the southern areas.

The delta-like efferent streams become smaller and less frequent as they approach the arid interior. The result is that soils of lighter texture are common to the east and the heavier flood plain soils are increasingly dominant to the west. There is also a tendency for soils to become saltier at shallower depths as one goes west into the more arid areas.

Although all types of soils are used for irrigated pastures the best are generally used for vegetables, fruit trees, or vines. South of the Murray, in Victoria, some of these better lighter-textured soils have become waterlogged and salted and have been reclaimed by a combination of leaching irrigations and the maintenance of a pasture cover (Morgan 1947; Morgan and Garland 1954). Salt damage was particularly severe in those parts of Tresco–Kerang on areas which, subsequently, were found to overlay a former bed of the Murray River (Pels 1964). The heavy-textured soils of the plains are free of salting problems mainly because of low permeability. They are suitable for grain crops and pastures. The least permeable are eminently suitable for rice but water supplies restrict their use for this purpose.

From an engineering point of view, the soils of the plain and the light-textured soils of the flatter levees are easiest to serve with a large irrigation scheme. The emphasis is on gravity methods of supply and flood irrigation because of their low initial cost and low labour requirements. The result is that pastures are grown on reclaimed salty soils or soils of low permeability.

Vegetation

The grey and brown soils of heavy texture of the plains are treeless and were originally semi-arid shrublands and shrub woodlands (see Chapters 16 and 17) but, especially to the south and east, grazing has induced a grassland dominated by *Danthonia* sp. and *Stipa* sp. but rich in other herbaceous species (Leigh and Mulham 1965).

The levee soils of the recent prior streams support woodlands of *Eucalyptus melliodora* and *Casuarina luehmannii* and, on the deeper sands, Murray pine (*Callitris columellaris*). The older prior streams buried beneath the heavy clay plain are often revealed by the presence of stands of black box (*E. largiflorens*). Along present permanent streams and areas liable to frequent flooding, river red gum (*E. camaldulensis*) form forests that are an important source of timber. Moore (1953a and b) has described and mapped the vegetation of the eastern Riverina in New South Wales.

Climate

The climate of the Murray Basin is continental and semi-arid and the result is a relatively high water use, especially in mid-summer. Evaporation recorded from the standard Australian tank typically exceeds 60 in. (1524 mm) per annum and evaporation of 0·3 in. (8 mm) per day is common in mid-summer. Mean annual rainfall varies from 20 in. (508 mm) at Yarrawonga in the east to 13 in. (330 mm) at Swan Hill in the west. The incidence of rain is slightly greater in winter. The winter rains and the lower evaporation in winter mean that irrigation is usually not required from May to August.

Pastures

Two types of pastures, annual and perennial, are common to all irrigation areas from southern Queensland (lat. 29°S) to Tasmania (lat. 42°S) and from eastern to western Australia. The separation of the two types depends on the predominant legume.

Annual pastures. Annual pastures are based on subterranean clover (*Trifolium subterraneum*), the annual reseeding clover so important all over southern Australia. The associated grass is often the annual, Wimmera ryegrass (*Lolium rigidum*), but the perennial *Phalaris tuberosa*, which is summer dormant, is sometimes sown.

Annual pastures are first irrigated in early autumn (late February to March–April) to germinate the clover and grass. Irrigation is continued until evaporation falls to low levels or winter rains are adequate, usually in May. Irrigation is resumed in August or September and continues until the clover sets seed and 'hays-off' in November. Usually, no irrigation is required from mid-May to mid-August and none is given after senescence of the clover in early November. Water requirements are as low as 12 to 18 in. (305–457 mm) per annum in areas with rainfalls of 15 in. (380 mm) or less, because the high evaporation of summer is avoided. If irrigation begins too early, for example in the late summer, much of this economy of water is lost. The optimum time to begin irrigation is a compromise between the benefit of growth beginning at a time of high temperature and long days and the penalty of a high water requirement. In addition, there are other risks to be assessed—low germination of subterranean clover because of high temperature dormancy and temperatures too high for the satisfactory germination of Wimmera ryegrass. The combination of wet soils and high temperatures can also lead to 'scalding' of the seedlings because of high respiration rates and reduced aeration. For maximum winter yields, Myers and Squires (unpublished) found 15 February to 15 March the optimum time for the first irrigation. The starting date is suggested to be 15 February because it is usually March before all parts of a farm can be irrigated at normal rates of delivery of irrigation water.

Yields of 4000 lb dm per acre (4480 kg per ha) can be attained by July on ungrazed pastures when irrigation begins in February. The spring ceiling yield, again of ungrazed pastures, is almost 8000 lb dm per acre (4860 kg per ha). Total irrigation water used varies from 18 in. to 24 in. (457–610 mm) per annum. Under continuous set stocking at 8 dry sheep per acre (20 per ha) sheep gain weight rapidly during autumn, winter, and spring, and subsist satisfactorily on dry residues from late November until irrigation begins the following year. The dry residues are low in quality and the sheep select seed heads of grass and the burrs of clover (Wilson and Hindley 1968). Weight losses up to 10 lb (4 kg) per sheep occur during summer, irrespective of stocking rate.

Perennial pastures. Perennial pastures are sown mostly with species with maximum growth in the spring and summer and are based on white clover (*Trifolium repens*). Sometimes strawberry clover (*T. fragiferum* L.) is included. Associated perennial grasses include perennial ryegrass (*L. perenne*), *Paspalum dilatatum*, cocksfoot (*Dactylis glomerata*), *Phalaris tuberosa*, Rhodes grass (*Chloris gayana*). These pastures require frequent irrigation, especially to maintain a reasonable proportion of white clover. Total water used can exceed 50 in. (1270 mm) per annum.

Factors governing productivity. Solar radiation levels in the Murray-Darling region are high; mean daily levels can exceed 600 cal. cm^{-2} day^{-1} for weeks at a time in the middle of summer. This is a mixed blessing—potential growth rates are high but to attain them water must be supplied generously, soil-plant-water relations must be ideal, and the plants must be adapted to high temperatures. Warren Wilson (1967) has recorded relative growth rates of up to 40 per cent per day with single plants of sunflowers over a period of 10 days at Deniliquin (lat. 35°S). At this rate, plants double their weight in 48 hours.

In the field at Deniliquin Sudan grass growth at mean rates of 1000 lb/acre (1120 kg per ha) dm per week over 20 weeks at non-limiting levels of applied nitrogen were recorded by J. L. Davidson (unpublished).

White clover growth rates of 300–350 lb per acre (336–392 kg per ha) dm per week over the summer period September to February inclusive were recorded by the late C. R. Kleinig. These rates are not particularly high by world standards. Measurements were made on heavy soils that are not well suited for irrigation and it was clear that the limiting factor was soil physical conditions, not solar radiation. In a growth experiment in the open, Myers and Davidson (unpublished) recorded growth rates of white clover exceeding 525 lb per acre (590 kg per ha) dm per week.

Fertilisers and soil fertility. The main nutrient deficiencies are phosphorus, sulphur, and nitrogen, and superphosphate is the common fertiliser used in the Murray Valley. Annual dressings of 2 cwt per acre (251 kg per ha) on annual pastures and 4 cwt per acre (502 kg per ha) on lucerne and perennial pastures are usual. Once a total of 30 cwt per acre (3765 kg per ha) has been applied these levels may often be reduced by half. Zinc deficiency occurs in lake beds at the western end of the valley and on grey and brown soils where calcareous subsoils have been exposed by grading (Kleinig and Loveday 1962). But, in general, trace element deficiencies are not common.

Until recently, nitrogen fertilisers have been expensive in Australia and pastures depend on nitrogen fixed by clovers (see Chapter 21). Even with the recent price subsidy it is doubtful if this situation will change. Liveweight gains from clover and lucerne are higher than from fertilised grass (Wilson 1966a) and available evidence suggests pasture responses to nitrogen, in terms of animal production, are not large enough to be profitable. Nitrogen is invariably applied to fodder crops such as sorghum and is clearly profitable.

Irrigated pastures seem to be unique in that organic matter accumulates on the surface rather than in the soil (Kleinig 1966). This may be due to the low porosity of many of the pasture soils, the frequent wetting, and the absence of earthworms (Barley and Kleinig 1964). The surface mat of organic matter can amount to 92,000 lb per acre (10,300 kg per ha), much of it considerably decomposed and containing up to 1000 lb N per acre (1120 kg per ha) in 8- to 15-year-old pastures (Kleinig 1966). Total nitrogen in mat and soil is correlated with age of pasture but the distribution of organic matter and nitrogen varies markedly and is not well understood. There seems to be no great advantage in incorporating this large amount of organic matter into the soil from the point of view of water relations, rate of breakdown or mineralisation of nitrogen (Rixon 1966; Rixon and Bridge 1967). Kleinig (1966) recorded an annual accumulation of nitrogen under irrigated subterranean clover pastures of 62 lb per acre (69 kg per ha) which is higher than for dryland pastures elsewhere. Rixon (1969) found yields of wheat were higher following perennial (summer irrigated) pastures than following subterranean clover. Yields equal to those following perennial pasture were attained on non-pasture land only by applying 1 cwt per acre (112 kg per ha) of N at sowing.

The use of pasture to raise soil fertility for a series of following wheat crops has become common practice in the irrigation areas, and since 1960 particularly, the production of small grains has become an increasingly important enterprise. This farming system may well be the pattern for the future, and irrigated pasture may be just as important as a fertility-building technique as for animal production.

Soil structure and pasture emergence. The grey and brown cracking clays that are used extensively for irrigated pastures show very little differentiation of the profile though some have some gypsum (calcium sulphate) and calcium carbonate at variable depths. As a class, they are structurally unstable to water and crack extensively when dry. At the end of summer an irrigation of up to 9 in. (229 mm) will be required to fill these cracks but after the first irrigation soil swelling closes the cracks and the infiltration rate becomes quite low. These soils have high cation exchange capacity and as much as 15 per cent of the cations are sodium. As a result, some are self-mulching on drying but the aggregates are water unstable and many form very hard crusts as the surface dries.

The unfavourable water relations and severe surface crusting makes pasture establishment difficult. Emergence of subterranean clover seedlings may be as low as 2 per cent of the seed sown and subsequent growth may be disappointing. Davidson and Quirk (1961) obtained spectacular responses in emergence and subsequent growth of subterranean clover from the application of gypsum in irrigation water at the rate of 5 cwt per acre (630 kg per ha) or from broadcasting 2 tons per acre (5 tons per ha) before the first irrigation. Emergence problems are most severe in the western areas just north of the Murray River (southern Riverina). Loveday and Scotter (1966) have specified the properties of soils likely to respond to gypsum and Noble (1962), Scott, Evans, and Noble (1968), by field tests, have specified the soil types likely to respond.

Soil-water relations. Frequent irrigations are required because of high solar radiation and a high potential transpiration rate. The low porosity of many of the soils, including the shallower levee soils as well as the clay soils of the plain, magnifies the effect of irrigation frequency on pasture yield. The amount of water that can be stored in the root zone of the common pasture species is often less than 2 in. (51 mm). Because of the heavy dense subsoils, rapid surface drainage is necessary to prevent waterlogging of the surface soil. In soils such as these, irrigation at an evaporation interval of 2 to 3 in. (51–76 mm) gives optimum yields of white clover in mid-summer (Myers and Baxter 1963). This means irrigation at 5–6 day intervals at the height of summer and water use of 2 in. (51 mm) per week. On soils of high porosity, yields are higher and the optimum irrigation frequency is less sharply defined.

The sensitivity of the irrigation frequency-yield relationship to soil-water characteristics is well demonstrated by the work of Sedgley

(1962). He obtained three-fold increases in yield of white clover by deep ripping and gypsum treatment. The effects persisted for at least four years. In the untreated soil, internal drainage was slow and white clover suffered from lack of aeration immediately after irrigation. With ripping and gypsum, internal drainage was improved and more soil water was available at lower tensions. The increase in time during which soil water was favourable to growth is sufficient to explain the large yield response. Other soils considered to be physically better than the heavy clay soil of Sedgley's experiment also respond to gypsum. In these the effect of gypsum is mainly to increase subsoil permeability and water storage in the root zone.

Annual pastures are not quite so sensitive to the moisture characteristics of the soil because they do not grow during high evaporation periods. The surface crusting of heavy plain soils makes the initial establishment of annual pastures difficult. It takes about four years for subterranean clover stands to reach densities at which productivity is maximal on these soils. By then seed yield, even under heavy and continuous grazing, will exceed 100 lb per acre (112 kg per ha) and can be as high as 900 lb per acre (1008 kg per ha). Gypsum treatment increases the initial density of clover plants to such an extent that high stocking rates are possible in the year following sowing (Myers and Squires, unpublished data).

Improvements to the impermeable soils of the Murray Basin, and these include the majority, would increase yields substantially and reduce the need for frequent irrigations. In this region soil physical conditions remain a major factor limiting yields of irrigated pastures.

Pasture species. Reliance on the two legumes, subterranean clover and white clover, for irrigated pastures in the diverse environments of such a large continent would suggest that Australia has been conservative in trying alternatives. The late C. Kleinig of CSIRO Deniliquin, N.S.W., and others, tested a range of the tropical legumes that had been brought into prominence by the work of CSIRO Division of Tropical Pastures in 1964 and 1965. Species of Lotononis, Phaseolus, Glycine, and Desmodium were grown successfully after initial difficulties with nodulation (see Chapter 22). In an unusually hot summer they appeared promising but subsequently they proved to be poorly persistent, frost liable and slow to recover from defoliation. Lotus species similarly did not justify their early promise. Subsequently, Jones *et al.* (1968) reported that the tropical legumes *Centrosema pubescens*, *Lotononis bainesii*, and *Desmodium uncinatum* were inferior to white clover as grazed irrigated pastures at Samford, south-east Queensland, that is in an environment better suited to these species than southern Australia. They found that frost damage, competition from grasses, and high grazing pressure all contributed to the lack of persistence of the tropical legumes and concluded that white clover was superior in persistence, production, and nitrogen fixation. Nearer the equator (Burdekin River), Allen and Cowdry (1961) have obtained cattle liveweight gains of 40 to 45 lb per acre (45 to 50 kg per ha) per month on irrigated tropical grasses and legumes for 10 months. Para grass (*Brachiaria mutica*) and *Centrosema pubescens* were the best species.

None of the legumes in present use has been the subject of intensive improvement. An irrigation white clover was selected by the Victorian Department of Agriculture and the cultivar Ladino has been used widely in recent years. A range of subterranean clovers is available but the most commonly used are cv. Mt Barker, Bacchus Marsh, and Yarloop. Yarloop has resistance to waterlogging and a slight superiority in winter growth but its high oestrogenic potency is a decided disadvantage (see Chapter 26). The Hunter River cultivar of lucerne has been used almost exclusively until recently. Rogers (1961) tested a wide range of lucernes under irrigation and found African and Siro Peruvian more productive especially in winter, but less persistent than Hunter River in the hot climate of Deniliquin.

Because of its capacity to respond to summer thunderstorms, lucerne is almost invariably included in annual winter irrigated pasture mixtures. It is sown at very low rates (0·5 lb to 1 lb per acre or about 0·5 to 1 kg per ha). The small amount of green feed produced improves the quality of the dry pastures in summer. The cultivar Cancreep, which persists under continuous grazing and exhibits creeping rootedness at low densities (Daday *et al.* 1968), may also be useful for this purpose. Persistent species capable of exploiting the occasional small amount of water available from summer rains would improve the feed quality of annual pastures at this time. For example, on annual pastures in summer irrespective of stocking rate, wool growth rate falls to a fifth of its maximum (winter) value because of the poor quality of the available feed. Myers and Squires (1968) showed the distinct advantage of a *Phalaris tuberosa* × P. *arundinacea* hybrid over P. *tuberosa* cv. Australian in wool production when significant rains fell in summer. Unlike P. *tuberosa*, the hybrid is not summer dormant and the small amount of green leaf it produced led to substantial increases in wool growth.

Management and integration of pasture types on farms. Irrigated annual and perennial pastures should make it possible to maintain a continuous supply of green feed and so avoid the expense of conserving fodder for seasonal shortages. In winter, irrigated subterranean clover grows at about 15 lb per acre (17 kg per ha) per day and Wimmera ryegrass at 35 lb per acre (39 kg per ha) per day (Davidson 1964). In the same period white clover produces less than 10 lb per acre (11 kg per ha) per day. The two contrasting pasture types are to some degree complementary. Animal gains on annual pastures are almost exclusively in winter and weights are only maintained in summer. Perennial pastures on the other hand produce more, and support more animals in summer than in winter. The integration of the two pastures into a farm system which supports animals for the whole year has been done successfully by I. D. Killeen, N.S.W. Department of Agriculture, for prime lamb production, and by Myers (1967) with dry sheep for wool production. Killeen found it possible wholly to support 6 to 8 ewes per acre (15–20 per ha) rearing 100 per cent of lambs using a ratio of two-thirds of annual (winter irrigated) pasture and one-third of perennial (summer irrigated) pasture. Myers and Squires (unpublished) supported 12 dry sheep per acre producing 120 lb per acre (134 kg per ha) greasy wool. Both experiments ran for more than three years.

The usual practice in the region is to conserve fodder and to stock at lower rates than those used experimentally. Part of the reason for the lower production on farm pastures may be due to under-utilisation of annual pastures (low stocking rates), deleterious effects of hay cutting on pasture production (Myers and Squires 1968), and an inappropriate ratio of areas of annual to perennial pasture.

Because annual pastures can be grown on about 18 in. (457 mm) of water, compared with 45–50 in. (1143–1270 mm) of water for perennial pastures, there is considerable advantage in maximising the area of annual pasture. A high proportion of summer irrigated pastures would exacerbate winter feed shortages in most areas. In farms affected by salt and high water tables a high proportion must be summer irrigated to avoid salt accumulation at the surface, but this does not explain the quite high proportions of

TABLE 18 : 2 Proportion of annual to perennial pastures in selected irrigation districts and private diversions in the Murray Basin

District	Water right ft (cm)	Area of pasture × 1000 acres (ha) Annual	Perennial	Ratio Annual/Perennial
Victoria				
Cohuna	1 (30·5)	22 (9)	40 (16)	0·55
Shepparton and Rodney	1 (30·5)	90 (36)	86 (35)	1·16
Kerang	0·5 (15·2)	37 (15)	10 (4)	3·70
Private diversions River Murray system	—	19 (8)	8 (3)	2·38
Other private diversions	—	7 (3)	98 (40)	0·07
New South Wales				
Berriquin	0·3 (10·2)	203 (82)	48 (19)	4·23
Wakool	0·1 (3·0)	73 (30)	10 (4)	7·30
Private diversions	—	155 (63)	59 (24)	9·68

Source: Adapted from *Annual Report*, State Rivers and Water Supply Commission (Victoria) 1965–6; *Annual Report*, Water Conservation and Irrigation Commission (N.S.W.), 1966–7.

perennial pastures in some areas (Table 18 : 2). For example, in the salt-affected Cohuna district, the ratio of areas of annual to perennial pasture is 0·55. In the Shepparton area this ratio is about 1 and the area of perennial pastures is greater than required to supply uniform amounts of forage throughout the year. Dairying is an important industry in irrigated areas and dairy farmers tend to favour perennial pastures even though hay must be grown or purchased for the winter. The proportion of the two pastures has a considerable bearing on farm profits because winter feed must be purchased if the proportion of annual pastures is too low. McColl (1963) has advocated the greater use of annual pastures on dairy farms, especially where water is less plentiful. The proportion of annual and perennial pastures may be more important than the grass species used in the pastures.

The role of irrigated pastures in droughts. In the earliest established irrigation areas, water was plentifully supplied and the water right is one acre foot per acre (3046 m^3 per ha). The water right is usually expressed as '1 to 1' or simply 'one foot' (30·5 cm). Additional water is available for purchase except in the severest droughts. Later irrigation facilities at the western end of the Murray Valley were designed to stabilise the production of the larger holdings in semi-arid areas devoted mainly to wool growing. In these irrigation districts so called, water rights are as low as 1 in 10, that is one acre foot for each 10 acres of land (1233 m^3 for 4 ha). Although the original intention was to use the irrigated areas as drought insurance, the tendency has been to treat the irrigated areas as an entity separate from the remaining dryland. For example, in the Berriquin Irrigation District (water right 1 in 4), Gruen (1953) noted a strong shift from wool growing to prime lamb production which requires intensive irrigation. In the Wakool District (water right 1 in 10) where farm size is most commonly 2000 to 5000 acres (800–2000 ha), 10 per cent of the irrigated area and 30 per cent of the water is used to grow rice. Rutherford (1958, 1959) examined the role of irrigated districts in droughts and found little or no evidence that they stabilised sheep numbers in drought periods. Myers (1962a) reviewed the integration of irrigated areas with dryland and found that sheep populations fluctuated with season in the same way in adjacent areas whether or not they contained irrigated pastures. Competition for irrigation water by other and more profitable forms of production such as dairying, rice, fat lambs, etc., has led to an almost complete separation of irrigation and dryland enterprises. Sometimes special circumstances, such as the occurrence of heavy clay soils ideally suited to rice but not to pastures, have contributed to the separation but the pressure for high returns to cover costs of irrigation is very strong. The number of droughts and their duration cannot be predicted so that the cost of insuring against droughts, whether it is the direct cost of fodder conservation or the loss of potential production from irrigation areas in favourable years, etc., cannot be assessed in the long term with any precision.

PRIVATE DIVERSIONS IN THE MURRAY SYSTEM

In contrast to the situation in irrigation districts, that is the government irrigation schemes, the private diversion of water from permanent streams inevitably leads to some integration of irrigated and dry land. These diversions account for a considerable proportion of the total irrigated area in Victoria and New South Wales. The private diversion to the large properties west of the Great Dividing Range in New South Wales are an example. Because of competition for water when they were first settled these properties often have small river frontages and large areas of semi-arid land extending away from the rivers. By this arrangement many properties can be served cheaply, simply by stabilising river flow by dams upstream. The earlier private irrigation developments were quite large and permitted a thousand acres (405 ha) or more to be irrigated. Future irrigation will be limited to 300 acres (122 ha) per holding, but on most streams often only 30 acres (12 ha) can be supplied with water. The areas of pastures irrigated for private diversions in New South Wales and Victoria are given in Table 18 : 2. The significance of irrigation to animal production can be gauged from the fact that the carrying capacity of dryland in western New South Wales is from one sheep to 2–6 or more acres (1·25–3·75 per ha) and that of irrigated pastures from 6 to 8 sheep per acre (15 to 20 per ha). Because of difficulties of supervision and water measurement, water rights for private diversions are specified in terms of area irrigated and not in terms of volumes of water. The result is that water economy is a secondary consideration and the proportion of summer irrigated to autumn-spring irrigated areas is often high (Table 18 : 2). On the Lachlan River, irrigation of one-twentieth of the holding has increased stocking rates two and a half times. The effect is not wholly due to the extra forage produced by the irrigation. The added confidence engendered by having irrigated pastures means that stocking rates on the dryland are raised above the low levels adopted to ensure stock survival in dry years. In times of drought, the irrigated area can be exploited to its ultimate limit. Instances of irrigation being used for survival feeding at very high stocking rates are fairly common. In one case, lucerne supported 40 ewes per acre (99 per ha) from September into mid-summer the year after it was sown. Each half of the area was grazed for one day in four and then after three grazings stock were moved to the other half (Myers 1962a).

The number of private diversions is increasing. The stream flow is greatest in September and October and when it exceeds the level specified for a particular stream, use of water is unrestricted. On-farm storage of this freely available water is increasing where sites suitable for storing water are present.

Methods of managing annual subterranean chosen pastures for drought relief have been proposed by Myers (1962b).

The economics of the proposal are difficult to assess but on-farm water storage for pastures is likely to be more profitable than the storing of fodder grown on the irrigated area.

The advocacy of water harvesting by Geddes (1964) has increased interest in 'on-farm' storage of water from runoff and uncontrolled streams. The method has been used mostly in high rainfall areas and in such areas the integration of the irrigated pasture with the rest of the farm is complete. Any convenient pasture is spray irrigated in times of stress. Pasture and irrigation management, and the economic benefits of the system applied to a dairy farm near Sydney, are described by Crofts, Geddes, and Carter (1963).

It has already been mentioned that areas irrigated from public schemes tend to be separate entities because of economic pressures forcing farmers to use irrigated land for animal enterprises best managed separately from dryland.

Movements of stock increase markedly during droughts but the movement appears to be to areas receiving above average rainfall rather than to irrigation areas. It is possible that establishment of irrigation districts may not be as efficient as other methods of drought insurance such as grain surpluses, money premiums, and stock movements (Morley and Ward 1966).

UNDERGROUND WATER

On-farm development of water resources by water harvesting, and use of underground water could be considerable aids in times of drought. Underground water from the great artesian basins of Australia made livestock industries in the semi-arid and arid regions possible. The water available from these sources is usually too salty to use for irrigation but it is an important source of water for stock.

Water suitable for irrigation is available from alluvial deposits and limestone. Examples are the Richmond and Hunter River valleys along the north coast of New South Wales, the south-east of South Australia and the coastal plain north of Perth, but there are many others. Williamson (1964) has reviewed the possibilities of expanding the use of alluvial ground water resources and it seems clear that much of the future irrigation will be from these sources. Williamson's review indicates an urgent need for more studies of safe yield, water quality, recharge techniques, and other problems of controlling these water resources. Like water harvesting these developments will lead to integration of irrigated pastures with the dryland of a farm. In the south-east of South Australia water from shallow underlying limestone is being used to irrigate pastures for dairying and for pasture seed production. Water recharge is estimated to be 60 mm per year over 2 million acres (0·8 million ha). The Swan Coastal Plain north of Perth in Western Australia is beginning to be irrigated from unconfined shallow aquifers above sub-artesian beds. These aquifers are recharged by rain and river flow at a rate estimated by F. Roberts of CSIRO (private communication) at 8 million acre feet (9862 million m^3) per year. This water could irrigate 500,000 acres (202,500 ha). It is quite possible this development alone could increase the area of irrigated pastures in Australia by 25 per cent or more.

CONCLUSIONS

Pastures are a major crop in the fairly intensively developed irrigation areas of southern Australia, particularly in the Murray Basin. In northern Australia, where most water is available, there is relatively little development, and knowledge of species suitable for irrigated pastures, though limited, is increasing.

Generally, irrigation areas do not play an important part in feeding sheep during droughts mainly because they are used for dairying and intensive meat production. Future 'on-farm' development by private diversion from permanent streams and from underground water may change this situation to some extent. There is less public enthusiasm for large government irrigation areas than formerly.

A major factor limiting production on existing irrigation districts appears to be the physical characteristics of the soils used for pastures. Further research on modifying the soil structure in existing areas and careful choice of soils for development of new areas would have favourable effects on production levels and the economics of irrigated pastures.

It is suggested that the economics of private and government schemes for pasture irrigation need careful assessment even though Australia is the world's driest continent.

C

FACTORS IN PRODUCTIVITY

19

TROPICAL AND SUB-TROPICAL PASTURE SPECIES

J. GRIFFITHS DAVIES AND E. M. HUTTON

About 260 million acres (105 million ha) await development through improved pastures and beef cattle in the tropical zone of Australia between latitudes 30°S and 11°S (Davies and Eyles 1965). The environment is a difficult one as a high proportion of the soils are poor and reliability of the summer rainfall is relatively low except in Cape York Peninsula and some coastal areas. Also in the east during winter, radiation frosts markedly affecting pasture quality are common south of the Tropic and extend inland and northwards sometimes as far as latitude 15° 30′S. In three-quarters of the Australian tropics, the annual rainfall is 22–40 in. (559–1016 mm) and except for limited coastal areas with more than 60 in. (1524 mm) the remainder receives 40–60 in. (1016–1524 mm). Below the Tropic on the east coast the climate is subtropical with some winter rain. Extending up the east coast beyond the Tropic and across the northern coastal areas of the continent, the climate is mainly a dry tropical one with an intense wet summer of 4–5 months followed by a hot dry season of 7–8 months. Only the northern half of the wet east coastal lowlands of 4 million acres (1·6 million ha) can be regarded as conventional wet tropics, and here sugar cane is the main crop with pastures confined to hilly areas.

Feeding value and productivity of the native grass pastures which dominate Australia's tropics are low, particularly in the dry winter season. Cattle numbers and beef production can be increased by replacing the native species with introduced tropical legumes and grasses selected for their high quality and response to application of fertiliser, particularly superphosphate.

Pasture species have been available for the northern wet tropics for over a quarter of a century. These include the grasses para (*Brachiaria mutica*), guinea (*Panicum maximum*), molasses (*Melinis minutiflora*), and elephant (*Pennisetum purpureum*), and the legumes stylo (*Stylosanthes guyanensis*), centro (*Centrosema pubescens*), puero (*Pueraria phaseoloides*), and calopo (*Calopogonium mucunoides*) (Schofield 1941). Species more recently added to this complement are pangola grass (*Digitaria decumbens*) and *Brachiaria decumbens*, and Grof (personal communication) considers that *Desmodium heterophyllum* and Embu creeping guinea grass are also valuable.

Provision of pasture species has been more difficult for the extensive areas in the sub-tropics and dry tropics of Australia where climate and soils are quite variable. Here research for two decades has resulted in the definition of soil mineral deficiencies and selection of adapted grasses and legumes. Productive and persistent pastures based on legumes are now available so that development of these areas is accelerating. Legumes still provide the most economic source of protein for increased production of beef and milk.

PLANT INTRODUCTION FOR TROPICAL AUSTRALIA

With the establishment of the Plant Introduction Section of the C.S.I.R. Division of Plant Industry in 1930 (McTaggart 1942) introduced legumes and grasses for both northern and southern Australia became available. A significant contribution was made by Miles (1949) who assessed a wide range of new tropical legumes and grasses in a series of plant introduction trials in central coastal Queensland during the period 1936–46. He concluded that, in view of the low protein and mineral status of the native pastures, dependence must be placed on summer-growing legumes, particularly perennials. The best of these in his trials were in the genera Stylosanthes, Arachis, Desmodium, Indigofera, Rhynchosia, Pueraria, Centrosema, Glycine, and Teramnus. Among his grass introductions, the most promising were strains of *Andropogon gayanus*, *Chloris gayana*, *Cenchrus ciliaris*, *Digitaria* sp., *Melinis minutiflora*, *Panicum maximum*, *Panicum coloratum*, *Paspalum notatum*, *Pennisetum pedicellatum*, *Pennisetum* sp., *Setaria sphacelata*, and *Urochloa* sp.

Following Miles's (1949) results in central Queensland, Hartley (1949) accompanied a plant collecting expedition to sub-tropical South America in 1947–8 organised by the Division of Plant Exploration and Introduction of the United States Department of Agriculture. Hartley concentrated on obtaining introductions of Arachis and Stylosanthes species, but in addition introduced a number of species in the genera Desmodium and Paspalum. Oxley fine-stem stylo (*S. guyanensis*) and Hartley plicatulum (*Paspalum plicatulum*) (Bryan and Shaw 1964) are two cultivars selected from Hartley's introductions. In 1951–2, Miles visited Africa and expanded the range of introductions in the genera Cassia, Dolichos, Glycine, Indigofera, Lotononis, Vigna, Cenchrus, Chloris, Echinochloa, Panicum, Setaria, and Urochloa. From his collections have come Miles lotononis (*L. bainesii*) described by Bryan (1961), Rongai *Dolichos lablab* (Wilson and Murtagh 1962), and Samford Rhodes grass documented by Barnard (1967).

Research on evaluation and adaptation of the available introductions has resulted in a range of promising pasture plants in the following legume and grass genera—Stylosanthes, Phaseolus, Desmodium, Glycine, Leucaena, Lotononis, Dolichos, Vigna, Indigofera, Cenchrus, Panicum, Setaria, Chloris, Paspalum, Sorghum, and Urochloa. A number of these have been commercialised and for some like silverleaf desmodium (*D. uncinatum*), Miles lotononis (*L. bainesii*), and the bred siratro (*Phaseolus atropurpureus*) it is their first appearance in world agriculture.

Following these successes, a series of plant collections with more specific objectives were made (Neal-Smith and Johns 1967). Jones (1964) collected in East Africa to extend the gene pool of *Setaria* spp. with particular emphasis on frost tolerance. Some of the *Setaria* spp. collected at high altitudes in the Abedare Range region of Kenya proved to be frost tolerant. McKee (1964) collected in Central America and the Caribbean to increase the variation available in the legume genera Phaseolus, Desmodium, Stylosanthes, and Centrosema. In 1964–5 Atkinson of the New South Wales Department of Agriculture also collected legumes and grasses in Central America and South America. Queensland Department of Primary Industries collections of legumes and grasses were made by Gartner in South America in 1963, Grof in Central America 1965, and Ebersohn in South America, Ethiopa, and Central Africa 1966. Williams (1966) collected in Brazil, Argentina, Paraguay, Bolivia, and Nicaragua, and brought back ecotypes of Stylosanthes, Desmodium, and Paspalum species. As a result of the recent more specialised plant introduction activities, there has been a marked increase in important genera in numbers of species and gene pools within species. For example, in Stylosanthes, fourteen additional species are now available. Plants from these later collections are being assessed over a range of climates in northern New South Wales, Queensland, and the Northern Territory.

THE MAIN LEGUMES

Tropical

Townsville lucerne (*S. humilis* formerly *S. sundaica*), an accidental introduction recognised at Townsville (19°S) around 1900, is naturalised in northern Australia. It is the most widely used legume and there are now two cultivars, Lawson and Gordon. Siratro (Hutton 1962), from crossing two Mexican ecotypes of *P. atropurpureus*, is the only cultivar that has been bred. A number of selected legume introductions have been commercialised and are adapted to particular soil and climatic conditions and types of agronomic practice. These are *Desmodium intortum* (cv. greenleaf), *D. uncinatum* (cv. silverleaf), *P. lathyroides* (cv. Murray), *Lotononis bainesii* (cv. Miles), *Leucaena leucocephala* (cvs. Peru and El Salvador), *Glycine wightii* formerly *G. javanica* (cvs. Clarence, Cooper, and Tinaroo), *Dolichos lablab* (cv. Rongai), *D. axillaris* (cv. Archer), *D. unifloris* (cv. Leichhardt), *Stylosanthes guyanensis* (cvs. Schofield stylo, Oxley fine-stem stylo), *Calopogonium mucunoides* (calopo), *Pueraria phaseoloides* (puero), *Centrosema pubescens* (centro),

TABLE 19 : 1 General descriptions of the main tropical legume cultivars

Cultivar	Growth habit	Leaves	Flowering habit	Seed pods	(a) No. seeds/kg (b) Seed yld/ha (c) Seeding rate/ha
Calopogonium mucunoides[a] (Calopo)	Trailing and climbing. Stems covered with long hairs, rusty brown on young shoots.	Oval leaflets 6·0–10·0 cm long, 4·0–6·0 cm wide; covered with long brown hairs.	Arranged in 2–4 flowered stalkless bunches in axils of leaves or in 2–5 flowered bunches on axillary raceme to 15·0 cm long on long hairy stalks. Flowers pale blue, 1·0 cm long.	2·0–4·0 cm long and 4–5 mm wide. 4–8 seeded. Pods covered with fine brown hairs. Seeds light tan.	(a) 65,000 (b) 200–300 kg (c) 1–3 kg
Centrosema pubescens[a] (Centro)	Trailing and twining; weakly rooting at nodes. Stems softly hairy when young, smooth with age.	Shiny, bright green sparsely hairy, ovate-elliptical leaflets 4·0–6·0 cm long, 2·0–3·0 cm wide with pointed tip.	Axillary racemes to 7·0 cm long of 2 to 3 pale blue/mauve flowers with broad rounded standard about 3·0 cm long.	Smooth brown straight pods, flattened with thickened margins and to 12·5 cm long with pointed apex. Contain up to 20 brownish mottled black seeds.	(a) 45,000 (b) 300–600 kg (c) 1–6 kg
Desmodium intortum[a] (cv. Greenleaf)	Trailing squared stems (with hooked hairs) which root freely.	Softly hairy, rounded leaflets 4·0–8·0 cm long, 2·0–5·5 cm wide. Deep green, brown flecking.	Compact terminal and axillary racemes 5·0–12·0 cm long on stalk 10·0–15·0 cm long; 30–40 deep lilac to pink flowers 1·0 cm long. In the bud the inflorescence is covered by large overlapping bracts.	Small narrow, recurved, 2·0 to 5·0 cm long; 8–12 single seeded segments. Hooked hairs so pods adhere to animals etc. Seeds light brown to green.	(a) 755,000 (b) 90–120 kg (c) 1–2 kg
Desmodium uncinatum[a] (cv. Silverleaf)	Trailing stems which root.	Hairy, ovate leaflets, 4·0–10·0 cm long, 2·0–5·5 cm wide. Light grey-green, irregular silver band along midrib.	Open terminal and axillary racemes 5·0–20·0 cm long on stalks 15·0–20·0 cm long; 10–30 paired lilac to mauve flowers 1·0 cm long. In the bud the inflorescence is covered by large overlapping bracts.	Sickle shaped, 3·0–7·5 cm long; 4–8 single seeded segments. Hooked hairs so pods adhere to animals etc. Seeds light brown to green.	(a) 216,000 (b) 220–340 kg (c) 1–3 kg
Dolichos axillaris[a] (Archer)	Trailing and twining; slightly hairy stems.	Bright green ovate leaflets 3·0–5·0 cm long and 3·0 cm wide. Slightly pubescent but glossy appearance.	Racemes usually of 3 flowers in the leaf axils on short stalks. Flowers greenish yellow, 1·2–1·5 cm long.	Slightly curved, hairy, 3·0 to 5·0 cm long and 6 mm wide. Seeds mottled light and dark; 7–8 seeds per pod.	(a) 120,000 (b) 200–560 kg (c) 2–5 kg

TABLE 19 : 1 (continued)

Cultivar	Growth habit	Leaves	Flowering habit	Seed pods	(a) No. seeds/kg (b) Seed yld/ha (c) Seeding rate/ha
Dolichos lablab[b] (Rongai)	Tall (to 1·5 m), leafy, well branched, becoming rampant and trailing under good conditions.	Broad ovate leaflets, 8·0–15·0 cm long, 8·0–10·0 cm wide. Almost smooth on upper surface and shortly hairy on lower.	Large lax inflorescence of many flowered racemes on long stalks. Flowers white, 2·0 cm long.	Broad, curved, beaked, 4·0–5·0 cm long; 2–4 pale brown seeds.	(a) 5000 (b) 560 kg (c) 13–22 kg
Dolichos uniflorus[c] (cv. Leichhardt)	Twining with softly hairy stems, 50·0–80·0 cm high.	Pale green ovate leaflets, 5·0 cm long and 3·0 cm wide, softly hairy on both surfaces.	2–4 flowered racemes in leaf axils on very short stalks (occasionally stalks absent). Flowers greenish yellow, 1·0–1·2 cm long.	Slightly curved, hairy, 4·0–6·0 cm long and 6 mm wide, on very short stalks. Seeds pale buff, 6–7 per pod.	(a) 34,000 (b) 600 kg (c) 8–11 kg
Glycine wightii[a] (cv. Clarence) (cv. Cooper) (cv. Tinaroo)	Trailing and twining; rooting along the stems.	Ovate leaflets, 5·0–10·0 cm long, 3·8–6·4 cm wide. *Clarence*—Coarse, hairy, dark green with brown pigment. *Cooper*—Softly hairy, ash green and obliquely asymetrical. *Tinaroo*—Thin, smooth, sparsely hairy, bright green.	Many flowered racemes 4·0–12·7 cm long in Cooper and Tinaroo, up to 20 cm in Clarence. Stalk 4·0–12·7 cm. Flowers white, 0·7 cm long in Cooper and Tinaroo, 1·0 cm in Clarence. Violet streaks on standard, pink tinged except in Tinaroo.	Dark brown, flat, straight; 2·5–3·8 cm long and 3 mm wide. 4–5 green or brown seeds.	(a) Clarence 175,000 Cooper 140,000 Tinaroo 130,000 (b) 200–350 kg (c) 2–5 kg
Leucaena leucocephala[a] (cv. El Salvador) (cv. Peru)	Tree: (cv. El Salvador erect to 3·7 m S. Queensland), (cv. Peru to 2·4 m S. Queensland, basal branching).	Smooth leaves, bipinnate, leaf stalk 15·0–25·0 cm. Pinnae 11–17 pairs of narrow leaflets 0·7–1·2 cm long.	Globose head 2·6–2·9 cm diam. on stalk to 5·0 cm long. 140–180 small white florets, 7 mm long.	Brown, flat, smooth, 11·0–17·0 cm long, 1·5–2·0 cm wide. 12–25 glossy brown seeds per pod.	(a) Peru 21,000 El. S. 28,000 (b) 150–300 kg (c) 4–6 kg
Lotononis bainesii[a] (cv. Miles)	Prostrate, rooting at nodes; well developed tap-roots.	3–5 trifoliate leaves at nodes. Smooth, narrow, pointed, with central leaflet 2·5–5·0 cm long, 0·8–2·5 cm wide.	Raceme 1·0–11·0 cm long of 8–23 small yellow flowers, 1·0 cm long on stalk 7·0–8·0 cm. Flowers frequently contracted into open head.	Dull brown, 0·8–1·2 cm long. 10–20 cream to yellow seeds per pod.	(a) 3·5 milion (b) 56 kg (c) 0·5–1·0 kg

TABLE 19 : 1 (continued)

Cultivar	Growth habit	Leaves	Flowering habit	Seed pods	(a) No. seeds/kg (b) Seed yld/ha (c) Seeding rate/ha
Phaseolus atropurpureus[a] (cv. Siratro)	Trailing and twining; rooting along stems.	Ovate leaflets, 5·0–8·0 cm long, 4·0–6·0 cm wide, with one or two notches; lower surface dense silvery hairs.	Racemes 10·0–15·0 cm of 6–12 deep red flowers ageing to dark purple on stalk 10·0–30·0 cm; prominent wings of flower each 1·2–1·5 cm across.	Narrow, cylindrical, straight, about 7·6 cm long; mean 14 seeds. Ripens from raceme base and shatters. Seeds light brown to black.	(a) 76,000 (b) 110–170 kg (c) 1–3 kg
Phaseolus lathyroides[b] (cv. Murray)	Erect, some branching. 60·0–91·0 cm high. Develops twining stems.	Smooth, thin, ovate to lanceolate leaflets, 3·8–7·6 cm long, 1·5–2·6 cm wide.	Raceme 12·0–20·0 cm of 15–30 deep pink to red flowers on stalk 20 cm or more. Prominent wings of flower each 7–8 mm across.	Narrow, cylindrical, slightly curved, 7·0–10·0 cm long. 18–23 seeds. Ripens from raceme base and shatters badly. Seeds mottled light and dark grey-brown.	(a) 130,000 (b) 200–250 kg (c) 1–3 kg
Pueraria phaseoloides[a] (Puero)	Trailing and twining; lax with long internodes. Stems conspicuously hairy.	Broad deep green ovate-rhomboid hairy leaflets, 8·0 to 18·0 cm long and 7·0–14·0 cm wide. Lower surface greyish green and densely hairy.	Axillary racemes 10·0–40·0 cm long made up of scattered pairs of flowers 1·5–2·5 cm long and white with violet central blotch.	Cylindrical, hairy, 7·5–10·0 cm long and 3–5 mm wide. 7–20 small brown seeds.	(a) 82,000 (b) 300–400 kg (c) 1–3 kg
Stylosanthes guyanensis[a] (cv. Oxley fine-stem stylo)	Semi-prostrate, sparse erect hairs on fine much branched stems; underground crown. Strong tap-root.	Narrow deep green leaflets 1·5–3·5 cm long, 3–5 mm wide. Scarcely hairy.	4–20 small yellow flowers subtended by leaf-like bracts in small compact spike. Mostly terminal, but sometimes in leaf axils.	Light brown pods are flattened single-seeded loments 3 mm long and 2 mm wide with a minute coiled beak; conspicuously fine veined without hairs. Pods fall as they ripen. Seeds yellow-brown.	(a) 350,000 (b) 200 kg (c) 2–5 kg
Stylosanthes guyanensis[a] (cv Schofield stylo)	Erect coarse branched, to 1·5 m high, stems hairy.	Narrow deep green pointed leaflets, 2·5–5·5 cm long, 5–7 mm wide. Some hairs on lower surface.	5–20 small yellow flowers subtended by leaf-like bracts in a compact spike. Mostly terminal, sometimes in leaf axils.	Dark brown pods are single seeded loments 2–3 mm long and 1–2 mm wide; beak scarcely discernible. Pods fall as they ripen. Seeds yellow-brown.	(a) 350,000 (b) 200 kg (c) 2–5 kg

TABLE 19 : 1 (continued)

Cultivar	Growth habit	Leaves	Flowering habit	Seed pods	(a) No. seeds/ kg (b) Seed yld/ha (c) Seeding rate/ha
Stylosanthes humilis[c] (Townsville lucerne or Townsville stylo) cv. Lawson cv. Gordon	Ascending fine stemmed to 60 cm or more high. Stems mostly smooth; sparse hairs, more obvious beneath each node.	Narrow pointed mid-green leaflets 1·5–4·0 cm long and 3–6 mm wide; almost smooth, veins conspicuous; prominent hairs on stipules.	A short ovoid compressed spike mostly 3–6 flowers with leaf-like bracts beneath each flower. Yellow flowers, 3–4 mm long. cv. Lawson mid-season, cv. Gordon late.	Grey-brown pods are loments of two segments, mostly only the upper segment fertile, with one seed and with a fine hook, much longer than the body of the fertile segment. Pod prominently reticulate-nerved and 4–6 mm long by 1–2 mm wide. Seeds yellow-brown.	(a) 346,000 (b) 220–680 kg (c) 1–3 kg
Vigna luteola[b] (cv. Dalrymple)	Semi-erect becoming trailing when well grown. Young shoots frequently hairy but smooth in older stems.	Smooth, shiny, bright green leaflets oval to ovate, 3·0–8·0 cm long and 2·0–5·0 cm wide with pointed tip.	Axillary racemes with many large flowers on stalk 5·0–30·0 cm long. Flowers yellow, 1·8–2·2 cm long with large prominent standard to 2·0 cm across; keel prominent to 1·8 cm long with short blunt beak.	Brown pods about 5·0 cm long and 6 mm wide, pendant on upright stalk. Sparse short hairs. 6–9 mottled brown seeds per pod.	(a) 35,000 (b) 140 kg (c) 5–11 kg

[a] Perennial.
[b] Biennial.
[c] Annual.

and *Vigna luteola* (cv. Dalrymple). General descriptions of the main cultivars are given in Table 19 : 1; for full details refer to Barnard (1967).

The tropical legumes usually enable a much higher animal intake of digestible protein and energy than the grasses. The higher feeding value of legumes compared with grasses is more evident in autumn and winter. Milford (1967) showed that several tropical legumes have a fairly high digestibility and are eaten even after frost damage and drying off.

All the tropical legumes nodulate well though there are important differences between and within species in this character (see Chapter 22). They are notably low in oestrogenic substances and the only occurrences of bloating in cattle have been with rapidly growing Rongai lablab and then very occasionally (Hamilton and Ruth 1968). Deleterious compounds have been recorded in leucaena (mimosine) by Hegarty, Schinckel, and Court (1964) and in *Indigofera spicata* (indospicine) by Hegarty and Pound (1968). The genus Crotalaria grows freely in coastal Queensland and has been used in rotation with sugar cane, but the most successful species (*C. striata*) contains significant amounts of pyrrolizidine alkaloids, including monocrotaline. Constant alertness is needed to avoid using tropical legumes which carry compounds deleterious or poisonous to stock.

The tropical legumes grow over large areas comprising a wide range of soils of low to medium fertility. With the exception of glycine, and possibly leucaena, they are well adapted to the acid soils of low calcium status provided the essential nutrients, particularly phosphorus, sulphur, and molybdenum, are supplied. This is due to their ability to extract calcium and nodulate at relatively low calcium levels (Andrew and Norris 1961). Henzell (1962) showed that nitrogen fixation by several tropical legumes, although not quite as good as that by lucerne and white clover, was nevertheless substantial. Townsville lucerne and lotononis are notable for high tolerance to excess manganese and aluminium compared with the sensitive glycine and common lucerne (Andrew 1963b, 1966a). Siratro also has very good tolerance to both these whereas the desmodiums have medium tolerance to excess manganese and high tolerance to excess aluminium.

Fresh hand-picked seed of most tropical legumes contains about 80 per cent hard seed but leucaena and siratro often have 90 per cent. Dormancy is present but normally disappears in 2–3 months. Complete loss of hard-seededness takes several years and occurs more quickly in legumes like Townsville lucerne than in leucaena. Hard-seededness is important in regeneration and persistence and grazing management should allow legume seed to build up in the soil.

The legumes vary markedly in their drought resistance, the most drought resistant being the free seeding annual Townsville lucerne and the perennials siratro and leucaena. With the exception of Miles lotononis, above ground growth is killed by frost. The perennial crown and root systems regenerate unless exposed to intense and repeated frosting.

Most of the legumes have good field resistance to root-knot nematode and the various virus, fungal, and bacterial diseases, and there are no records of any severe epidemics. *P. lathyroides* is very susceptible to root-knot nematode and siratro is highly resistant (Hutton and Beall 1957); occasionally the tap-root of Townsville lucerne may be attacked but its widespread success on light soils in northern Australia is evidence that any damage is not critical. In some areas, particularly in dry seasons, the virus-like disease 'legume little leaf', due to a mycoplasma (Bowyer *et al.* 1969), can markedly affect stands of Miles lotononis and the desmodiums and cause some loss in siratro. In high rainfall coastal areas extended wet periods can induce defoliation by the ubiquitous *Rhizoctonia solani*, particularly in siratro. Rongai lablab which grows well over the main part of summer and in autumn has replaced cowpeas (*V. sinensis*) as a forage crop because of the latter's susceptibility to *Phytophthora vignae*. This has left a serious gap in the production of early summer forage usually filled by cowpeas.

Up to the present, insect pests have been a problem in only limited areas, but could cause more widespread damage as extensive areas of tropical legumes are developed. On the north coast of New South Wales the Amnemus weevil is a serious pest of glycine and the desmodiums whereas Miles lotononis and lucerne are resistant to it and siratro is seldom attacked severely (Braithwaite 1967). Other native weevils have damaged a range of legumes in north Queensland.

Bean fly (*Melanagromyza phaseoli*) can cause serious damage to *P. lathyroides* and prevent regeneration of this annual. Siratro is completely resistant to bean fly except at the seedling stage but seedlings can be protected by dusting the seed with deildrin (Jones 1965).

To increase the productivity of tropical pastures it is necessary continually to examine the possibility of bringing new legumes into use and of replacing existing cultivars with ones better adapted by breeding or selection to climate, soil, and grazing practice. *D. canum* and *Indigofera spicata* are examples of two old introductions which have not yet been used in pastures. Breeding work has been done with *I. spicata* (Hutton and Guerassimoff 1966) but the problem of developing strains free from the hepatotoxin indospicine (Hegarty and Pound 1968) is unresolved. Although breeding is a potent tool in adaptation, objectives need to be clearly defined and a knowledge of the breeding system, cytology, genetics, and physiology of species is required. Breeding systems vary (Hutton 1960) from close self-pollination in Townsville lucerne, siratro, *P. lathyroides*, Indigofera, Glycine, Centrosema, and Lotononis through a combination of self- and cross-pollination in the desmodiums, to dominantly cross-pollination in lucerne and white clover. Leucaena is self-pollinating (Hutton and Gray 1959) although the heads of small flowers are exposed. A high relative humidity is needed in several of the self-pollinating tropical legumes for successful fertilisation.

Temperate

Medicago sativa (cv. Hunter River lucerne) and other Medicago species. Lucerne with its ability to grow from late autumn to early summer will become increasingly important on a range of soils, particularly south of the Tropic where annual rainfall exceeds 17 in. (432 mm). It is highly drought resistant and its frost resistance enables provision of high quality herbage in winter when feeding value of summer pastures is at a low ebb. The potential of lucerne for the sub-tropics was shown by Christian and Shaw (1952). More recently, 't Mannetje (1967a) showed its value as a component of sub-tropical pastures in the spear grass region on an acid granitic soil where its cool season growth complemented the summer growth of siratro. Lucerne is already widely used on fertile clay loams as found in the brigalow. On non-acid fertile soils the use of ample superphosphate and inoculated lime-pelleted seed is the key to successful establishment and growth. Its main deficiency in sub-tropical pastures is lack of persistence due to rotting of ageing crowns in the hot moist summers and inability to withstand continuous grazing. Breeding work is aimed at developing a persistent sub-tropical lucerne which will integrate with tropical legumes and grasses and offset their low feeding value in the autumn to winter period. Selections from the creeping-rooted Rambler lucerne (Heinrichs 1954) were crossed with the cultivars Hunter River, Indian, Saladina, Hairy Peruvian, and Pampa. In the progenies there was a correlation between creeping-rootedness, yield, and survival (Edye and Haydock 1967; Bray 1967, 1969). The creeping rootedness of Rambler has been transferred to a number of promising lines in which moribund crowns are continually replaced with young vigorous crowns from buds on roots spreading 10–15 cm below the soil surface.

The winter-growing annual medics *Medicago truncatula* (cvs. Jemalong and Cyprus), *M. polymorpha*, *M. scutellata*, and *M. littoralis* (cv. Harbinger) have been used increasingly on the red-brown and black earths of northern New South Wales and southern Queensland. *M. polymorpha*, *M. laciniata*, and *M. minima* are widely naturalised in this sub-tropical sub-coastal zone (see Map 5). Attention to nutrient requirements, especially phosphorus, has greatly extended their use on solodic soils (Russell 1966).

Trifolium repens (cvs. of white clover) and T. semipilosum (Kenya white clover). For the moist coastal zone south of latitude 25°S in southern Queensland and northern New South Wales white clover (*Trifolium repens*) is a valuable species for spring and early summer. It is also a valuable legume in irrigated pastures (Jones *et al.* 1968) and on the moist elevated Maleny, Eungella, and Atherton Tablelands at latitudes 27°S, 21°S, and 17°S. The species has become widely naturalised and free flowering annual ecotypes are recognised. Although common on kraznozems, chocolate soils and river alluviums, it can be grown on a wide range of poorer soils, provided their low nutrient status is corrected. Elements needed include phosphorus, sulphur, calcium, potassium, zinc, copper, and molybdenum. Special attention to calcium status is vital and inoculated lime pelleted seed to ensure nodulation is needed for establishment. With adequate attention to nutrient supply, the naturalised forms will commonly develop strongly; higher production can generally be achieved by using the cultivars Ladino, Irrigation, Louisiana S1, and Grasslands Huia in appropriate ecological niches. Ladino is the most vigorous but its paucity of flowers can often result in failure to set sufficient seed for regeneration following dry winters. Louisiana Sl has the free flowering habit of the naturalised ecotypes and may persist better. There is evidence that natural crossing between the various strains results in superior types but at present there is no program to breed adapted strains. In the Northern Rivers area of New South Wales, white clover does not persist due to attack by the endemic Amnemus weevil (Braithwaite, Jane, and Swain 1958). Control methods are being sought at the Wollongbar Research Station. The chlorinated hydrocarbons cannot now be used because of health regulations in milk and meat production. On sandy soils serious damage can be caused by root-knot nematode. However, at the CSIRO Beerwah Research Station, nematode damage on the Wallum sands, though detrimental, is not severe enough seriously to impair the value of white clover in sown pastures.

The closely allied Kenya white clover (*T. semipilosum*) with its deeper root system, greater drought resistance, and field resistance to Amnemus weevil (Mears, personal communication) has distinct potential in the areas suited to white clover ('t Mannetje 1964). It is highly specialised in its Rhizobium requirements (Norris and 't Mannetje 1964) and establishes slowly. Once established it gives superior winter and spring yields to white clover and also grows in summer.

AGRONOMIC CHARACTERS AND IMPROVEMENT OF THE MAIN TROPICAL LEGUMES

Stylosanthes humilis (Townsville lucerne, now Townsville stylo) (Pl. 30)

The potential of this free-seeding summer annual was recognised in the 1920s by Pollock (Humphreys 1967a). He encouraged its spread by scattering seed about in north Queensland. It is naturalised widely in Queensland, Northern Territory, and north of Western Australia over the latitudinal range 11°S to 24°S where the annual rainfall ranges from 25 to 70 in. (635–1778 mm). Isolated areas occur further south on the coast in Queensland and northern New South Wales.

Townsville lucerne grows in dense stands and varies from prostrate to semi-erect in habit. It has fibrous stems which may branch freely. Flowering occurs from late summer (February) to winter (May) depending on the type. The hooked pods adhere to the seed and form clusters or fall to the ground after the plants dry off. Commercial yields of 400 lb per acre (448 kg per ha) of the single seeded pods are common and up to 700 lb per acre (784 kg per ha) is obtained under favourable conditions. 'Seed' is sown with or without dehooking.

Townsville lucerne is adapted to a wide range of low fertility soils and regenerates from seed on all soil types except heavy cracking clays. It is particularly suited to sandy loams and deep sands. It nodulates freely and establishes readily from surface broadcasting of seed by ground or aerial methods at 2 to 3 lb per acre (2·2 to 3·4 kg per ha) into spear grass (*Heteropogon contortus*) or other types of country after heavy grazing, a late winter burn, or light cultivation. Good establishment is possible in partially cleared country with an open canopy. In the Northern Territory, Stocker and Sturtz (1966) and Miller (1967) obtained good establishment of Townsville lucerne if it was sown immediately after burning the rapidly growing native sorghum and other grasses at the start of the wet season.

Norman and Arndt (1959) and Norman (1960) showed the value of Townsville lucerne as dry season grazing in the Northern Territory for maintaining liveweight gains of cattle. The year-round carrying capacity of Townsville lucerne-spear grass country was studied for the first time by Shaw (1961) at Rodd's Bay near Gladstone (24°S) in Queensland. With application of molybdenum and annual dressings of 1 cwt superphosphate per acre (125 kg per ha) he increased the number of steers carried three times and liveweight gains per unit area five times compared with untreated native pasture (see Chapter 8). The increased productivity is due to almost doubling available dry matter and increasing its protein content by a third and its phosphorus level over twofold. It has been found by Andrew (1966b) that Townsville lucerne absorbs greater quantities of phosphorus per unit weight of root tissue per unit time than other species at both low and high phosphorus concentrations. The ability of Townsville lucerne to grow and spread on soils with only 3 to 10 ppm available phosphorus is due to this characteristic. The agronomy and use of Townsville lucerne in Queensland is described by Sillar (1969).

Townsville lucerne is increasingly well adapted north of the Tropic of Capricorn (23° 30′S). 't Mannetje (1965) found that it was a short-day plant. Downes *et al.* (1967) recorded greater vegetative growth at lower temperatures but Sweeney's results quoted by Humphreys (1967a) showed optimum dry matter production at 33/28°C. Cameron (1967a) found that temperature effect on flowering was not a factor in the present distribution. South of the Tropic, except on a narrow coastal strip, the species does not persist well and is not as vigorous. Its southern limit in Queensland and northern New South Wales is probably imposed by a combination of factors including an increase in frost incidence and winter rainfall, greater competition from perennial species, and lower spring and autumn temperatures affecting vigour of seedlings and late season growth respectively.

Cameron (1965) found significant variation in flowering time, growth habit, hardseededness, and other characters in collections from the natural populations of Townsville lucerne in Queensland and the Northern Territory. Late flowering ecotypes came from the far north where annual rainfall is 45 in. (1143 mm) or more, and midseason and early ones from between the 22 in. and 40 in. (559 and 1016 mm) isohyets (Cameron 1967b). Erect growers yield best and are more compatible with grasses due no doubt to intolerance of Townsville lucerne to shading (Sillar 1967). Upright, high-yielding strains with early, midseason, and late maturity were selected for the different rainfall zones, and this has resulted in release of the cultivars Lawson (midseason) and Gordon (late). In a diallel cross of Australian ecotypes ranging in maturity there was a strong dominance for lateness of flowering (Cameron 1967c). A small proportion of very early types occurred in some crosses and could extend Townsville lucerne into drier country. Crosses between Australian and recently introduced ecotypes of *S. humilis* may give new lines with greater adaptability to pastures and soils.

Species in the genus Stylosanthes constitute a polyploid series with a basic chromosome number of n = 10. Among the species, *S. humilis*, *S. guyanensis*, and *S. hamata* are diploids, *S. mucronata* is a tetraploid and *S. erecta* a hexaploid, and all are perennials except *S. humilis* (Cameron 1967d). Sterile hybrids resulted from the crosses *S. humilis* × *S. hamata* and *S. humilis* × *S. guyanensis* cultivars (Schofield stylo and Oxley fine-stem stylo) but colchicine treatment gave fertile tetraploids (Cameron 1968). These could produce vigorous types as adaptable as Townsville lucerne but with perenniality.

Stylosanthes guyanensis

Schofield stylo. Schofield stylo is naturalised on the wet tropical coast of north Queensland and is derived from Brazilian introduction in 1933 by the Queensland Department of Agriculture and Stock (Schofield 1941) and C.S.I.R. (McTaggart 1937). Its agronomic value was first demonstrated by Schofield (1941) at the Bureau of Tropical Agriculture, South Johnstone (17° 30′S). This tall growing perennial flowers late during winter (June to August) and is self fertilised. Seed production is heavy but the small pods shed on ripening so only a fraction of the 'seed' crop can be mechanically harvested.

Schofield stylo is adapted to frost-free tropical conditions and in Queensland grows on annual rainfalls from 35 to 160 in. (889–4064 mm). Good growth is obtained on a range of poor acid soils low in phosphate, but both yield and protein content are increased by superphosphate application (Miles 1949). Ability to extract phosphorus from soils low in this element is probably similar to that of Townsville lucerne. Best growth and persistence of Schofield stylo is at high summer temperatures with ample soil moisture on tropical kraznozems, gleys, loams, and sands. It can establish on undisturbed land but best results follow cultivation and sowing at about 2 lb per acre (2·2 kg per ha) on the soil surface or just below. It nodulates freely and promiscuously without inoculation

Plate 61 Siratro (*Phaseolus atropurpureus*) (CSIRO photo)

although it is good practice to inoculate the seed when sowing new areas.

Dense stands of Schofield stylo are thinned out markedly by fire and heavy grazing. It is intolerant of shading but is compatible with tropical grasses like guinea and molasses in well-managed pastures. Palatability of this legume tends to be higher in the later stages of growth. Several recent introductions of *S. guyanensis* are prostrate, branch freely near the ground, and are much more resistant to frequent cutting and heavy grazing (Grof, personal communication).

Oxley fine-stem stylo. Hartley (1949) obtained several ecotypes of fine-stem stylo in Paraguay during his 1947–8 collecting trip. The Oxley cultivar selected from these was shown by Shaw (1967a and b) and the Department of Primary Industries (Stonard 1968) to be a valuable and persistent legume at Brian Pastures and Moolboolaman in the spear grass area of southern Queensland. It is a low growing perennial flowering in early summer and autumn. An extended flowering period and rapid shedding of ripe pods makes it difficult to harvest seed in quantity. This is preventing its widespread use at present. Oxley fine-stem stylo has good frost tolerance and is more drought resistant than Schofield stylo. Also its greater complement of buds both below and above the ground level make it much more resistant to grazing. It is adapted to sub-tropical areas with annual rainfalls from 28 to 50 in. (711–1270 mm) and grows on a range of soils.

Oxley fine-stem stylo is proving of particular value on granitic and other sandy soils in southern Queensland where Townsville lucerne is poorly adapted. Its phosphorus extracting ability from poor soils also appears similar to that of Townsville lucerne. It has a highly specific Rhizobium so seed must be inoculated for successful establishment. Scarified seed at 1 to 2 lb per acre (1–2·2 kg per ha) should be sown no deeper than 0·5 in. (13 mm). It responds to molybdenised superphosphate, is compatible with buffel and Rhodes grasses, contains

12 per cent crude protein, and gives annual dry matter yields per acre of up to 1000 lb (1120 kg per ha). Poor initial stands of the legume will increase in density with time.

Phaseolus species

P. lathyroides (*cv. Murray*). Murray *P. lathyroides* was first recorded by Bailey and Tenison-Woods (1879) as naturalised in the Brisbane district and now occurs in moist situations on the coast of central and southern Queensland. This vigorous, upright, and free-seeding annual or biennial nodulates freely with native Rhizobium and is adapted to a range of soils in sub-tropical areas with more than 30 in. (762 mm) annual rainfall. It is also useful on the fertile brigalow soils of Queensland. On the heavy-textured Adelaide River flood plains in the Northern Territory, the most promising legumes are Murray *P. lathyroides* and the perennial deep-rooted *Clitoria ternatea* (butterfly pea). Paltridge (1942) selected Murray *P. lathyroides* for its vigour, palatability, and high protein content. It is valuable in pasture mixtures on newly cleared land but persists only in waterlogged areas with grasses like para and Paltridge scrobic. Usually it becomes a minor pasture component due to poor regeneration, palatability of the seedling and susceptibility to bean fly and root-knot nematode. Paltridge (1955) achieved regeneration of *P. lathyroides* by cultivating the space between rows of the grass scrobic. Cultivation of old pastures containing *P. lathyroides* usually induces it to regenerate. Murray *P. lathyroides* is used as a test legume in soil fertility and plant nutrition studies (Andrew and Henzell 1964). Among recent *P. lathyroides* introductions are some promising vigorous semi-prostrate types which branch strongly.

P. atropurpureus (*cv. siratro*) (Pl. 61). Hutton (1962) bred the perennial cultivar siratro from two Mexican ecotypes of *Phaseolus atropurpureus*. The main roots are strongly developed and swollen and it is very hardy compared with most perennial tropical legumes. In summer droughts large leaves are shed and small leathery ones produced until conditions are favourable. Winter frosts cause rapid defoliation but it perennates well. Growth is vigorous in a moist summer.

Siratro grows on a wide range of soils, except the poorly drained, in annual rainfalls from 25 to 70 in. (635–1778 mm) in north-eastern Australia and from 40 in. (1016 mm) in the Northern Territory. In the lower rainfall areas of southern Queensland it persists only on sandy soils and not on brigalow soils. It nodulates freely with native Rhizobium but seed should be inoculated at sowing. Siratro establishes readily on cultivated land sown at 2 lb per acre (2·2 kg per ha) in mixtures at a depth of 0·5–1 inch (13–25 mm). It establishes more slowly from surface seeding into burnt or well-grazed native pasture. Hard seed in commercial samples varies from 50 to 70 per cent so seed is often scarified before sowing. On most solodic and granitic coastal soils 3 to 4 cwt per acre (376–502 kg per ha) molybdenised superphosphate is needed at sowing to stimulate growth of the legume and associate grass. Siratro is compatible with a range of grasses including Rhodes, buffel, green panic, guinea, and the setaria cultivars Nandi and Kazungula. Near the equator in areas 4500 feet (1350 m) or more above sea level its growth is restricted by cool nights during summer. This applies particularly to countries like Kenya.

Depending on the rainfall, siratro persists in pastures grazed continuously at a cattle beast to 1·3 to 2 acres (0·5–0·8 ha). At Rodd's Bay, Queensland, very satisfactory liveweight gains were obtained from a siratro-Rhodes grass pasture. Its feeding value is good (Milford 1967) and crude protein and digestibility are well maintained with age of plant (Milford and Haydock 1965). A good intake of digestible energy and a satisfactory energy value of its organic matter have been reported for siratro by Minson and Milford (1966).

In one experiment growth of siratro was very poor at 21/16°C and 18/13°C in short (8-hour) and long (16-hour) days and maximum dry matter was produced at 30/25°C and 27/22°C in a long day. Flowering occurred in short and long days at a range of temperature regimes except 18/13°C and was best at 24/19°C, 27/22°C, and 30/25°C. Another experiment (Whiteman, personal communication) at a constant 28°C resulted in flowering in daylengths of 8, 10, and 12 hours but not at 16 and 24 hours, indicating that siratro could be a short-day plant.

The main aims of the breeding work with *P. atropurpureus* are to produce lines with greater

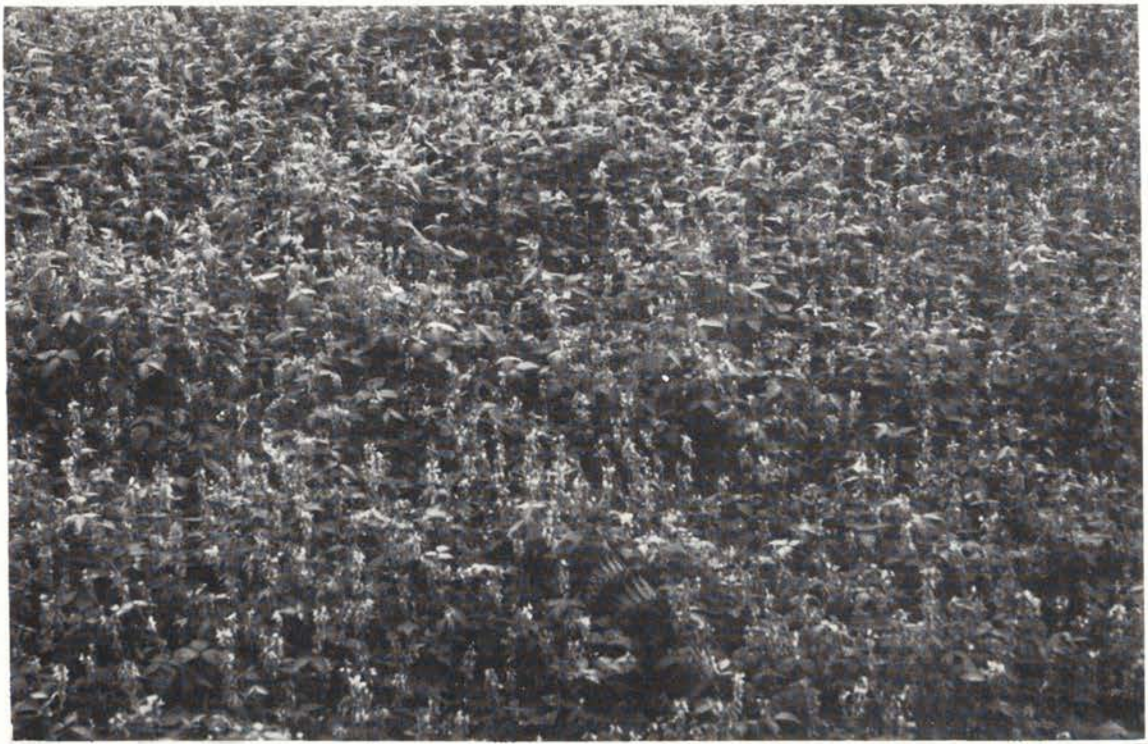


Plate 62 Greenleaf desmodium (*Desmodium intortum*) in flower at CSIRO station, Beerwah, Queensland (CSIRO photo)

yield, persistence, and stoloniferous development than siratro, and with a longer period of active growth, higher seed yield, and slower shattering pods (Hutton 1965). Progress has been made with most of these characters from crosses incorporating a number of new Central American ecotypes. The extended growing season of some advanced lines in southern Queensland is due to the ability to grow actively at temperatures of 50° to 70°F (10–21°C) in the autumn-winter-spring period. Leaf loss during extended humid periods is reduced markedly in some lines with high tolerance to the disease *Rhizoctonia solani*.

Desmodium species

Bryan (1966) has reviewed the value of desmodiums as pasture plants. *D. uncinatum* (cv. silverleaf) is from Brazil and *D. intortum* (cv. greenleaf) is a mixture of three similar introductions from El Salvador and Guatemala. A range of *D. sandwicense* and *D. canum* ecotypes has been introduced but none is promising enough for use in pastures. The shrub *D. gyroides* is of distinct value as it persists under grazing and where frosts are light or absent will retain green leaf into winter and spring. *D. heterophyllum* is a prostrate perennial, widespread in the tropics and naturalised in small areas of the northern tropical coast of Queensland where annual rainfall is 100 in. (2540 mm) or more. It is much branched, slender and stoloniferous and at South Johnstone Research Station persists under heavy grazing and combines well with dense sward-forming grasses including pangola. Its use is restricted as seed collection is difficult, the small pods maturing over a long period within the green foliage.

D. intortum (*cv. greenleaf*) (Pl. 62). Greenleaf desmodium is coarser than silverleaf with rather thick stems, the leaves containing about 7 per cent tannin (Hutton and Coote 1966). Flowering induced by short days is late and occurs May to June, so seed production south of the Tropic is often affected by frosts. In frost-free areas of north Queensland where irrigation is available, excellent seed crops are being grown. It is one of the most dependable legumes for coastal areas with annual rainfalls of 35 in. (889 mm) or more ranging from northern New South Wales to north Queensland. In the Northern Territory it grows where rainfall is 45 in. (1143 mm) or more. It tolerates acid conditions and grows on a range of soils from sands to red loams and is especially promising on the Atherton Tableland of Queensland. Experience in other tropical countries shows that near the Equator it grows from the coast to elevated areas around 6500 feet (1950 m) above sea level and is more versatile in this respect than siratro. Autumn and spring growth are good where frosts are light or absent and its rapid summer growth is maintained at the highest temperatures. Although hardier and more persistent and adaptable than silverleaf desmodium, it is not very drought resistant and is restricted to moist areas. Greenleaf is damaged as severely as silverleaf by Amnemus weevil (Braithwaite 1967; Mears 1967) but is not as susceptible to legume 'little leaf'.

Seed is small and after inoculation is sown in prepared soil at 1–2 lb per acre (1–2·2 kg per ha). Seedlings nodulate and establish rather slowly but in a moist summer a dense sward to 90 cm deep soon forms if grazing is light. It responds markedly to fertiliser, particularly molybdenised superphosphate, combines well with most of the main grasses, and builds up a layer of decomposing organic matter on the soil surface. Cattle readily eat leaves and shoots and tend to leave the less palatable stems (Bryan 1966). Nutritive value is high and good liveweight gains are obtained from greenleaf-based pastures at a beast per acre (0·4 ha) (Bryan and Evans 1967).

Breeding work with greenleaf aims at earlier flowering, higher production of dry matter and seed, quicker nodulation to improve establishment, greater hardiness, and resistance to legume 'little leaf'. If Amnemus weevil cannot be controlled by insecticides or other means, breeding resistant plants should be attempted. The genus Desmodium has a basic chromosome number of n = 11 and species important in pasture research are diploids. With the objective of introducing other valuable genes into greenleaf and generating new variation the interspecific crosses *D. intortum* × *D. uncinatum* and *D. intortum* × *D. sandwicense* were made (Hutton and Gray 1967). The first had a high degree of sterility (95·7 per cent) and the second was fully fertile, and both are giving promising progenies.

D. uncinatum (*cv. silverleaf*). Silverleaf desmodium has thin hairy leaves containing about 3·6 per cent tannin (Hutton and Coote 1966). Short days induce flowering in April to May, and seed usually sets in southern Queensland before winter frosts. It is adapted to a range of soils in coastal areas particularly of northern New South Wales and southern Queensland where annual rainfall is 35 in. (889 mm) or more. Growth is often better in elevated areas where nights are cooler. It is tolerant of light frosts and early spring and autumn growth is good. Growth is retarded by summer temperatures above 85°F (30°C) and it is not as hardy as greenleaf desmodium which is replacing it in a number of districts. It is susceptible to legume 'little leaf' which often kills it in drier areas but recovery is usual in moist areas. Amnemus weevil often decimates stands, especially in dry seasons.

Seedlings establish and nodulate readily from inoculated seed sown into moist cultivated soil at 2 lb per acre (2·2 kg per ha). It responds strongly to fertiliser and has the capacity to extract copper from soils low in this element (Andrew and Thorne 1962). Cattle graze it readily and intake by animals and digestibility are good, even after frosting (Milford 1967). Leaves and shoots are mainly eaten (Bryan 1966) and overgrazing causes runner damage. It combines well with a range of grasses including setarias, paspalums, and panicums. In a fertilised silverleaf desmodium pasture mown and grazed intermittently, there was a surface accumulation of organic matter and an annual addition per acre of 90–100 lb (101–112 kg per ha) nitrogen to the soil-plant system (Henzell, Fergus, and Martin 1966).

Glycine wightii (*cvs. Clarence, Cooper, Tinaroo*)

Three cultivars of glycine are at present available in Australia—Clarence from the Transvaal, Cooper from Tanzania, and Tinaroo from Kenya, the first tetraploid (2n = 44) and the last two diploids (2n = 22) as shown by Pritchard and Wutoh (1964). Clarence is less stoloniferous than Cooper and Tinaroo and all are deep-rooting. Clarence and Cooper are early types and flower April to May, but Tinaroo is very late and flowers June to July. Seed of Clarence and Cooper can be produced along the coast in northern New South Wales and southern

Plate 63 Leucaena (*Leucaena leucocephala*) showing flowers, fruit pods, and habit of growth (CSIRO photo)

Queensland but Tinaroo seed has to be grown in frost-free areas of north Queensland.

Glycine is more drought resistant than the desmodiums, is tolerant of light frosts, and adapted to areas with an annual rainfall of 30–70 in. (762–1778 mm). The species thrives on kraznozems, self-mulching black soils, and well-drained alluviums and appears to have a higher demand for lime and potassium than other tropicals. It does not establish or grow well on solodic or podzolic soils and is not suited to acid soils, though Clarence and Cooper are more tolerant. Usually it is not severely attacked by insects or disease but Amnemus weevil is a major pest in northern New South Wales (Braithwaite 1967), and *Rhizoctonia solani* infects it in extended wet periods on the Atherton Tableland.

Various aspects of the agronomy of glycine have been described by Allen (1960), Tow (1960), Kyneur (1960), Cowdrey (1960), and Murtagh and Wilson (1962). Tinaroo is adapted to fertile soils and long growing seasons as on parts of the Atherton Tableland where it grows actively in winter. Clarence is the best cultivar in northern New South Wales, and Cooper is extending the use of glycine into somewhat drier areas. Inoculated glycine seed is sown at 2 to 4 lb per acre (2·2–4·5 kg per ha) but seedling vigour is rather poor and first-year growth relatively slow. Care is needed to reduce competition by judicious grazing, sowing on clean seedbeds, and using light rates of seeding of associate grasses. Seedlings do not nodulate rapidly and strongly and there is evidence that glycine lines vary in nodulating ability. In the second and subsequent years, growth is strong throughout summer and autumn and its capacity to retain leafiness and greenness into winter where frosts are light or absent makes it a valuable reserve of winter fodder for cattle. It associates well with a range of grasses including green panic, guinea, molasses, and setaria and can be maintained in competition with them by lenient summer grazing. Digestibility and animal intake are good (Milford, personal communication) and very satisfactory beef and milk production are obtained from glycine-based pastures.

Tow (1967) showed that green panic produced much more dry matter than Tinaroo glycine per unit of intercepted light and per unit of water transpired and that green panic had higher shoot-root ratios than glycine. Five other glycine varieties had higher shoot-root ratios than Tinaroo, some similar to green panic. Wutoh, Hutton, and Pritchard (1968a) found the temperature regime 27/22–16°C (day-night) the most suitable for seed production and growth of glycine. The varieties used were short-day types and in the sensitive ones temperature had little effect on flowering, but seed formation did not occur in day temperatures above 27°C.

Edye and Kiers (1966) and Edye (1967) studied variation in flowering time, seed set and yield, stolon development, and frost resistance in a large number of glycine introductions. The early cultivar Cooper (CPI 25702) was released as a result of this work. Although most lines of *G. wightii* are self-pollinating (Hutton 1960), crossing apparently occurs as populations of some show variation, a fact also noted by Bogdan (1966). Wutoh, Hutton, and Pritchard (1968b and c) studied inheritance of a range of characters in a number of crosses. Some of the results showed that early flowering, high yield, and good stolon development could be combined in one variety. Breeding work of the Queensland Department of Primary Industries is aimed at developing lines adapted to the poorer soils of the Atherton Tableland. That of the CSIRO Cunningham Laboratory is concerned with inheritance of nodulating ability and development of early persistent types for the brigalow and drier coastal areas.

Leucaena leucocephala (*cvs. El Salvador, Peru*) (Pl. 63)

Leucaena has been used for a long time as a shade tree in cocoa and coffee plantations. Its forage value was first shown by Takahashi and Ripperton (1949) who produced 8–9 tons dry matter per acre (20–22·5 tons per ha) containing 1–1·5 tons (2·5–3·8 tons) crude protein on a 50–60 in. (1270–1524 mm) annual rainfall in Hawaii. At Samford, near Brisbane, Hutton and Bonner (1960) recorded dry matter yields per acre from 1335 lb (1495 kg per ha) for the Hawaiian type to 11,236 lb (12,584 kg) for the Peru type with corresponding protein yields from 405 to 3217 lb per acre (454–3623 kg per ha). Hutton and Gray (1959) classed introductions into three types based on differences in growth habit, yield, and maturity. Hawaiian, the common type naturalised in north Australia and many tropical countries, is relatively short and bushy, low yielding, and early flowering. The taller high yielding and late flowering El Salvador and Peru types are Central American and introductions of these are used as cultivars. Peru is favoured as it has the best yield and its strongly branched habit is suited to grazing. All types are deep-rooted and have an extensive distribution of dormant buds, and so become shrubs under heavy grazing.

Leucaena is self-pollinating and the heavy seed yields are at present hand harvested. Fresh samples contain 70–90 per cent hard seed, but Gray (1962) found immersion for 4 minutes in water at 80°C greatly increased germination. Treated seed inoculated with Rhizobium is drilled at 4–5 lb per acre (4·5–5·6 kg per ha) into a well-prepared seedbed in rows 8–10 feet (2·4–3·0 m) apart. It responds to molybdenised superphosphate which is applied at 2–4 cwt per acre (251–502 kg per ha). Seedling establishment is slow and weed control with inter-row cultivation or weedicides is necessary until plants are 2–3 feet (61–91 cm) high and growing vigorously. The inter-row spaces are then planted with a grass such as pangola, green panic, guinea, and setaria. Well-established stands can be heavily grazed and if trees grow out of reach of animals they can be controlled with a heavy slasher.

Leucaena will become more widely used in the future when its high feeding value, drought resistance, strong perenniality, and ability to form two-level pastures with valuable but competitive grasses like pangola are recognised. It will give liveweight gains in steers of 2 lb (0·9 kg) per day or better over much of its long growing period from spring to late autumn. Leucaena-based pastures can be stocked up to a cattle beast per acre (0·4 per ha) without damage as leucaena stems are pliable. Stands of the leguminous shrub *Cajanus cajan* with non-resilient stems are destroyed by the grazing animal. Leucaena is adapted to most well-drained soils of coastal northern Australia where annual rainfall is 30 in. (762 mm) or more and frosts are light or absent.

There has been some concern that feeding leucaena to cattle affects reproduction as 0·5 per cent of the nitrogen in the herbage is mimosine, an undesirable depressant of cell division (Hegarty, Schinckel, and Court 1964). Experiments at the University Agricultural Experiment Station in Hawaii (Anon. 1948) showed no reduction in reproductive efficiency of dairy cows continuously fed leucaena. At Samford, Hamilton, Donaldson, and Lambourne (pers. comm.) showed that a pure diet of freshly cut leucaena did not affect oestrus or reproduction in dairy heifers. Sheep, however, will shed their fleece on a diet of leucaena as the mimosine causes follicle degeneration (Hegarty, Schinckel, and Court 1964).

There is no urgency to breed mimosine-free lines of leucaena for cattle pasture as most of the mimosine is destroyed in the rumen. The breeding and genetical work at the Cunningham Laboratory is aimed at developing leucaena lines with high forage yield and a dense, compact branching habit suitable for grazing. The inheritance of the characters involved have been studied by Gray (1967a, b, c) in crosses between the different types. The tall sparsely branched habit of El Salvador and Guatemala is dominant over the multibranched habit of Peru and the short bushy habit of Hawaii. The most promising bred lines incorporating high leaf yield and dense branching are being obtained from the cross Hawaii × Peru.

Lotononis bainesii (*cv. Miles*)

Miles lotononis originated from seed collected by J. F. Miles in 1952 in the Worcester Veldt Reserve, South Africa. Bryan (1961) describes the plant and discusses its use and adaptability in pastures. This slender perennial is self-pollinating (Byth 1964) and produces very small seed. The original material was unselected so there is some variation in leaf size and shape and time of flowering in the cultivar. Miles lotononis did not become agronomically important until its highly specialised Rhizobium was isolated by Norris (1958a).

It is best adapted to sandy and self-mulching soils in sub-tropical coastal areas with annual rainfalls of 35–40 in. (889–1016 mm) or more. It is the only frost-resistant tropical legume but makes little growth at low winter temperatures. The inoculated seed is surface sown on a cultivated and fertilised seedbed. The seedlings are small and sparse at first but then the plants rapidly colonise the area and form a dense stand. Establishment can also be achieved with stolon cuttings. It combines well with a range of grasses and is one of the few legumes able to thrive in association with pangola grass. Henzell (1962) has shown that it can fix appreciable quantities of nitrogen, but competes for nitrogen if adequate amounts are available in the soil. Constant grazing maintains its productivity as stoloniferous development is encouraged and grass shading reduced. Even with good management on sandy soils Miles lotononis at times will almost disappear and then recolonise vigorously. Poor persistence on tight soils appears due to failure of stoloniferous roots to develop. In somewhat drier areas its lack of persistence is due to infection with legume 'little leaf' (Hutton and Grylls 1956).

At present Miles lotononis is adapted to a rather restricted area along the sub-tropical coast of Australia. There is need to introduce numbers of different ecotypes and breed more vigorous lines able to grow over a wider range of conditions.

Dolichos species

D. lablab (*cv. Rongai*). Rongai lablab is described by Wilson and Murtagh (1962) and is a vigorous annual or biennial collected in Kenya by J. F. Miles. It is late flowering and self-pollinating and seed yields up to 600 lb per acre (672 kg per ha) are obtained. It grows on a wide range of soils where annual rainfall is 25 in. (635 mm) or more, and the inoculated seed is usually sown into a prepared seedbed at 10–15 lb per acre (11–17 kg per ha). In many areas it is displacing cowpeas as a forage crop because of its drought resistance, cold tolerance, longer growing season, biennial habit, resistance to root and stem rot and insects. Rongai establishes readily, suppresses weeds, and adds nitrogen to the soil, so is a good preparation for sowing perennial pastures. Cattle grazing it do best when it is young and leafy and highly digestible, although it occasionally causes bloat at this stage (Hamilton and Ruth 1968). When well grown and mature, intake and liveweight gain are reduced because stems are tough and unpalatable.

D. axillaris (*cv. Archer*). Archer axillaris is a short-lived perennial derived from a Kenya introduction (Luck 1965). It is adapted to a variety of well-drained soils in areas with an annual rainfall of 40 in. (1016 mm) or more and grows with a range of grasses. It is drought tolerant and has the ability to grow quickly in the spring before the main rains and then continue growth late in the season. The herbage is not particularly palatable to cattle until mature and in frost-free areas it is used as a stand-over crop for winter feeding.

D. uniflorus (*cv. Leichhardt*). The origin of Leichhardt is unknown, but the species is native to Asia and tropical Africa. It is a short season annual which has shown promise on a variety of soils in north Queensland where the annual rainfall is 25 to 45 in. (635–1143 mm) (Staples 1967). It is palatable to stock at all stages of growth. The mature crop can contain over 2000 lb seed per acre (2240 kg per ha) held in the pod so is valuable for deferred grazing in the dry season.

Vigna luteola (*cv. Dalrymple*)

Dalrymple is a biennial or short-lived perennial collected in Costa Rica by W. W. Bryan. It needs an annual rainfall of 35 in. (889 mm) or more and will grow over a wide range of conditions in north-east Australia. It is tolerant of moderate soil salinity and is among the few legumes able to grow well in poorly drained situations. At Samford Jones, Griffiths Davies, and Waite (1967) found it persisted only two years under grazing but was high-yielding, very palatable and the nitrogen released when it died markedly stimulated the associate grass. Clusters of large nodules are formed on the young stoloniferous roots. Early growth of Dalrymple is rapid but it should be grazed lightly until hard woody runners have developed. It is subject to insect and frost damage.

Calopogonium mucunoides (*calopo*)

Calopo is a vigorous short-lived perennial, naturalised in many tropical countries, and is South American in origin. It lacks cold tolerance and is adapted to a range of soils in warm humid areas with an annual rainfall of 50 in. (1270 mm) or more. It is a good pioneer legume and soon forms a dense mass of herbage which is hairy and rather unpalatable to cattle. Its free seeding habit enables it to regenerate. Calopo is unlikely to become widely used in the Australian tropics.

Centrosema pubescens (*centro*) (Pl. 64)

Centro is one of the most important perennial legumes for wet tropical areas, and is indigenous to South America. It is very late flowering so seed has to be produced in frost-free areas with a long growing season. It has a strong root system and survives extended dry periods. Centro will also survive frost but does not thrive in the sub-tropics and is adapted to warm humid coastal areas with an annual rainfall of 50 in. (1270 mm) or more. It grows on a variety of soils and responds significantly to molybdenised superphosphate on the poorer types. It combines well with grasses like guinea and para. Centro seed should be inoculated and sown into a prepared seedbed at 2–4 lb per acre (2·2–4·5 kg per ha) for best results. Initial establishment is rather slow but subsequent growth is rapid. In wet coastal environments in north Queensland, centro-based pastures, with proper management and fertilisation, have persisted for twenty years and have given good liveweight gains at carrying capacities of a cattle beast per acre (0·4 per ha). Bruce (1965) showed that soil under a 16-year-old centro-guinea grass pasture contained significantly more nitrogen and carbon than soil under a guinea grass one of similar age. Heritable variation in nodulating ability is present in centro (Bowen and Kennedy 1961) so improvement in its nitrogen fixation is possible. Variation has also been shown by L. G. Miles in other characters including vigour, earliness, winter-hardiness and seed production (Schofield 1945), so selection and breeding of superior strains can be envisaged.

Pueraria phaseoloides (*puero or tropical kudzu*)

Puero is indigenous to Malaysia and like calopo is a pioneer tropical legume adapted only to warm humid conditions where annual rainfall is 50 in. (1270 mm) or more. It establishes quickly on a variety of soils and sends out long vigorous runners and soon produces a deep mass of herbage. Puero responds to superphosphate on most coastal soils in north

Plate 64 Centro (*Centrosema pubescens*) (CSIRO photo)

Queensland. Because of its rapid growth it is being increasingly used at about 2 lb per acre (2·2 kg per ha) with species like centro and guinea grass in pasture mixtures for new land. Being very palatable puero gradually disappears under heavy grazing while centro and guinea grass form the permanent pasture.

THE MAIN GRASSES: THEIR AGRONOMIC CHARACTERS AND IMPROVEMENT

The important introduced tropical grasses are all perennials and include *Brachiaria decumbens* (signal grass), *B. mutica* (para), *B. ruziziensis* (cv. Kennedy), *Cenchrus ciliaris* (nine cultivars including Biloela and Gayndah), *Chloris gayana* (cvs. Callide, Katambora, Pioneer, and Samford), *Digitaria decumbens* (pangola), *Melinis minutiflora* (molasses), *Panicum coloratum* var. makarikariense (cvs. Bambatsi, Burnett, and Pollock), *Panicum maximum* (cvs. coloniao, Gatton, hamil, and sabi), *P. maximum* var. *trichoglume* (cv. Petrie), *Paspalum commersonii* (cv. Paltridge scrobic), *P. dilatatum* (paspalum), *P. plicatulum* (cvs. Hartley and Rodd's Bay), *Pennisetum clandestinum* (kikuyu), *P. purpureum* (cv. Capricorn), *Setaria sphacelata* (cvs. Nandi and Kazungula), and *Sorghum almum* (cvs. Crooble and Nunbank). *Urochloa mosambicensis*, not yet commercialised, shows considerable promise in drier areas of north Queensland as it appears compatible with Townsville lucerne and has green shoots in the dry season. Full descriptions of a number of these grasses are given by

Barnard (1967). It must not be overlooked that the feeding value of native spear grass (*H. contortus*) which occurs over extensive coastal and sub-coastal areas in north-eastern Australia is upgraded when fertilised and grown with Townsville lucerne (Shaw 1961).

P. maximum cv. hamil has an unusually high photosynthetic efficiency (Ludlow and Wilson 1967) and this may be characteristic of many tropical grasses (see Tow 1967). In moist coastal areas of north-eastern Australia, a number of grasses given heavy nitrogen applications and adequate phosphorus and potassium produce annual dry matter yields per acre from 20,000 lb (22,400 kg per ha) by Rhodes grass to 33,000 lb (36,900 kg per ha) by *B. decumbens* (Henzell 1963; Grof 1967). Nitrogen rather than soil moisture is the main limiting factor to grass growth in this coastal region (Henzell and Stirk 1963), and the relatively low nitrogen content of tropical grasses compared with temperate is considered by Henzell and Oxenham (1964) to be due in part to greater nitrogen deficiency in the tropics. Tropical legumes are not able to fix enough nitrogen to allow the full growth potential of most tropical grasses to be realised.

High grass yields induced by fertiliser nitrogen are not an advantage unless the dry matter is of high feeding value and well utilised by the grazing animal. At the young leaf stage most tropical grasses provide enough protein and have a high animal intake but with increasing maturity protein level falls (Milford and Haydock 1965), and there is a rapid decline in digestibility and intake. This is thought to be due to a shortage of digestible energy from the quick increase in crude fibre (Minson and Milford 1966). Decline in feeding value is slower in pangola grass and kikuyu which give very good animal production with fertiliser nitrogen, provided stocking rate is heavy.

In many situations and particularly in the drier coastal and sub-coastal areas which comprise the bulk of the cattle country, use of fertiliser nitrogen is problematical. Here a high legume content in the pasture is the most efficient way to maintain quality and offset the rapid loss in feeding value of grasses. As a result of the work of Norman (1960) and Shaw (1961) this is being achieved with Townsville lucerne, particularly north of the Tropic. Bunch grasses including buffel, panicums, Rhodes (*C. gayana*), and setarias are being sown increasingly with a range of perennial legumes. In the resultant pastures a high proportion of legume can be maintained with fertilisers, notably superphosphate, and by suitable stocking rates.

Seeding rates of the grasses usually vary from 0·5 to 4 lb per acre (0·5–4·5 kg per ha) according to species and conditions. Common paspalum with its poor germination and the large-seeded *S. almum* are often sown at rates greater than 4 lb per acre (4·5 kg per ha). Low seeding rates of 1 to 2 lb per acre (1–2·2 kg per ha) of most grass cultivars are used in dry areas and in mixtures with legumes to prevent suppression of the legume during establishment.

Only a few insects and diseases have been problems in the grasses. In dry seasons at Rodd's Bay and Beerwah, stands of Paltridge scrobic have been severely affected by mealy bugs which attack the bases of the plants (Shaw, Bryan, personal communication). The felted grass coccid occurs on Rhodes grass and is not at present serious under Queensland conditions (Brimblecombe 1968). In wet summers loss of leaf occurs in Nandi setaria from Piricularia leaf spot and the yield and persistence of *Sorghum almum* is affected by rust, leaf blight, and sugar cane mosaic. The main problem in tropical grasses is the rapid loss in feeding value with maturity which is accentuated by their lack of frost resistance in the dry season, particularly south of the Tropic. Improvement in feeding value could be achieved by breeding for high *in vitro* digestibility (McLeod and Minson pers. comm.), high protein content at maturity, and frost resistance and winter greenness (Milford 1960).

C. gayana, *P. coloratum*, *Pennisetum purpureum*, *S. sphacelata*, and *S. almum* are cross pollinating and variable, so superior types can be obtained from them by selection. *P. purpureum* and *P. clandestinum* are usually propagated vegetatively. In *P. clandestinum* the ecotypes are either fully fertile or facultative apomicts (Narayan 1955). Pangola grass is completely sterile and is only propagated vegetatively. All the other grasses listed are obligate apomicts (e.g. Snyder, Hernandez, and Warmke 1955; Warmke 1954; Bashaw and Holt 1958) which prevents variation and poses a problem to the breeder unless sexual ecotypes or species which can be used in crosses are found.

Panicum species

P. maximum (*guinea grasses*). The cultivars of *P. maximum* are all tufted perennials with blue-green softly hairy leaves. They vary from the tall robust hamil and coloniao 3·6 to 4·2 m high to Gatton panic 1·5 m high, and the less robust Petrie green panic and sabi only 1·0 m high. The origin of hamil grass is unknown, coloniao came from Brazil, Gatton panic was introduced from Rhodesia, sabi is South African, and Petrie green panic occurred in blue panic seed from India (Marriott and Winchester 1951). The inflorescence is an open branched panicle and lemma and palea closely invest the caryopsis. There are about 725,000 seeds per lb (16,111,000 per kg).

Hamil grass (Walsh 1959) and coloniao are very productive in moist frost-free situations in north Queensland. During the main growth period they are quite palatable to stock in spite of their apparent coarseness, but in the dry season the almost hairless coloniao is much more palatable and is grazed to ground level. Gatton panic thrives in a 30 to 40 in. (762–1016 mm) annual rainfall and is adapted to much the same conditions as Petrie green panic, but is more vigorous and could displace the latter in some areas. Sabi is a similar type, but not as adaptable as Petrie green panic which grows from north Queensland in a rainfall of 70 in. (1778 mm) to the brigalow in a rainfall as low as 22 in. (559 mm) (Fox and Wilson 1959). The drought resistance of Petrie green panic has been proved in recent severe droughts and it has a measure of cold tolerance. It is well grazed by stock and accumulates a high proportion of its surplus carbohydrate in the above ground parts (Humphreys and Robinson 1966). Petrie green panic is the most shade tolerant cultivar, a useful feature in semi-cleared situations. It combines well with most of the perennial legumes including lucerne and is responsive to nutrients.

P. coloratum. This is a complex containing several forms such as the varieties makarikariense and kabulabula. There are three cultivars of *P. coloratum* var. *makarikariense*: Bambatsi from Rhodesia (West 1952), Pollock from South Africa (Cameron 1959), and Burnett from Botswana. They are tussocky perennials with glaucous stems and bluish glabrous leaves with a prominent white mid-rib. Bambatsi grows to 1·8 m high and Burnett to 1·4 m and both have short rhizomes. Pollock grows to 1·2 m high and is stoloniferous and develops large crowns. The panicles are large with glumes tinged purple at the tip and the shiny dark seeds comprise the caryopsis closely invested by lemma and palea. The seed ripens unevenly and is shed as soon as mature, which reduces the yield.

The makarikari cultivars have deep fibrous root systems and are drought resistant and persist well under grazing. They are adapted to sub-tropical areas with an annual rainfall of 20 to 40 in. (508–1016 mm) and do best on self-mulching clay soils where they grow well with lucerne. Pollock will thrive on deep clay soils subject to waterlogging, but Bambatsi is intolerant to these conditions (Wilson 1963). Bambatsi is the most frost tolerant cultivar and all have a degree of winter greenness and make some growth after winter rains.

In the wetter coastal areas of south-east Queensland, several introductions of *P. coloratum* var. *kabulabula*, including CPI nos. 16796, 16296, and 14375 have given high yields over a long growing season. They persist well under grazing but become unpalatable if allowed to grow rank. Seed drops as it matures so its collection is difficult.

Digitaria decumbens (*pangola grass*)

Pangola grass was developed from material collected in the Nelspruit district of eastern Transvaal (Chippindall 1955) and its name was derived from a misspelling of Pongola, the river which crosses the region. It is now one of the most important grasses throughout the world in the sub-tropics and tropics. This is because of its adaptability to a wide range of soils, its strongly stoloniferous and invasive habit and resistance to heavy grazing, its high feeding value, and its superior response to fertiliser nitrogen in terms of animal production. With dressings of 400 and 800 lb per acre (448 and 896 kg per ha) of nitrogen in the moist Beerwah environment, it gave annual liveweight gains in cattle of 1100–1200 lb per acre (1220–1340 kg per ha) (Bryan and Evans 1967).

Pangola grass has glabrous leaves 14–30 cm long and 0·7 cm wide and relatively thin many-noded stems which are much branched and usually decumbent and which root vigorously in contact with the soil. The sterile inflorescence

Plate 65 Kazungula setaria (*Setaria sphacelata*) growing at CSIRO Pasture Research Station Samford, near Brisbane, Queensland (CSIRO photo)

consists of 6–10 thin racemes up to 13 cm long and arranged digitately. It is propagated vegetatively in various ways and is established quickly by cutting coarsely with a forage harvester and blowing the pieces on to moist cultivated soil and then rolling.

In north-eastern Australia pangola grass does best along the coast where annual rainfall is in excess of 40 in. (1016 mm). However, it will persist in the drier and colder brigalow and subcoastal areas. It is damaged by winter frosts but recovers quickly in warmer weather. At Beerwah Bryan and Sharpe (1965) found that growth of pangola grass was restricted while the average night temperature was below 58°F during May to October.

Although feeding value of pangola grass is high, animal intake near maturity can be limited by protein deficiency (Minson 1967) unless a late application of nitrogen fertiliser is given or it is grown with a legume. It will combine with legumes like Miles lotononis (Bryan 1961) and centro, and Kretschmer (1965, 1966) has grown it successfully with Townsville lucerne and siratro in southern Florida. The tree legume leucaena interplanted with pangola grass produces a high quality pasture giving high liveweight gains in cattle.

In Australia no serious insect and disease problems have occurred as yet in pangola grass. A close watch has been kept for the damaging virus disease discovered in it by Dirvin and Van Hoof (1960) in Surinam. As pangola grass is an aneuploid ($2n = 27$) it is not possible to improve it by conventional breeding methods. Attempts to resynthesise pangola grass types may be a worthwhile objective.

Setaria sphacelata (*setaria*) (Pl. 65)

Nandi was selected by D. C. Edwards from an ecotype collected in the highland Nandi district of Kenya and subsequently improved by

Plate 66 *Sorghum almum* (CSIRO photo)

Bogdan (1959). Kazungula is a Zambian ecotype developed in South Africa (Chippindall 1955). Both are tussocky perennials with very short rhizomes, Nandi growing to 1·5 m at flowering and the coarser Kazungula to 2·1 m. Tillers are compressed at the base which is purplish-red. Leaves are broad and glabrous although hairy plants occur in Kazungula. Inflorescence is a spike-like panicle which in Nandi is orange-brown and up to 23–25 cm long, and in Kazungula light in colour and up to 38 cm. Stigmas are white in Nandi and purple in Kazungula. Lemma and palea tightly enclose the caryopsis and there are 600,000 to 850,000 seeds per lb (13,330,000 to 18,900,000 per kg).

The setarias are the most promising grasses for coastal areas with annual rainfalls greater than 30 in. (762 mm), particularly south of the Tropic. They also thrive on the Atherton Tableland of north Queensland. Both cultivars are adapted to a range of soils and tolerate waterlogging (Colman and Wilson 1960). Kazungula establishes quicker than Nandi and is somewhat hardier and more aggressive and competes more strongly with legumes. Both combine well with a range of legumes and have a long growing season. Kazungula is a little more frost tolerant than Nandi but both are damaged by severe frost.

Breeding work is aimed at producing high yielding frost-resistant lines with high digestibility and an extended growing season. Jones's (1964) frost-resistant collections are proving invaluable in this program. Nandi is diploid (2n = 18) and Kazungula tetraploid (2n = 36). The *S. sphacelata* complex also contains pentaploid, hexaploid, octoploid, and decaploid races (Hacker 1966), and appears to be an autopolyploid series (Hacker 1968). Cross-fertilisation occurs not only within ploidy levels but between ploidy levels except diploid and tetraploid, so isolation is necessary to maintain purity of most lines (Hacker 1967).

Sorghum almum (Pl. 66)

S. almum (Parodi 1943) is considered to be a cross between Johnson grass (*S. halepense*) and a variety of *S. vulgare*. Its characteristics and potential in Australia have been discussed by Davies and Edye (1959). Most of the introductions originated in Argentina. The cultivar Crooble (Boyle 1961) is more persistent than Nunbank but both are rather short lived perennials. They are vigorous with large glabrous leaves, numerous tillers, and short rhizomes. Their stems are solid and pithy and they grow to a height of 3·0 to 3·6 m. The inflorescence is a pyramid-shaped panicle with branches in whorls. Seed is produced freely and the light brown caryopsis is enclosed in shiny black glumes. There are about 55,000 seeds per lb (128,000 per kg) in these cultivars.

S. almum requires a soil of high fertility and is adapted to areas in Queensland and north-western New South Wales with an annual rainfall of 18–35 in. (457–889 mm). It is of high feeding value and capable of giving high liveweight gains (Yates *et al.* 1964). *S. almum* is drought resistant and salt tolerant (Gates *et al.* 1966) and although frost susceptible is still palatable to stock when frosted. *S. almum* is cyanogenetic but no more so than other sorghums. It is an outstanding pioneer species sown alone on newly cleared brigalow where in favourable seasons it can be grazed within 6–8 weeks of sowing and offsets clearing costs in the first year. After two seasons when brigalow suckers are eliminated by shallow ploughing (Coaldrake 1967b) *S. almum* is of further value in combination with lucerne and Petrie green panic or buffel grass, and also with annual medics in the southern brigalow. This pasture phase has a longer life as *S. almum* is mainly replaced by the other grasses in four or five years. *S. almum* does not thrive in the Northern Territory where the need for a forage crop is supplied by bulrush millet (Norman and Begg 1968).

In comparative trials with a wide range of *S. almum* strains and other forage sorghums in south-east Queensland, Pritchard (1964) found that Crooble and the cultivar Krish selected from the cross *S. halepense* × *S. roxburghii* (Krishnaswamy, Raman, and Chandrasekharan 1956) have superior yielding ability and persistence. *S. almum*, a tetraploid (2n = 40), has well developed non-invasive rhizomes but Krish, a diploid (2n = 20), has almost no rhizomes. When cut about 15 cm from the ground, Krish produces little stem and a large bulk of palatable leaf. Without cutting or grazing it will develop solid pithy stems 3·5–4·0 cm thick and grow to 4·5 m at flowering. Panicles are similar to those of Crooble but larger with slightly drooping branches and the glumes enclosing the caryopses are straw coloured or tinged pink and there are about 73,000 seeds per lb (162,000 per kg).

The aim in breeding is to combine high yield and persistence, juicy stems, distinctive brown glumes, late flowering, and tolerance to leaf diseases. Pritchard (1965a) made crosses between *S. almum* and perennial sweet sudan grass (Hoveland 1960) and the juicy stem and brown glume and plant colour of the latter were linked and inherited mainly tetrasomically. Lines combining all the desired characters have been bred and these have a 20 per cent higher stem sugar content than Crooble (Pritchard 1965b) and have a higher feeding value as shown by increased animal intake.

Cenchrus ciliaris (*buffel grass*)

Buffel grass was accidentally introduced into Australia (Marriott 1955). The subsequent history of introduction and use of buffel grasses in Australia are outlined by Humphreys (1967b). Nine main cultivars are described by Barnard (1967): Biloela (from Tanzania), Molopo and Lawes (from South Africa), Boorara, Nunbank (from Uganda), Tarewinnabar and Gayndah (from Kenya), West Australian (accidental introduction), and American (from Georgia). All are strongly perennial.

Biloela (Grof 1957) is representative of the tall vigorous types growing to 1·5 m high, which include Boorara (Davidson 1966), Nunbank (Edye 1966), Tarewinnabar (Bisset 1963), Molopo (Flemons and Whalley 1958), and Lawes. Biloela, Boorara, and Nunbank are deeply rooting and rhizomatous with glaucous leaves, and Tarewinnabar is similar but has deep green leaves. Molopo and Lawes resemble Biloela but are much more rhizomatous and tend to be sparsely tillered. The inflorescence is a spike-like panicle about 7·0 cm long with immature spikelets often reddish in colour and the mature head is straw coloured.

Gayndah (Marriott and Anderssen 1953) and American (Wilson 1961) are non-rhizomatous and grow to 1·0 m high and tend to be prostrate. Compared with Biloela their leaves are green and smaller, their stems thinner, and tiller density is greater. American is a little earlier flowering than Gayndah and the heads are purplish. West Australian (Suijdendorp 1953) is non-rhizomatous and densely tillered, has fine green leaves, is very early flowering with purple heads, and grows only 46–76 cm high.

The buffel grasses have wide application in sub-coastal areas of northern Australia because of their marked drought resistance, adaptability to a wide range of soils, and persistence under heavy grazing. They grow in areas with annual rainfalls of 14–35 in. (355–889 mm) and the short early maturing cultivars are best suited to the more arid conditions. Seedling drought resistance of Biloela and Gayndah is superior to that of West Australian. Buffel grass grows best on neutral or moderately acid soils and responds to superphosphate (Edye *et al.* 1964). It is intolerant of waterlogging and the more rhizomatous cultivars like Molopo and Lawes are better adapted to heavy soils (Wilson 1961).

The lower growing non-rhizomatous cultivars like Gayndah and West Australian are more compatible with legumes than tall vigorous rhizomatous cultivars like Biloela which tend to suppress legumes, particularly on heavier soils.

Plate 67 Rhodes grass (*Chloris gayana*) (CSIRO photo)

On granitic soil at Brian Pastures, Shaw (1967a) obtained the best yields from Molopo and Tarewinnabar buffel combined with siratro which comprised over 40 per cent of the mixtures. At Westwood near Rockhampton, on shallow prairie-like soils, Hall (personal communication) has found that all the main buffel cultivars are compatible with siratro except Molopo which markedly depressed growth of the legume. In the Northern Territory at Katherine, birdwood grass (*C. setigerus*) is preferred to buffel as a companion for Townsville lucerne (Norman 1962).

Milford (1960) showed that the short West Australian buffel cultivar had a markedly higher intake than the tall-growing Biloela even though their dry matter digestibilities were similar. With regrowth 7–8 weeks old Minson and Milford (1968) found that feeding value of Molopo was less than that of kikuyu grass but not greatly different from that of Nandi setaria. In common with most tropical grasses the feeding value of buffel grass is relatively low at maturity and is reduced further if frosted. At present Molopo and Lawes are the only cultivars with a degree of cold tolerance.

Until the sexual buffel grass plant from Texas (Bashaw 1962) became available, breeding work with this species had not been possible. The aim of current work is to breed lines of higher feeding value and also with a degree of frost tolerance to increase adaptation of buffel grass south of the Tropic.

Chloris gayana (*Rhodes grass*) (Pl. 67)

Pioneer, the common Rhodes grass, was probably introduced from South Africa at the end of last century (Breakwell 1923). The cultivar Katambora is from Zambia (West 1952), Callide from Tanzania (Grof 1961), and Samford from Kenya (Hutton 1961). Pioneer is a tufted perennial with glabrous leaves and grows to 1·5 m high and spreads rapidly by stolons which root readily. The digitate panicle has 8–12 sessile spikes 6–10 cm long clustered at the apex. Spikelets have 3–5 florets with only the lowest fertile and are straw coloured at maturity. Seeds are small with 1·5–2 million per lb (3·4–4·4 million per kg). Katambora has thin stems, narrow leaves, and long thin stolons which develop strongly so that a dense stand is produced. Inflorescences have up to 20 spikes and it matures later than Pioneer. Callide is a 'giant' type and plant parts are coarser than those of the other cultivars. It has broad leaves, is strongly stoloniferous and late flowering, and usually grows taller than Pioneer. Samford has vigorous stoloniferous development and produces an abundance of leaf into autumn before flowering. Inflorescences have 10–20 spikes.

Rhodes grass is very adaptable and grows on a range of soils and where annual rainfall is 25–45 in. (635–1146 mm). It is used extensively in the brigalow and has high tolerance to salt (Teakle 1937). Rhodes grass is very responsive to high fertility (Henzell 1963), and will not persist on poor unfertilised soils. Pioneer is the only cultivar with some frost tolerance which is expressed particularly under fertile conditions. Rhodes grass has fair drought resistance but is inferior in this respect to buffel grass and Petrie green panic. It establishes readily from seed, covers an area quickly, and is persistent under grazing. Pioneer is compatible with a range of legumes including lucerne ('t Mannetje 1967a) but little is known of the compatibility of the other cultivars. A major disadvantage with Pioneer is the production of inflorescences throughout the season which lowers palatability and feeding value. Samford and Callide are late and leafy and very palatable. Milford (1960) showed that Pioneer has quite fair feeding value until it becomes stemmy and frosted. In a study of Pioneer, Samford, Callide, and three selected *C. gayana* introductions Milford and Minson (1968) found no real differences in their feeding value and concluded it would be difficult to improve this character in Rhodes grass.

Rhodes grass is mainly cross-pollinated (Bogdan 1961) so a large range of variation in different characters is available. All the cultivars have been selected from introduced ecotypes but breeding may be necessary to improve them.

Paspalum species

P. dilatatum var. dilatatum (common paspalum). Common paspalum, a native of South America, was introduced into Victoria by Baron von Mueller in 1881 (Davies 1951). It became naturalised in coastal areas of southern Queensland and northern New South Wales where it has played a most important part in dairying, especially when associated with white clover. Paspalum is also found in other parts of Australia where conditions are favourable. It is a tufted perennial with glabrous leaves and develops a crown with leafy shoots from a knotted base of very short rhizomes. Flowering stems grow to a height of 120 cm and have 3–10 compressed racemes 2·5–11·0 cm long with two dense paired rows of spikelets which produce hairy oval seeds. In the sub-tropics the florets are attacked by ergot which has an objectionable sticky phase before development of the sclerotia.

Common paspalum needs an annual rainfall in excess of 30–35 in. (762–889 mm) and is adapted to fertile alluvial soils and red loams. It is tolerant of waterlogging and fairly drought resistant and has a degree of frost tolerance. It does not combine well with legumes, except white clover, and is only eaten readily when pastures are kept short and flower heads suppressed. Work by Shaw *et al.* (1965) has shown that a number of species and varieties of Paspalum can give higher yields and better seasonal distribution of production than common paspalum under favourable conditions. Two promising recent introductions, *P. guenoarum* and *P. rojassi*, are frost-tolerant and yield better than common paspalum. Should it be desired to improve *P. dilatatum* and other paspalum species by breeding, it may be possible to bypass the apomictic barrier with the use of fertile species (Bashaw and Holt 1958, Pritchard 1962) and methods now available (Burton and Forbes 1960).

P. commersonii (cv. Paltridge). Paltridge scrobic is a cultivar of *P. commersonii* from Rhodesia and was developed as a result of work at Lawes in the Lockyer Valley of Queensland (Paltridge 1955). It is a loosely tufted short-lived perennial with glabrous light green leaves and succulent branched stems up to 90 cm high. The inflorescence has 3–4 characteristic paspalum racemes 4–9 cm long, each with two rows of spikelets on one side of the rachis. The light brown shiny seed consists of a hardened lemma and palea closely investing the caryopsis. There are 300,000 seeds per lb (666,000 per kg).

The cultivar Paltridge needs an annual rainfall of 30 in. (762 mm) or better and grows on a range of soils from fertile clay loams to the granitic types of the spear grass region. It is not particularly drought resistant and persists under waterlogged conditions. It is compatible with a number of legumes and grows well with Murray *P. lathyroides.* Milford (1960) showed that the cultivar Paltridge was readily eaten and highly digestible up to the flowering stage but had very low intakes after it was killed by frost.

P. plicatulum (cvs. Hartley and Rodd's Bay) Hartley from Brazil, and Rodd's Bay from Guatemala are the two *P. plicatulum* cultivars which have been developed (Bryan and Shaw 1964). Both are similar tufted perennials growing to a height of 120 cm. Hartley leaves are glabrous but Rodd's Bay leaves have a few coarse marginal hairs at the base of their upper surface. Young plants of Hartley form saucer-shaped tufts with broad dark green horizontal leaves having sinuous margins towards the base. A young stand of Rodd's Bay is a dense mass of narrow pale green erect leaves. Inflorescences have about ten characteristic paspalum racemes 2–6 cm long with two rows of paired spikelets. Seeds are dark brown and shiny with the caryopsis closely invested by the hardened lemma and palea. Hartley has about 430,000 seeds per lb (955,000 per kg) and Rodd's Bay 340,000 seeds per lb (755,000 per kg).

Hartley and Rodd's Bay need annual rainfalls of 30–35 in. (762–889 mm) or better and will grow and persist on poorer soils but respond to high levels of fertility and moisture (Shaw *et al.* 1965). They are compatible with a range of legumes and are frost susceptible. Milford (1960) found that Hartley had a higher feeding value than Rodd's Bay at every stage of growth. It is of interest that cattle produce golden-coloured dung while grazing these cultivars.

Pennisetum species

P. clandestinum (*kikuyu grass*). Kikuyu grass is native to tropical east Africa and was introduced into New South Wales in 1919 (Breakwell 1923). It is naturalised along the coast in New South Wales and southern Queensland and in favourable situations throughout Australia. It forms a dense prostrate mass of leaves and stems due to profuse branching, vigorous nodal rooting, and rhizomatous development. The bright green leaves are folded at first and then expanded. The greatly reduced inflorescence is almost enclosed in the leaves, and stigmas and stamens do not usually mature simultaneously. A fair quantity of seed is often produced but is difficult to harvest.

Kikuyu grass is usually established vegetatively and needs an annual rainfall of at least 35 in. (889 mm). It has a degree of cold tolerance and makes good autumn growth and some winter growth. It requires fertile conditions and is well adapted to the soil and climate which prevail on the basaltic tablelands in the coastal ranges of north-east Australia. Here white clover grows with it provided attention is given to nutrient requirements (White 1967). Kikuyu grass thrives on the basaltic soils of the north coast of New South Wales, and although it can be grown here with Clarence glycine and silverleaf desmodium, a better return is obtained from fertiliser nitrogen under these favourable conditions. The high feeding value of kikuyu grass and its resistance to heavy grazing make it valuable for use with a compatible legume or nitrogen fertiliser in the somewhat limited areas to which it is adapted.

P. purpureum (*elephant grass*). The elephant grass cultivar Capricorn was selected by Grof (1961) from open pollinated progenies of a Brazilian selection. It is a tufted perennial with broad light green leaves and short creeping rhizomes, and grows 1·8–2·4 cm high, so is smaller than common elephant grass. It flowers late, the inflorescence is a dense spike, and the seeds are smooth and yellow with about 1·4 million per lb (3·1 million per kg).

Capricorn is vegetatively propagated and is adapted to tropical coastal conditions with an annual rainfall up to 100 in. (2540 mm). It is fairly drought resistant, makes little winter growth, and is frost susceptible. Capricorn is a grazing type and in a moist summer stools vigorously and produces high yields of leaf and thick succulent stems.

Elephant grass is cross-pollinating and although seed set is poor, improvement can be effected by selection within the populations raised from seed. The sterile F1 between *P. typhoides* (2n = 14) and *P. purpureum* (2n = 28) is a vigorous and promising fodder plant and can be vegetatively propagated (Krishnaswamy and Raman 1953).

Melinis minutiflora (*molasses grass*)

Molasses grass is indigenous to tropical Africa and came to Australia early this century via Brazil. It is now naturalised in coastal areas of north Queensland. The grass is a spreading perennial with open tussocks to 1·0 m high and forms fairly dense stands. The leaves are soft and covered with short hairs which exude a sticky substance with a molasses-like odour. It flowers in late autumn to early winter and the distinctive reddish-purple inflorescence is a small plume-like panicle with short branches. Spikelets have fine awns up to 1·0 cm long. Seed is small and light with 6–7 million seeds per lb (13–15 million per kg).

Molasses grass needs an annual rainfall of 40 in. (1016 mm) or more and is sensitive to frost. The species is a good pioneer on a range of soils provided they are well drained. It provides cover on dry steep slopes and is compatible with a number of the perennial legumes. It needs to be well established before grazing and soon thins out with heavy stocking. The grass burns readily with a hot fire which can be an advantage in land development.

Brachiaria species

B. decumbens (*signal grass*). Signal grass is indigenous to Uganda and was introduced to north Queensland in 1936 and tested initially at the South Johnstone Research Station (Schofield 1944). It is a vigorous strongly stoloniferous perennial with bright green leaves about 18 cm long, and forms a dense sward 30–66 cm high under fertile conditions. The inflorescence is a lax panicle and has 2–6 short spike-like racemes in which 1–2 rows of relatively large hairy spikelets are crowded on one side of a broad flattened and winged rachis. Like the other Brachiaria species it is apomictic (Pritchard 1967) and fair quantities of seed are produced which need treatment with concentrated sulphuric acid for 15 minutes and storage for 10 months for a germination of more than 50 per cent to be obtained.

Signal grass is one of the most promising grasses on the wet tropical coast of north Queensland where the annual rainfall is 60 in. (1524 mm) or more. It grows on a range of soils but needs good drainage and fertile conditions for best results. With nitrogen fertiliser it outyields the other main tropical grasses including para, pangola, and hamil. Signal grass is palatable to cattle, withstands heavy grazing, and gives high weight gains per acre.

B. mutica (*para grass*). Para grass is indigenous to tropical Africa and was introduced to Queensland in the 1880s, and is now naturalised in swampy areas along the coast of tropical and sub-tropical Australia. It is a trailing perennial with coarse runners and erect shoots with broad, hairy leaves produced from the densely hairy nodes which root strongly. It flowers freely only in the tropics and the inflorescence is a panicle of 8–20 erect racemes in which several rows of glabrous spikelets are densely packed on a thin rachis. Seed production and viability are low so it is usually established vegetatively.

It requires an annual rainfall of 40 in. (1016 mm) or more and, although frosted in the subtropics, will persist there in favourable moist situations. Para grass thrives on most soils in warm moist conditions. It withstands prolonged waterlogging and is planted in swamps and along creek edges. In poorly drained areas it can be grown with Murray *P. lathyroides* and Schofield stylo and where drainage is better it combines well with centro. It is palatable and of high quality and can be stocked fairly heavily. In the tropics it provides valuable dry season feed.

B. ruziziensis (*cv. Kennedy*). Kennedy ruzi grass was introduced from Madagascar and probably came originally from Kenya. It is a tufted perennial growing to 1·5 m high and has greyish-green and very hairy leaves and stems. The inflorescence is a lax panicle with 3–9 relatively long racemes in which 1–2 rows of spikelets are crowded on one side of a broad, flattened, and winged rachis as in *B. decumbens*. It seeds freely and yields of 100 lb seed per acre (112 kg per ha) have been obtained. Initial seed germination is poor but is markedly improved by treatment with concentrated sulphuric acid for 15 minutes or storing for 12 months.

It requires an annual rainfall of 40 in. (1016 mm) or more and good drainage, and grows on a range of soils. It thrives in coastal areas of north Queensland but gives good growth south of the Tropic where frosts are light or absent. Kennedy ruzi grass establishes easily from seed and is vigorous on fertile soils or where adequate amounts of fertiliser are applied. More work is needed to determine its compatibility with legumes like centro. The stems do not become fibrous and it is eaten readily by stock and is proving to be a valuable grass for the more tropical areas.

PASTURES FOR DIFFERENT SITUATIONS

Pure Grass Pastures

Where animal production is based on grasses heavily fertilised with nitrogen, factors necessary for success include grasses which give a high yield of digestible nutrients, a favourable moist environment or cheap irrigation water, and adequate applications of superphosphate and potash.

TABLE 19 : 2 Examples of pasture mixtures for important areas in north-east Australia

Area	Annual rainfall	Seeding rates per ha
1. Wet coast north of the tropic	1270 mm or more	2 kg guinea grass, 3 kg centro, 1 kg stylo.
2. Red soils from basalt, acid volcanic rocks, and granite	1140 mm or more	2 kg Nandi or Kazungula setaria, 3 kg greenleaf desmodium. On basaltic soils 3 kg of one of the glycine cultivars can replace greenleaf desmodium.
3. Well-drained coastal soils of all types	889 mm or more	4 kg Peru leucaena in rows 2·5–3·0 m apart interplanted with pangola grass.
4. Native pastures of spear grass and other grasses	635–1524 mm	3 kg Townsville lucerne seeded into the native grass.
5. Granite soils of spear grass zone south of the tropic	711–1270 mm	3 kg siratro, 4 kg common lucerne (lime pelleted), and 3 kg Rhodes grass if rainfall 889 mm or more or 3 kg Biloela buffel or 3 kg green panic if rainfall less than 889 mm.
6. Brigalow south of the tropic	559–711 mm	4 kg *S. almum*, 2 kg green panic or 2 kg Biloela buffel (if area not to be cropped), 2 kg lucerne, 2 kg Cyprus or Jemalong barrel medic.

At present, the only suitable grasses are the vegetatively propagated pangola and kikuyu and the seeded signal grass (*B. decumbens*).

Pasture Mixtures

It is difficult to give precise information on seed mixtures for use in the various areas. Much depends on soil type, amount of soil preparation, weed competition, distribution of rainfall during establishment, and quality of the seeds. Tropical grasses establish more quickly and are more vigorous in the initial stages than legumes so pasture mixtures should be designed to reduce grass competition in the year of establishment. Examples of seed mixtures for a range of conditions are given in Table 19 : 2.

SEED PRODUCTION

Seed of the grasses is normally produced where each grass grows best. Legume seed yields are usually higher in frost-free areas as most legumes flower in autumn or early winter and seed during the dry season. As a result, much of the legume seed production has gravitated to northern Queensland and the Northern Territory, although that of some cultivars like Miles lotononis is firmly established in favourable coastal areas of southern Queensland. There is also a tendency for more grass seed to be produced north of the Tropic. A supply of cheap irrigation water assures high seed yields, particularly of legumes, and allows several seed crops of some legumes like siratro to be produced in the dry season. Seed certification schemes are being developed in Queensland and the Northern Territory to cope with the increasing number of new legume and grass cultivars.

Seed production problems in Australia with tropical legumes and grasses are discussed by Redrup (1966) and Strickland (1969). Row cropping of grasses is favoured as this allows weed control and applications of fertilisers containing nitrogen, phosphorus, and potassium which stimulate seed production. Correct use of nitrogenous fertilisers in particular ensures high seed yields of most grasses. Direct harvesting of grass seed with 'all crop' headers is common, but sheaving and stooking followed by threshing will increase yields of most except the paspalums. Drum speeds with the grasses need to be kept at a minimum. Seed is sometimes stripped from the grass heads with a comb fitted in front of a vehicle, the seed being collected in a bin behind the comb.

A number of techniques, some novel, have been developed for harvesting legume seed. Rolling crops of twining legumes just prior to flower initiation reduces the vegetative cover and gives even flowering with the pods well clear for heading. Judicious grazing serves the same purpose. With Townsville lucerne in which the pods drop, special suction harvesters are used to pick up the seed from the ground. More recently blower type harvesters have been developed for this crop. In most of the twining legumes the best results are achieved by mowing and windrowing and allowing the seed to mature in the swathe before picking up and threshing with a suitable 'all crop' harvester. With the desmodiums, greenleaf with its tougher stems has to be left to dry out longer in the swathe than silverleaf. Siratro and a number of the legumes are usually direct headed. Mechanical harvesting of most of the legumes markedly reduces the hard seed content of the seed.

20

TEMPERATE PASTURE SPECIES

C. M. DONALD

THE ROLE OF NATIVE AND INTRODUCED SPECIES AS SOWN PASTURE PLANTS

All the sown pasture plants of southern Australia have come from overseas. Since there are many thousands of native fodder plants, we may well ask why none has been developed for artificial seeding. Have we failed to examine our own plant resources, are we prejudiced towards plants from older agricultures, or are we in a transitional phase which will be followed by the use of native species?

All the evidence indicates that our native plants have neither actual nor potential value as artificially sown species. Though they may continue indefinitely to sustain our livestock in regions where artificial seeding is uneconomic, they will be progressively replaced in more favoured areas by plants from other parts of the world. This is because they suffer a serious disability—that they are incapable of high production, of response to high levels of fertility. They are adapted to the environment prevalent in Australia in the millenia before European settlement, to poor soils, to light grazing by nomadic, soft-footed marsupials and possibly also to drier climatic conditions than prevail today.

The weak response by our native herbage plants to improved nutrient status is illustrated in a study on the tablelands of New South Wales, where a comparison was made of the influence of phosphorus on native and introduced herbage legumes (Begg 1963). The four native legumes were of the genera Psoralea, Lespedeza, Glycine, and Desmodium, while the five introduced legumes were all Trifolium species. The response to phosphorus by the European clovers was 6-fold, while that by the native legumes was only 3-fold.

This adaptation of native species to the low nutrient status of our soils is not surprising, but on the other hand their use of water has unexpected features. A comparison was made near Uralla, New South Wales, of the rates of water use and growth by two communities of native grasses and by a pasture of introduced species, fertilised with superphosphate (Begg 1959). Table 20 : 1 shows the contrast in their growth rates, a compounding of the effects both of different species and the different fertility regime.

Figure 20 : 1 shows the status of soil moisture under these three pastures. The Danthonia community had no water available for growth at 3 in. (7·6 cm) depth on 59 days each year, but it

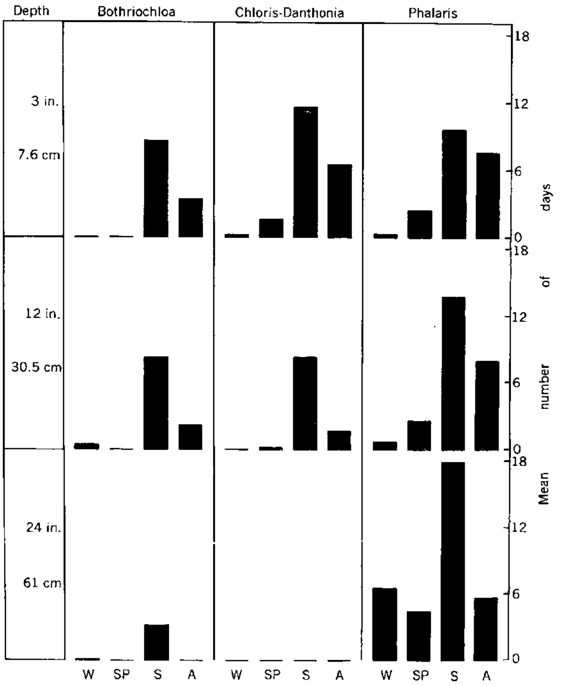


Fig. 20 : 1 A comparison of the soil water status of two native communities, *Bothriochloa macera* and Chloris-Danthonia, and a sown pasture of introduced species (phalaris-white clover-subterranean clover). At each of 3 depths, the chart shows the number of days in each of four 3-monthly periods on which there was no available soil water. Mean of 4 years (W = Winter: June, July, August; Sp = Spring; S = Summer; and A = Autumn). (From data by Begg 1959, Uralla, N.S.W.)

TABLE 20 : 1 A comparison of the growth rates of two communities of native grasses[a] and a pasture of introduced species at Uralla, N.S.W.; data for 2 years (Begg 1959)

Type of pasture	Minimum rate of growth		Maximum rate of growth		Mean rate for all months
	month	lb/acre/day (kg/ha/day)	month	lb/acre/day (kg/ha/day)	lb/acre/day (kg/ha/day)
Native:					
Bothriochloa macera syn. *B. ambigua*	June–Aug.	< 1 (< 1)	Dec.	19 (21)	7 (8)
Native:					
Chloris truncata and *Danthonia pilosa*	April–Aug.	< 1 (< 1)	Oct.	8 (9)	3 (3)
Introduced:					
Phalaris tuberosa, *Trifolium repens* and *T. subterraneum*	July	8 (9)	Oct.	57 (64)	27 (30)

[a] A third type, characterised by Sorghum-Themeda, was shown to occupy a substantially different site.

was never without water at 24 in. (61 cm). In contrast, while the phalaris-clover pasture was likewise without water at 3 in. for 59 days, it had also exhausted the water at 24 in. on 103 days.

This contrasting pattern of growth and water use was further demonstrated in a study at Canberra (Donald, unpublished) which compared a native Stipa-Danthonia community and a phalaris-clover pasture, both grazed by sheep. The maximum rate of dry matter production by the Stipa-Danthonia community was 30 lb/acre/day (33 kg/ha/day), while the maximum rate by the sown pasture was 122 lb/acre/day (137 kg/ha/day), each over a 3-week interval. Figure 20 : 2 shows the water use during a long dry period. In the previous 63 days from 17 October to 18 December, the Stipa-Danthonia community grew at an almost constant mean rate of 13 lb/acre/day (14·6 kg/ha/day), whereas the phalaris-clover pasture grew at a mean rate of 46 lb/acre/day (51·5 kg/ha/day). When dry weather was experienced, the sown pasture rapidly depleted the whole profile. In contrast, though the water beneath the native community fell sharply at 4 in., 12 in., and 20 in. (10, 30, and 51 cm), it declined only slowly at 36 in. (91 cm) and at 48 in. (122 cm) was never depleted.

The recharging of the soil profile beneath grassland before it has been depleted of water means that the grasses have not made full use of the water available to them. Whereas an 'empty profile' under a sown pasture will accept the maximum quantity of water when rains come, the still part-filled profile under native grasses will take less—the balance must enter drainage systems by surface runoff or deep percolation. Field observations support these results. Open farm dams fill less frequently when the watershed has been sown to introduced species.

One may speculate regarding the incomplete use of water by our native grasslands. Two interrelated explanations suggest themselves. First, it is clear that the slow use of water ensures vegetative survival by native perennial species, even through droughts of extremely long duration, such as might occur once in a century. However, this scarcely accords with the usual relationship of plants to their environment. Secondly, it may be that these native grasses are adapted not to current climatic conditions but to an earlier drier period.

Whatever the evolutionary reasons for this slow growth of our native species and their weak response to fertiliser, there seems to be no prospective role for these plants in the changed environment in which sown pastures are now established. The main components of this change since European settlement are the improvement in the soil fertility, especially the phosphorus and nitrogen levels, and the use of hoofed animals on a year-round basis at relatively heavy stocking rates. We may expect that throughout 'the better rainfall areas' of southern Australia, extending inland to the drier limit of

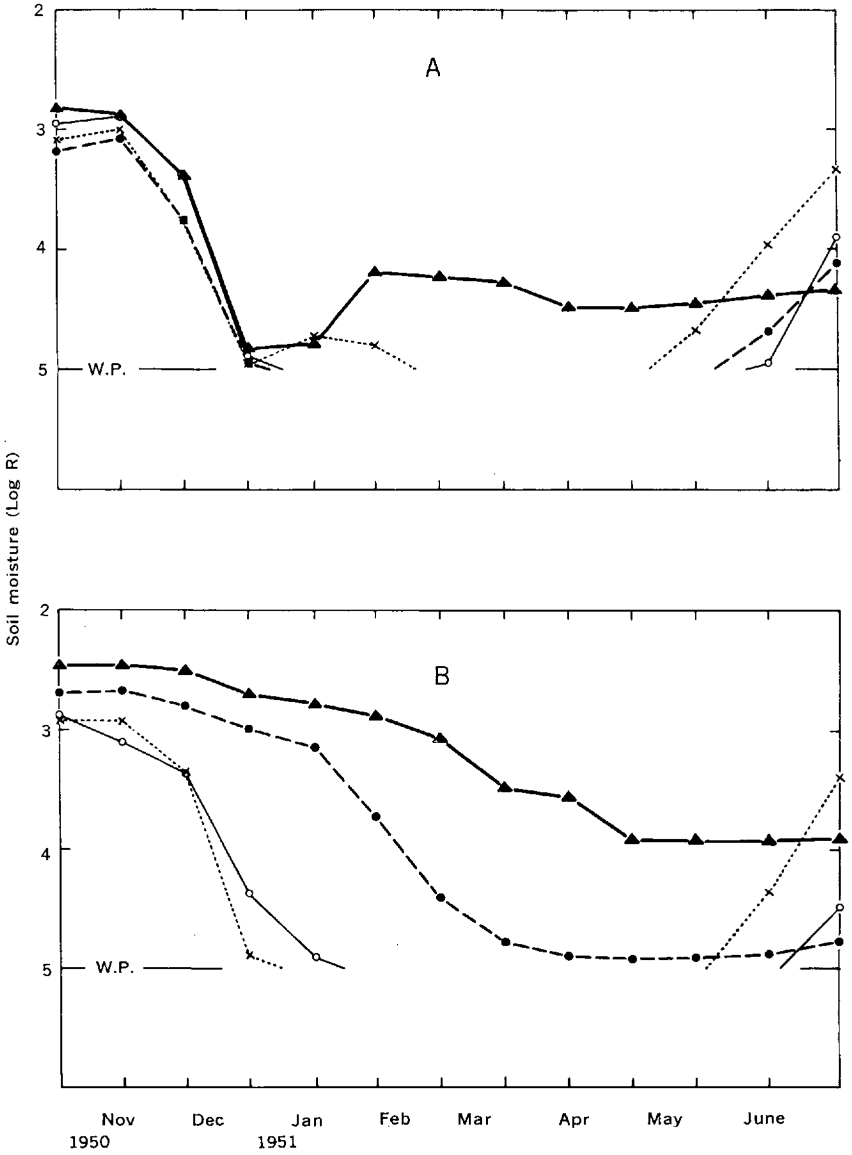


Fig. 20 : 2 Use of water by (A) sown pasture (phalaris–subterranean clover) and (B) by a native Stipa-Danthonia grazing land during a long dry period at Canberra. The scale on the left is the logarithm of the resistance in ohms of plaster blocks buried at the depths indicated; the curves so derived indicate the level of soil moisture. (A resistance exceeding 100,000 ohms was accepted as indicating no available water, i.e. wilting point.) (From Donald, unpublished)
Depths 10 cm × 51 cm ○ 91 cm ● 122 cm ▲

cereal cultivation, native species will eventually yield to pasture plants from other parts of the world in all but rough, steep, or forested country.

THE INVASION BY EXOTIC SPECIES

It is likely that accidental introductions of pasture seeds occurred with every ship bringing settlers or livestock to Australia in the early years of colonisation, and that many temperate species became established in the earliest years of settlement. Partly through natural spread and partly assisted by man, such species as perennial ryegrass (*Lolium perenne*), cocksfoot (*Dactylis glomerata*), and white clover (*Trifolium repens*) have become common in favourable habitats in the south-east of the continent, a region with relatively mild summers and an appreciable summer component in the winter-dominant rainfall. But this ingress of temperate European species was of insignificant proportions compared to the massive invasion of southern Australia by the annual grasses, legumes and forbs of the Mediterranean region. These plants were subject to multiple accidental introduction. Though undisturbed native grasslands showed some capacity to resist invasion by these aggressive annuals, the delicate equilibrium between the vegetation and its sparse population of marsupials was all too readily upset. The plough almost totally destroyed the ground flora of many communities in a single stroke. The native perennial grasses, usually with weak seed production, uncertain germination, and slow growing seedlings, have little capacity as pioneer plants on land lying bare after crops. On the other hand the free-seeding, fast-growing annuals of the Mediterranean basin have strong capacity to establish and multiply on any climatically suitable open site. The most successful invaders have been the sharp-seeded annual grasses of the genera Hordeum, Bromus, Vulpia and Avena, with Lophochloa, Briza, Monerma, Parapholis and other genera as lesser associates.

These annuals have not only established on cultivated land; when native grasslands were overgrazed, many of the perennial grasses, unadapted to close or regular defoliation or to treading by sheep or cattle, became so weakened as to permit the ingress of invaders. This replacement of the native perennial grasses by Mediterranean annuals without the incidence of cultivation occurred most readily in the marked Mediterranean-type climate of the south-west of Western Australia and the south of South Australia, less readily in the tableland areas and the zones of more even distribution of annual rainfall in Victoria and New South Wales (see Chapters 12, 14, and 15).

The Mediterranean invaders were not only grasses. Many species and biotypes of Trifolium and Medicago have become widespread and sometimes abundant without direct aid by man (Map 5). *T. glomeratum* (cluster clover) and *M. polymorpha* (burr medic) have perhaps been the most successful of these naturally established legumes. Yet neither has become a 'sown species', cluster clover because of its limited productivity, and burr medic because of the recurved hooks on its pods, which lead to serious contamination of wool.

Black's *Flora of South Australia* (1943–57) usefully indicates the composition of the invaders from the Mediterranean basin. It lists no less than 122 annual herbage species from the Mediterranean basin (Table 20 : 2). In contrast to this array of annual plants, only one perennial grass has come from the Mediterranean as an accidental introduction; *Oryzopsis miliacea* has long been common in ungrazed places, just as it is typical of the surrounds of ancient monuments in southern Europe.

TABLE 20 : 2 Numbers of annual herbage plants of Mediterranean origin naturalised[a] in South Australia

Grasses			Legumes		
Bromus spp.	5		*Trifolium* spp.	21	
Hordeum spp.	3		*Medicago* spp.	8	
Vulpia spp.	5		Other legumes	*6*	
Lolium spp.	2		Annual legumes:		*35*
Other grasses	*27*		Other species		
			Erodium, Echium,		
Annual grasses:		*42*	Geranium, etc:		*50*
All Mediterranean annuals 127					

[a] Based on Black's *Flora of South Australia;* data by D. E. Symon.

The ingress of annual herbage plants from the Mediterranean basin to Australia shows some seemingly quixotic features. Why was *Trifolium subterraneum* subject to multiple accidental introduction and establishment, while *T. cherleri*, comparably widespread in the Mediterranean basin, was not? Why were the annual Bromus and Hordeum species introduced and widely established, but not the annual, sharp-seeded Aegilops species—nor the annual *Stipa tortilis* of Morocco? Chance? Perhaps, but possibly there have also been ecological or historical factors, as yet unknown to us.

Only the Mediterranean basin itself has developed this ecologically powerful group of annual herbage plants. Though some annuals are found in the flora of other 'Mediterranean' regions, only the annuals of the Mediterranean basin itself have colonised successfully in other parts of the world. None of the herbaceous flora of southern Australia has become naturalised in the Mediterranean basin, nor the flora of Pacific coastal U.S.A. in Australia or Central Chile. *Danthonia pilosa*, an Australian perennial grass once sparsely used as a sown species, is perhaps the single Australian pasture plant established overseas; it is weakly naturalised in California.

The only other 'Mediterranean' region which has contributed importantly to our introduced pasture flora is South Africa, where all shipping called before the construction of the Suez Canal; these invaders are mainly perennials. Unfortunately a majority of them are weedy plants, some of minor importance, others such as Cape tulip (*Homeria* spp.), South African daisy (*Senecio pterophorus*), and soursob (*Oxalis pes-caprae*) of serious pest status (see Chapter 23). The Iridaceae (20 species) and Liliaceae (5 species) are heavily represented. We have but a single useful perennial grass from South Africa, *Ehrharta calycina*; an annual of the same genus and origin, *E. longiflora*, is common in waste places or as a garden weed.

A very widespread plant from South Africa is *Arctotheca calendula*, an annual composite known as 'capeweed'. It is characteristic of an improved soil nitrogen status and dominates extensive areas of pastures in all southern States. Despite its earlier reputation, capeweed does not seem to be appreciably inferior to other annual non-legumes in its capacity to produce wool or meat. So far Australia has undertaken no systematic exploration of the Mediterranean tip of South Africa, and it is possible that useful sown plants may be available from that region.

One other region has given southern Australia important grasses by invasion—warm temperate South America. These are mainly summer-growing grasses of the genera Paspalum, Axonopus, and Stenotaphrum, in particular *Paspalum dilatatum*, which became established on the coast of New South Wales during the latter part of the nineteenth century. It displaced the native grass flora over considerable coastal areas and was a major factor in the development of the dairy industry in that region. Yet, in the past few decades, kikuyu grass (*Pennisetum clandestinum*), introduced from central Africa in 1919, has in turn invaded and displaced paspalum in many localities. *Bromus unioloides* syn. *Ceratochloa unioloides*, the only important winter-growing grass of the pampas of Argentina, has also become naturally established in more fertile or lightly grazed places, but has never achieved importance as a sown species.

These then are the regions from which the 'invasion' of southern Australia by pasture plants has occurred—the Mediterranean basin, northern Europe, the Mediterranean tip of South Africa, and the pampas of Argentina. Even without artificial seeding or fertilisers, these species have proved successful competitors against our native flora under the influence of cultivation and domestic livestock.

THE MIGRATION OF SUBTERRANEAN CLOVER TO AUSTRALIA

Much more is known of the migration of subterranean clover to Australia than of any other annual pasture plant. Its natural habitat is the Mediterranean basin, and the Atlantic regions of Morocco, Iberia, France and the southern British Isles (Morley and Katznelson 1965). Here it is a common but rarely abundant species.

In Australia subterranean clover has become widely naturalised across the south of the continent, quite apart from artificially established stands; 39 biotypes (usually known in Australia as 'strains' or 'lines') were collected in Victoria in 1928–9 (Aitken and Drake 1941), and 86 have been collected in Western Australia, 72 of them by Gladstones (1966). Smaller numbers have been found in other southern States.

A positive relationship has been found between the flowering times of these naturalised lines and the rainfall at the sites of collection in Australia. But this relationship is very imperfect (e.g. $r = +0{\cdot}66$: Donald and Neal-Smith 1937). Those lines found in drier areas must necessarily be early flowering in order to have survived. On the other hand, the flowering times of lines collected in regions of moderate or long rainfall season have proved to be rather weakly related to the environment, because many of them mature before the end of the growing season. Thus strains found in Western Australia where the growing season is short are of early to early mid-season maturity (Gladstones 1966) while those found in the wetter parts of Victoria (greater than 9 months effective rainfall) have a range from early to very late (Aitken and Drake

1941). For this reason, and also because of the wide and parallel subspeciation patterns in the Mediterranean basin and in Australia (Morley, Brock, and Davern 1956), all workers are agreed that there have been numerous independent introductions of biotypes and that except rarely the biotypes collected in Australia have not evolved locally (Donald and Neal-Smith 1937; Aitken and Drake 1941; Frankel 1954; Gladstones 1966). The many lines collected in Australia are believed to have come as assisted migrants in fodder, bedding, clothing, and packing from the Mediterranean. All regions of southern Australia have presumably received a great array of introductions, but since those lines that came to rest in environments inadequate for their needs have disappeared, those lines fitted to their new environments and those with 'lesser needs' all seem so far to have survived. Hence the imperfection of the relationship of genotype to environment in southern Australia.

In assessing this situation it is important, however, to appreciate that there is no perfect relationship of climate to maturity type within the Mediterranean basin itself. During the 1951 collecting trip, multiple collections were commonly made; for example, seed was collected from the soil surface and sub-surface at five points spaced at about 10 metre intervals along the contour of a hillside near Izmir, Turkey. This gave lines with a range of 34 days in date of flowering compared with 85 days for the whole Mediterranean collection of 1951. There is no reason to anticipate any closer 'fit' in Australia; presumably a degree of heterogeneity within the population in date of seed maturation may itself be an adaptation to fluctuation of the climate from season to season (Morley 1960).

Natural crossing and mutation since introduction are considered to have made only a slight contribution to variation; probable instances are quoted by Morley (1960) and by Gladstones (1966) as indicated by hybrid swarms or intermediate types, or by the incidence of biotypes differing in only one or a few characters from a nearby putative parent. Gladstones suggests that some of the new forms have better adaptation than their parents, and that they may demonstrate weak natural evolution in Australia.

It is of interest that of 199 biotypes of subterranean clover collected in the Mediterranean basin in 1951, none was identical with any of the 60 strains previously collected within Australia. The same was true in a comparison by Gladstones of his 72 Western Australian collections with 50 lines of Mediterranean origin. It is clear both from these data and from collecting experience that there is a vast number of distinct biotypes in the Mediterranean basin so that the chance that a deliberate introduction will be identical with an earlier accidental introduction is small indeed.

There is some conflict of views regarding the probable date and sources of introduction of all these biotypes. Morley and Katznelson (1965) consider that because of the large number of very early flowering strains, ships en route to Australia since 1869 by the Suez Canal must have picked up seed in hay, bedding or other materials in such Mediterranean ports as Lisbon, Gibraltar, Naples, Malta, and Piraeus. On the other hand Gladstones (1966) develops historical and distributional evidence to indicate that there were two active periods of importation of subterranean clover to Western Australia—the first in 1829 to 1842, and the second during the 1860s. Since the Suez Canal was not opened until 1869, he considers that the strains in Western Australia are predominantly from England, Portugal, Madeira, and the Canary Islands, all points of call on the voyage to Australia around the Cape of Good Hope. Gladstones further deftly interprets the distribution of the strains in Western Australia as indicating that they were carried inland from Perth along the stock routes in imported hay or similar materials, with secondary distribution as undigested seed in faeces or as contaminants in wool.

THE SOWN SPECIES OF SOUTHERN AUSTRALIA

The sowing of white clover was recorded in Tasmania by 1820, within seventeen years of settlement of that colony. The sowing of the 'traditional' pasture plants of the United Kingdom doubtless continued on a small scale throughout the nineteenth century, but as in Europe itself, sown pastures were of little significance relative to crop production during this period. Not only was there little knowledge of the value of pastures or of the techniques involved, but the well nigh ubiquitous phosphorus deficiency in Australia prevented the effective use of sown pasture plants.

The northern European species, particularly perennial ryegrass, cocksfoot, and white clover, are now of major importance as sown species in areas of longer rainfall season and cooler summer in the south-east of the continent. Their use under irrigation (see Fig. 18 : 3) extends considerably beyond the boundary shown for northern European perennials in Map 5. However, these inland centres have high summer temperatures, and on the irrigation areas of western New South Wales, for example, perennial ryegrass grows poorly during the hottest summer months.

New Zealand is the principal source of seed of the northern European cultivars of these species but there is a growing use of Australian-derived ecotypes, with a somewhat greater capacity for summer drought survival (e.g. the western Victorian cultivars of perennial ryegrass). More recently the introduction of ryegrass and cocksfoot from the Mediterranean basin (e.g. Currie cocksfoot) or the breeding of cultivars from such introductions (e.g. Berber cocksfoot and Medea perennial ryegrass) have given prospects for the use of these traditional species beyond the limit for northern European cultivars, particularly because of satisfactory summer survival.

The great expansion of sown pastures in southern Australia had its beginnings in 1889, when Amos Howard, a nurseryman in the Adelaide Hills, initiated the sowing of Mediterranean pasture plants; in a field near Mt Barker he noticed a strange clover, which he acclaimed and publicised for forty years. This was subterranean clover (*Trifolium subterraneum*), which was to become the key to pasture establishment and soil improvement over millions of acres. Though Howard made his first commercial sale of seed in 1907, there was little progress in the use of subterranean clover until the 1920s when the need to use superphosphate as a pasture fertiliser was recognised (the use of phosphate until then was confined to crops) and when departments of agriculture began their sponsorship of this species.

Subterranean clover may have been sown on as much as 80 per cent of the present estimated area of some 50 million acres (20 million ha) of sown pastures in southern Australia. It has been 'oversown' or 'scratched' into native grasslands; it has been established on prepared seed beds; it has been surface broadcast, and drilled with ground implements and sown from the air. Despite limitations due to soil type, subterranean clover has been used successfully within diverse vegetation formations, in land cleared from heath, temperate woodland, and dry and wet sclerophyll forest. This has been due not only to the partial elimination of nutrient deficiencies of both major and trace elements, but also to the development of a wide range of cultivars of differing environmental adaptation. Above all it has given an input of nitrogen into soils extremely deficient in this nutrient. Yet despite its great value as a pasture plant, subterranean clover may show toxic properties, leading to serious reproductive disorders, and in particular to low lambing rates. The constitution of these oestrogenic substances is being progressively resolved; meanwhile the commercial strains of subterranean clover have been characterised for their degree of potency, and in regions susceptible to clover dominance, strains of low potency are preferentially sown (see Chapter 26).

The use of subterranean clover as a pasture legume has been followed by the development of a number of other Mediterranean species as cultivars. Among the legumes are *Medicago truncatula* (barrel medic), *M. littoralis* (strand medic), *M. scutellata* (snail medic), *M. rugosa* (gama medic), *Trifolium cherleri* (cupped clover), *T. hirtum* (rose clover, previously developed in California), and *Ornithopus compressus* (yellow flowered serradella). This group of Mediterranean annuals provides a suitable legume for a considerable range of rainfall and soil types; subterranean clover is mainly used on acid soils, while the species of Medicago are successful on soils of high pH. In addition, the perennial *T. fragiferum*, more particularly an ecotype collected in Israel (cv. Palestine), has proved of outstanding value on nearly a million acres (400,000 ha) of winter-flooded rendzina soils in the south-east of South Australia.

As well as the temperate and Mediterranean legumes, lucerne (*Medicago sativa*) has long been used in Australia both for cut fodder and for grazing. Its distribution in relation to climate has not been adequately studied, but it has proved remarkably successful under grazing in diverse climatic and soil environments, from southern Queensland around the south-east of the continent to Adelaide, though it is unsuccessful under the extreme summer drought conditions of the south-west of Western Australia. The principal cultivar, Hunter River, is of Provence type and without winter dormancy; like most lucerne cultivars in the world, it will not withstand continuous grazing and must be stocked intermittently (see Chapter 27).

Fewer sown grasses are available. Following the long use of northern European grasses in more favoured areas, the development of grasses of Mediterranean origin began in Victoria in 1919 with the recognition of annual ryegrass (*Lolium rigidum*) as a valuable sown species. It is the most widely sown grass in southern Australia, though it is a serious weed of cereal crops in some districts. A further important step was the development as a sown species of the perennial grass, *Phalaris tuberosa*, a Mediterranean species which survives summer drought by dormancy. Though it has some toxic properties (see Chapter 26), it continues in use as the principal sown perennial grass in areas too dry for perennial ryegrass. This short list of sown grasses in southern Australia concludes with perennial veldt grass (*Ehrharta calycina*), its use largely confined to deep sands in South Australia on 15–18 in. rainfall (381–457 mm). The newly developed cultivars of cocksfoot and perennial ryegrass may become useful additions to this list of perennial 'Mediterranean' grasses.

While the role and use of pasture legumes in southern Australia is reasonably well defined or at least sufficiently envisaged, the same is not true of associate grasses. There is inadequate information on the differences, if any, in the capacity for livestock production of pastures composed of legumes with perennial grass, legumes with sown annual grasses, or even legumes with such 'weedy' grasses as Bromus or Hordeum species; this point is further discussed in a later section.

THE DEVELOPMENT OF CULTIVARS

Until 1950, the pasture plant cultivars used in southern Australia had been derived principally in two ways. For the temperate species we depended on cultivars developed overseas (most seed too was imported), while in the case of the Mediterranean species our cultivars were developed by direct multiplication of locally occurring material—that is to say, accidental introductions of unknown history.

The classic example of this latter practice is provided by the cultivars of *Trifolium subterraneum*. No fewer than eleven 'naturally occurring' biotypes of this species are currently in use as cultivars, and it is of interest to consider the reasons for which each of these was commercialised (Table 20 : 3). In the earlier years there was emphasis on fitting biotypes to climates, more particularly the length of the rainfall season, so that the first four cultivars differed widely in maturity (Dwalganup, Bacchus Marsh, Mt Barker, and Tallarook, in order of maturity). Subsequently agronomic characteristics became the basis of commercialisation (e.g. tolerance of flooding in Yarloop, competitive ability in Clare, and rapid seed maturation in Geraldton), while in a third phase low oestrogenicity especially combined with the ability to displace high oestrogen cultivars has become a principal criterion (Daliak, Seaton Park). Of the scores of other genotypes of subterranean clover found in Australia, most have simply been held in collections; in some instances over thirty years have elapsed before the characteristics of a line have appeared to warrant its commercialisation. Other Mediterranean species in which biotypes found in Australia have been directly multiplied as cultivars, mainly to meet local climatic needs, include *Lolium rigidum* (cv. Wimmera), *Trifolium fragiferum* (cv. Shearman's and O'Connor's), and *Medicago truncatula* (cv. Hannaford and Jemalong).

Because of this almost total dependence to 1950 on imported cultivars or on locally occurring biotypes it is not surprising that there was criticism of the effectiveness both of plant introduction services and of the few pasture plant breeding programs. It was fairly asked 'What have these activities contributed to our array of sown plants?' In retrospect, we can perhaps offer a reply. As pasture improvement gained impetus in southern Australia, we had a vast terrain in which we sought to fit species to environments. It was commonly a crude matching of plants to places, without need for refinement. For example, a strain of *Medicago truncatula* found occurring south of Adelaide and commercialised in 1938 (cv. Hannaford), filled a need for a ley species in a large part of the South Australian wheat belt. It was another seventeen years before a second biotype found in Australia (cv. Jemalong) was commercialised, and twenty-

TABLE 20 : 3 The cultivars of subterranean clover in commercial use in 1969

Cultivar	Locality, and date first named	Date commercialised or registered	Maturity	Seed production—mean of 1966–7 and 1967–8 (tons)	Reasons for commercialisation[a]
Mt Barker	Mt Barker, S.A. 1889	1906	Mid-season	1127	New species, fitted to Mediterranean-type environment.
Dwalganup	Boyup Brook, W.A. 1900	1929	Very early	394	Very early flowering. Successful in lower rainfall areas.
Tallarook	Tallarook, Vic. 1928	1935	Late	17	Dense, leafy; good late spring growth in late districts.
Bacchus Marsh	Myrniong, Vic. Early 1930s	1937	Early mid-season	144	Suitable for areas marginally dry for Mt Barker.
Yarloop	Yarloop, W.A. 1937	1939	Early	444	Good winter growth on waterlogged soils.
Clare	Clare, S.A. 1941	1950	Early mid-season	62	Good early winter growth. Ability to compete with weeds (long petioles).
Geraldton	Moonyoonka, W.A. 1950	1958	Very early	2103	Matures seed rapidly. Successful in very dry spring conditions.
Woogenellup	Manjimup, W.A. 1951	1958	Early mid-season	2013	Highly competitive against Mt Barker. Much better persistence than Bacchus Marsh.
Dinninup	Boyup Brook, W.A. 1957	1961	Early	83	Replacement for Yarloop (highly oestrogenic). Used where season too short for Woogenellup. Well adapted gravelly and sandy soils.
Daliak	York, W.A. 1929	1967	Early	61	Low oestrogenicity. Will replace Dwalganup (highly oestrogenic) under heavy grazing.
Seaton Park	Adelaide, S.A. 1932	1967	Early	52	Low oestrogenicity. Good competitor. Will replace Yarloop (highly oestrogenic).
Howard	Bred, CSIRO Canberra	1964	Early mid-season	86	Resistant to clover stunt virus.
Uniwager	Bred, Univ. of W.A.	1966	Early	13	Very low oestrogenic activity.

[a] The characteristics listed in this column do not include those which have become known subsequently to commercialisation, e.g. a degree of tolerence of high pH by cv. Clare, or the medium to low oestrogenicity of cv. Woogenellup.

one years before a biotype collected overseas (cv. Cyprus, from that island) extended the usefulness of the species into lower rainfall parts of the Western Australian wheat belt. Breeding of this annual medic and related species is now in progress.

In southern Australia we are moving out of the phase in which major gaps in our requirements, whether for climatic or soils needs or for technical reasons, can be met by the direct use of 'new' species or naturalised biotypes of a 'recognised' species. The days of dramatic 'new species' may be almost over for southern Australia, as they have long been in northern Europe. The emphasis since 1950 has therefore moved towards the greater use of biotypes systematically collected during visits overseas, and towards the breeding of cultivars for particular regions or purposes (Table 20 : 4).

EXPLORATION FOR PASTURE PLANTS FOR SOUTHERN AUSTRALIA

Many individuals and agencies, especially the State Departments of Agriculture, have long been concerned with the introduction of pasture plants to Australia. These efforts were systematised and consolidated when the Common-

TABLE 20 : 4 The origin of Australian cultivars in use in 1967[a]

Group of plants	Introduced to Australia as a recognised cultivar	Developed as a cultivar in Australia		
		From biotypes found in Australia	From biotypes introduced in seed exchange programs	From biotypes collected on expeditions from Australia
Temperate plants	17	7	1	0
Mediterranean plants	0	22	10	8
Lucerne	2	1	1	0
Tropical plants	4	2	28	2
Total	23	32	40	10
Mode of development	Natural biotypes 7 Bred cultivars 16 (all before 1960)	Natural biotypes 70 Bred cultivars 12 (11 since 1960)		

[a] Based on cultivars listed by Barnard (1967 and Supp. 1968). The tropical plants are not used in southern Australia but are included for comparison.

wealth established a plant introduction service in 1929. At first all introductions were made through correspondence with workers in other countries, but after two decades it became clear that in partial contrast to crop plants, the effective introduction of pasture plants depended on the collection of material *in situ* by workers familiar with Australian needs.

For example, the introduction of pasture plants from the Mediterranean region was seriously hampered by the lack of communion between Australian and Mediterranean workers. The Mediterranean fodder agronomist directed his thoughts towards crops to be harvested by cutting or as grain within a village agriculture. The plants of the village common or the hillside—the plants potentially of greatest value on the Australian scene—were usually of no interest to him: they were 'wild' clovers or grasses. It was not until Australia sent agronomists to collect plants showing survival and production under grazing that the introduction of pasture biotypes from the Mediterranean region became more purposeful.

The first collecting trip was made in 1951, when all countries of the Mediterranean basin were visited; on this occasion the collection of herbage plants was unrestricted, excluding only patently weedy plants. The 1254 individual collections included 410 grasses of 130 species, about equally of perennials and annuals, and 770 legumes of 200 species, of which 80 per cent were annuals. Subsequent collecting visits to the Mediterranean region were made in 1954, 1956 and 1967, but these later visits were aimed at particular groups such as Dactylis, Phalaris, and Lolium in 1954, or the annual medics in 1967. The extent to which these collecting trips extended our plant resources is partly illustrated for the 1951 expedition in Fig. 20 : 3. Though these data relate only to time of flowering, they show the great contribution through collection in some species, the smaller contribution in others.

Trifolium subterraneum	
MEDITERRANEAN	85 DAYS
AUSTRALIAN	68 DAYS
Medicago truncatula	
MEDITERRANEAN	53 DAYS
AUSTRALIAN	28 DAYS
Trifolium cherleri	
MEDITERRANEAN	
AUSTRALIAN	NIL
Dactylis glomerata	
MEDITERRANEAN	64 DAYS
VICTORIAN COMMON	26 DAYS
Phalaris tuberosa	
MEDITERRANEAN	33 DAYS
AUSTRALIAN	6 DAYS
Hordeum bulbosum	
MEDITERRANEAN	44 DAYS
AUSTRALIAN	NIL

Fig. 20 : 3 Comparison of maturity range of Mediterranean and Australian material of several species

In the course of these visits we gained partial understanding of the distribution of plant material in the Mediterranean basin in relation to

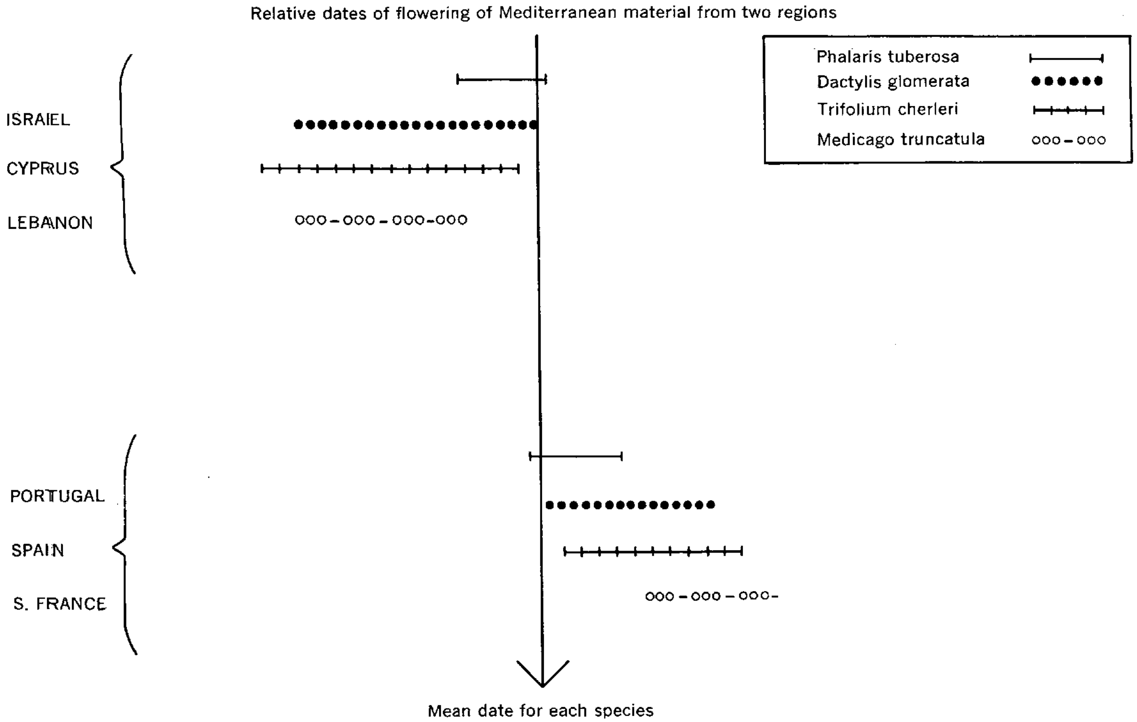


Fig. 20 : 4 Comparison of the time of flowering of the biotypes collected in two parts of the Mediterranean basin Early ↔ Late

TABLE 20 : 5 Cultivars developed in Australia from material collected in the Mediterranean basin in 1951 (C. M. Donald and J. F. Miles) and in 1954 (C. A. Neal-Smith)

Cultivar	Habit	Collected	Commercialised
A. *Direct use of collected biotypes*			
Cyprus barrel medic (*Medicago truncatula*)	Annual	Cyprus 1951	W.A. 1959
Beenong cupped clover (*Trifolium cherleri*)	Annual	Cyprus 1951	W.A. 1963
Yamina cupped clover (*Trifolium cherleri*)	Annual	Israel 1951	W.A. 1963
Olympus rose clover (*Trifolium hirtum*)	Annual	Cyprus 1951	W.A. 1966
Woolly podded vetch (*Vicia dasycarpa*)	Annual	Turkey 1951	N.S.W. 1968
Menemen puccinellia (*Puccinellia* sp.)	Perennial	Turkey 1951	W.A. 1964

Cultivar	Habit	Collected	Bred at	Registered
B. *Cultivars bred from collected biotypes*				
Berber cocksfoot (*Dactylis glomerata*)	Perennial	Morocco (3 lines) 1954	Waite Inst.	S.A. 1967
Medea perennial ryegrass (*Lolium perenne*)	Perennial	Algeria (3 lines) 1954	Waite Inst.	S.A. 1967
Sirocco phalaris (*Phalaris tuberosa*)	Perennial	Morocco 1954	CSIRO	N.S.W. 1967
Cyfield barrel medic (*Medicago truncatula*)	Annual	Cyprus 1951 (recurrent parent)	Univ. of W.A.	W.A 1969

Australian needs. For example, Fig. 20 : 4 shows the composition in terms of maturity of several species of the 1951 collection in relation to the region of collection. It will be seen that most of the material collected in the eastern Mediterranean was of early flowering biotypes, with later material from the wetter and/or colder environments of the west.

The subsequent development of commercial cultivars from the 1951 and 1954 collecting trips (Table 20 : 5) shows a clear pattern. Five annuals have been used directly; they all are legumes from the eastern Mediterranean, and all but one were developed in south-west Western Australia, where almost complete dependence is placed on annual pasture plants. One perennial, the very salt tolerant Puccinellia, has also been used directly. The principal use of the perennial material introduced from the Mediterranean basin has, however, been within breeding programs. Berber cocksfoot and Medea ryegrass have been bred with summer survival, autumn recovery, and winter production as the important attributes, so that they have a potential role on the drier margin of the northern European perennials. Sirocco phalaris is more productive and persistent in areas where rainfall is suboptimal for the standard cultivar, and thus will lie on the dry margin for Mediterranean perennials.

When we consider the number of plant introductions made to Australia during these visits to the Mediterranean basin, the list of new cultivars is disappointingly small. Undoubtedly these few will handsomely repay the cost of the collecting trips, but we might perhaps have hoped to use some of the introductions of subterranean clover or of 'new' grass species, as well as the special purpose Puccinellia. Perhaps we are not so open-minded about the acceptance of further 'new species' as we believe ourselves to be; certainly the rate of introduction of Mediterranean material to Australia has tended to outstrip its proper examination and assessment.

A second feature of our plant exploration programs has been the long time lag between the introduction of the new material and its use on a commercial scale, whether directly or as a component of bred material. For the three perennial grasses derived by breeding programs there was a lapse of thirteen years, and even for biotypes brought into direct use the time lag was little less, eight to fifteen years (Table 20 : 5). It can be argued that the dissemination of more material to farmers, without such prolonged testing, leaving it to stand or fall in farm use, would be at least as efficient and certainly a good deal quicker.

Australia now holds a considerable array of the pasture flora of the Mediterranean basin both at the specific and ecotypic level. Future collecting visits to the Mediterranean basin are likely to be undertaken only for defined purposes of predictable value, such as the collection of perennial Medicago species with winter-active growth or creeping habit, or of material at the boundaries of the Mediterranean distribution of individual species. In particular we are likely to seek material for breeding rather than for direct use.

THE BREEDING OF PASTURE PLANTS

Interest in the breeding of pasture plants began in southern Australia in the 1930s. It is now clear that the programs of those years were commonly defective in two major ways—first, they lacked objectives, other than vaguely to produce bigger and better plants, and second, they were based on an altogether inadequate range of genotypes. For example, a breeding program with perennial ryegrass in the thirties had material only from northern Europe and New Zealand, either direct or from within Australia. The opportunity to contribute significantly to the southern Australian scene was small indeed. Early programs with subterranean clover, though based on a wider range of material, were equally unproductive because they lacked aim; hybridisation was regarded as purposeful *per se*. A third restraint, by no means confined to Australia, was the belief of agronomists and plant breeders that they knew the characteristics of 'the ideal pasture plant', whereas in fact these are still but partially defined.

Overseas collecting expeditions contributed directly to the initiation of worthwhile breeding programs. To continue with the example of perennial ryegrass, there became available a range of new material from the Mediterranean with capacity to survive summer drought—a character almost totally lacking in all earlier material. Thus both new material and new purpose lay before plant breeders.

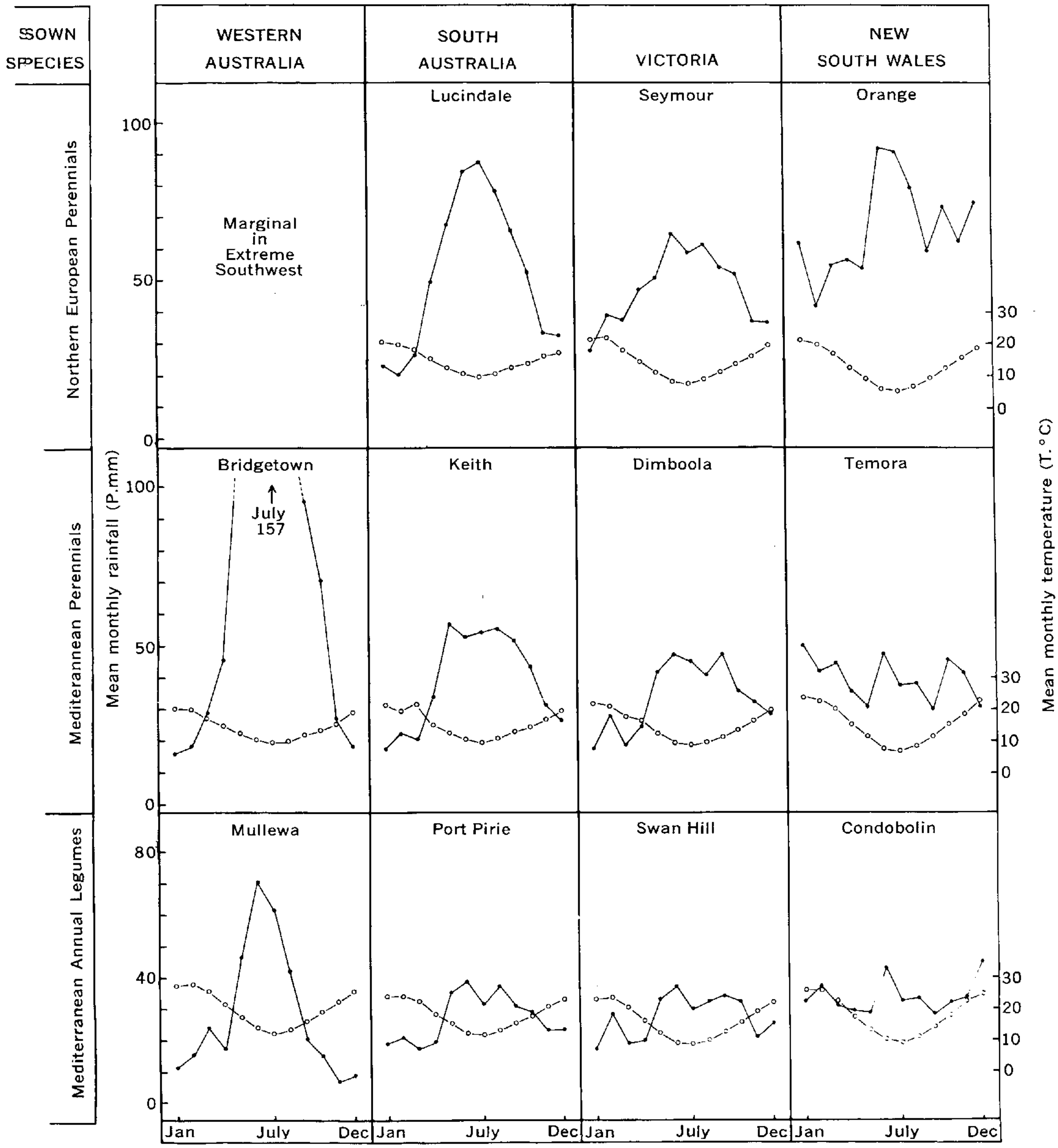


Fig. 20 : 5 The mean monthly rainfall (mm) and mean monthly temperature (°C) at centres of the inland (low rainfall) limits of cultivation of three ecotypic groups of pasture plants, showing their different minimal requirements. The figure also shows the progression across Australia from the Mediterranean climate of the south-west of Western Australia to the uniformly distributed rainfall at the latitude of Sydney in the east. (It will be noted that the temperature scale on the right is 10 units above the rainfall scale on the left. Thus the interval in which the rainfall curve lies above the temperature curve is the length of the growing season in terms of de Martonne's expression, $P/(T + 10) > 1$.)

Another factor which has stimulated breeding programs has been our increasing knowledge of the defects of existing cultivars. Research findings on the substances in subterranean clover leading to the reproductive disorders in sheep has led to a program of producing 'safe' cultivars of satisfactory productivity. Similar positive objectives have been the introduction of the creeping habit into an Australian lucerne cultivar (cv. Cancreep), of the non-shedding of seed in *Phalaris tuberosa* (cv. Seedmaster), and of resistance to clover stunt virus in subterranean clover (cv. Howard).

Despite this progress, the breeding of pasture plants in southern Australia is still but weakly developed. The emphasis in plant breeding continues to lie with cereals, where testing is less difficult, multiplication rapid, and gains readily evaluated. Yet the scope for the worthwhile breeding of pasture plants in Australia is expanding as we progressively define our environments and recognise defects in existing cultivars.

THE INFLUENCE OF CLIMATE ON THE DISTRIBUTION OF SOWN SPECIES

The most obvious factor governing the distribution of sown pasture plants in Australia is the rainfall.

Map 5 shows the inland limit of three classes of sown pasture plants in southern Australia, namely northern European perennials (as illustrated by *Lolium perenne*), Mediterranean perennials (e.g. *Phalaris tuberosa*), and Mediterranean annuals (e.g. *Trifolium subterraneum* and/or *Medicago truncatula*). The boundaries across southern Australia clearly follow the concentric pattern of the annual isohyets, but the amount of rainfall is confounded with its seasonal distribution; thus the areas in which northern European perennials are grown not only have a higher rainfall but also a better distribution of the rain with a greater proportion in summer; temperatures are also lower, so that rainfall effectiveness is greater (Fig. 20 : 5).

Several workers at the Waite Institute in the 1930s sought to characterise the climates of southern Australia with greater precision by using the ratio of rainfall to evaporation or of rainfall to saturation deficit. Trumble (1937) proposed that the length of the growing season be defined as the period during which $P/E > 1/3$, where P = Precipitation and E = Evaporation from a standard Australian 36 in. (914 mm) evaporimeter. (An equivalent ratio for monthly precipitation and saturation deficit (in. Hg) is $P/SD = 7\cdot7$.)

For South Australia he nominated the minimum length of season for various species as follows:

Lolium perenne	9·0 months
Phalaris tuberosa	6·0 months
Trifolium subterraneum	
Mid-season cultivars	7·5 months
Early flowering cultivars	6·0 months

These boundaries have been substantially confirmed in South Australia since that time, but the annual *Medicago truncatula* is now sown to the 5-months limit, and it may be that the early strains of subterranean clover could also be so extended, were it not for the absence of suitable soils in these drier areas (Morley 1961). Indeed in Western Australia early cultivars of *M. truncatula* and *T. subterraneum* extend to the 4-months boundary (Rossiter, personal communication), but this may be an understatement of the true length of the season.

Prescott's 1949 alternative expression for the length of the season ($P/E^{0\cdot75} > 0\cdot54$) gives similar boundaries. Actually the beginning and end of the growing season in South Australia and Western Australia tend to be marked by such a rapidly changing relationship of rainfall (sharply increasing in the autumn) and saturation deficit (conversely falling) that the season is well defined and the determination of its length is not very sensitive to refinement of expression.

When these formulae are applied in eastern Victoria and especially in New South Wales, they are no longer useful indices of the length of the season, partly because growth in the south-east of the continent, especially on the tablelands, is limited by low winter temperatures, and partly because the proportion of rain falling in the winter period becomes less and less. As the Queensland border is approached summer rainfall predominates. As a consequence the boundaries of each of the temperate or Mediterranean species in New South Wales move eastwards across the isohyets towards higher rainfall (Fig. 20 : 5), though with a less winter component.

THE CLIMATIC LIMITS OF SUBTERRANEAN CLOVER

Though rainfall is the dominant factor governing the distribution of sown species in southern Australia, we recognise other influential components of climate, as illustrated by subterranean clover. The principal indices of survival and success of any self-regenerating annual herbage plant are the number of seeds

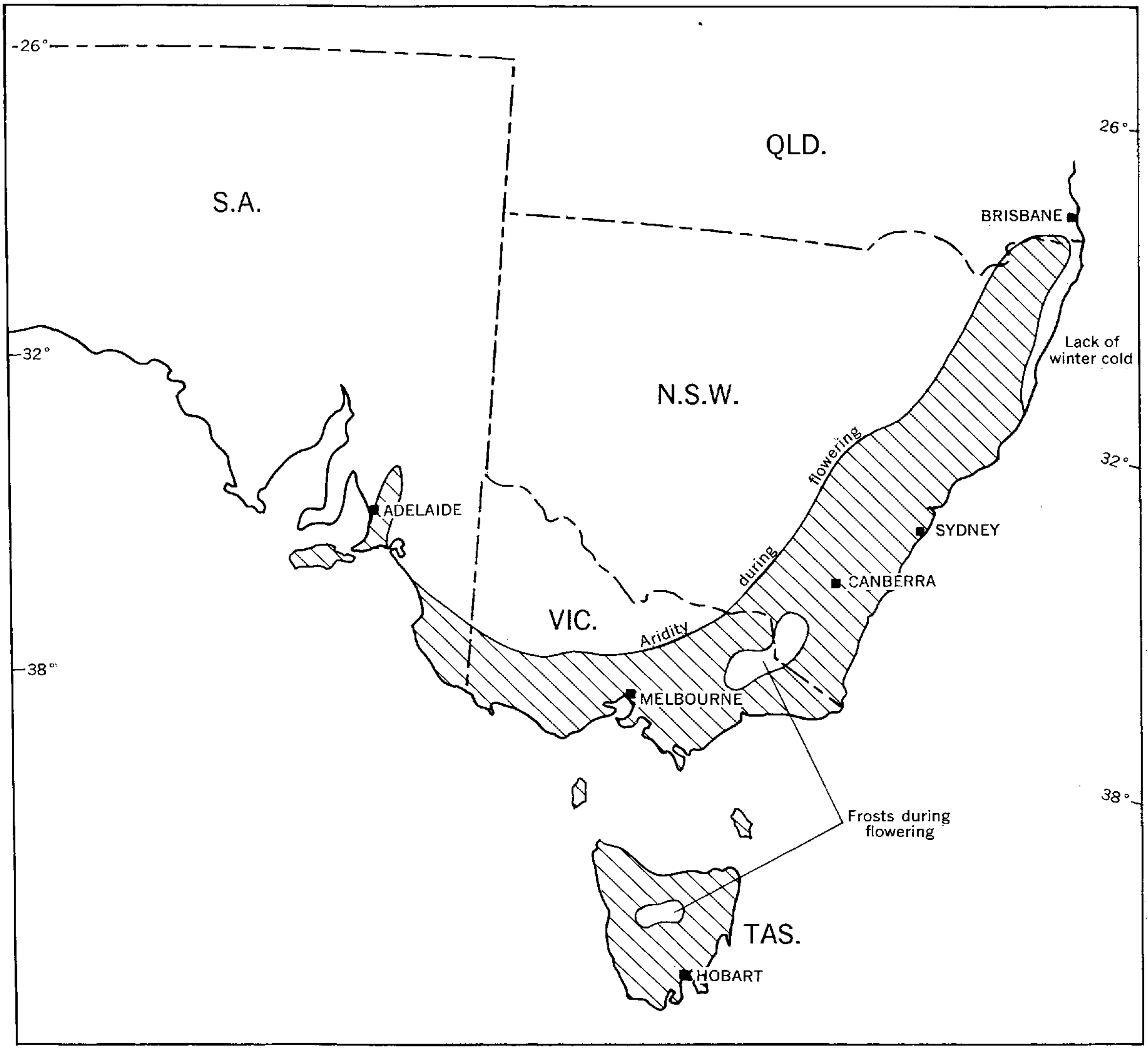


Fig. 20 : 6 The climatic boundaries of the mid-season Mt Barker variety of subterranean clover in south-east Australia (Donald 1960a)

produced, and the persistence of those seeds until favourable conditions occur for seedling establishment. In these terms we can recognise three climatic boundaries for subterranean clover in southern Australia (Donald 1960a), an arid boundary, a warm boundary, and a cold boundary (Fig. 20 : 6).

The arid boundary is simply the inland limit at which the effective winter rainfall season is so short or so erratic that the life cycle from germination to seed setting cannot be completed. More specifically there is a failure of soil moisture supply during flowering and seed development in the spring, commonly associated with atmospheric dryness, itself adverse to fertilisation. As indicated earlier the 'length of growing season' needed for the successful growth of the mid-season variety Mt Barker is 7–7·5 months and of very early flowering varieties such as Dwalganup 4–5 months. The economic significance of maturity in relation to length of rainfall season is strikingly apparent in Western Australia. When Mt Barker was the only cultivar available, the area climatically suited to subterranean clover in the south-west of that State was only about 20,000 sq miles (52,000 km^2). The advent of the early varieties Dwalganup and Geraldton has extended the climatic limits of this species to some 60,000 sq miles (155,500 km^2).

'Earliness' has usually been designated by the date of commencement of flowering, and for most cultivars this criterion is satisfactory, but it is not applicable in all instances. Thus cv. Geraldton has better seed setting and persistence in very dry spring conditions than has Dwalganup, even though it is slightly later (7–10 days) in beginning to flower (Millington 1960). The reasons for the success of Geraldton are threefold (Tennant 1968)—the peak of flowering is attained soon after its commencement; flower numbers are greater; and the interval from anthesis to seed maturation is shorter by 6–9 days than in Dwalganup.

The warm boundary of the mid-season cultivar of subterranean clover (Mt Barker) lies approximately at the 55°F (13°C) July isotherm. North of that isotherm its cold requirements are not met and it remains vegetative or flowers erratically. As shown in Fig. 20 : 6 this warm boundary lies just north of the Queensland–New South Wales border and then runs south along the eastern scarp of the tablelands of New South Wales. Thus at latitude 30°S, Mt Barker will produce seed on the New South Wales tablelands, but not in the warmer conditions of the coast.

The early varieties have a less cold requirement than do later varieties. Thus with a 14-hour day, Dwalganup will flower at any temperature below 80°F (27°C) (it has almost no cold requirement at all) while the late cultivar Tallarook will flower only at a temperature below 60°F (16°C) (Aitken 1955). For this reason, early varieties, or more specifically those of little cold requirement, will flower on the north coast of New South Wales where Mt Barker will not.

The cold boundary of subterranean clover excludes only a small area of high country (Fig. 20 : 6) lying above about 4000 ft (1200 m), but seed production is seriously reduced at intermediate elevations (2000–4000 ft, 609–1200 m) especially when cold springs are experienced. Thus in the cold spring of 1946 near Canberra (elevation 2040 ft, 610 m) seed production was less than 20 per cent of the estimated potential production under frost-free conditions (Donald 1959). The effect of cold may have two components, the first the effect of frosts on flowering and seed setting, and the second the possible influence of prolonged low temperature in delaying flower induction (Morley and Evans 1959). At these higher elevations, lateness has clear advantage in delaying flowering until the weather is warmer.

Thus at the three boundaries the ecological advantage lies with cultivars as under:

Near the arid boundary: Early flowering (e.g. Dwalganup) and/or rapid seed maturation (e.g. Geraldton).

Near the warm boundary: Lack of cold requirement, commonly found in earlier varieties (e.g. Clare).

Near the cold boundary: Escape from cold spring conditions, as by late flowering biotypes and/or those of minimum frost susceptibility. Selection is needed, not to extend the boundary but to ensure good seed production in higher parts of the present distribution.

The general relationship of biotypes to climate may be similar for many Mediterranean annuals.

EDAPHIC LIMITS

Most of the soils of southern Australia are phosphorus and nitrogen deficient in terms of the normal growth of our sown pasture plants; in other instances trace element deficiencies may differentially limit the growth of pasture species. For example, Anderson (1946) reports the response of a phalaris-lucerne mixture to copper. With copper deficiency, phalaris was the principal component; with copper added, lucerne was dominant in the mixture.

But apart from these more readily corrected restrictions to distribution, there is also a pattern of edaphic limitations which, though imperfectly understood, impose geographic boundaries on particular species. Perhaps the most notable of these is the influence of soil pH on the distribution of subterranean clover and the annual medics (Trumble and Donald 1938b). Subterranean clover thrives on acid or neutral soils, generally of lighter texture, and has succeeded mainly at pH 5–7. In contrast, the annual medics, of which barrel medic is the most widely sown, are adapted to alkaline soils of about pH 7–8·5. It was long thought that these relationships might involve differing mineral needs between these species, and this view was supported when Higgs (1958) showed that the subterranean clover cultivar, Clare, which is unusual in its degree of tolerance to alkaline soils, has a lesser requirement for zinc and manganese than has Bacchus Marsh, a cultivar which shows poor persistence on these soils. But a complete understanding of the influence of soil type on the distribution of subterranean clover and the medics is still lacking.

Morley and Katznelson (1965) suggest that the limited success in Australia of cultivars of *Trifolium subterraneum* subspecies *Brachycalycinum*, which includes cv. Clare, may be due to their natural distribution in the Mediterranean basin on alkaline calcareous soils, whereas a large proportion of the soils within favourable climatic limits in Australia are acid in reaction. Morley (1961) also raises the query as to whether the accepted arid limit of subterranean clover in Australia, which falls far short of the lower rainfall limits of the annual medics, may be an artefact due to soil factors, and that the true climatic limit may lie in much drier areas.

Some species have shown success only on particular soils. Strawberry clover (*T. fragiferum*) cv. Palestine has proved singularly adapted to the rendzina soils of the south-east of South Australia, but is of relatively little significance elsewhere in Australia. In contrast, perennial veldt grass, *Ehrharta calycina*, is of little value other than on inland sandplain and sand dunes in parts of South Australia and Victoria. For each of these species the limits of distribution are clearly two-fold, climatic and edaphic. Water relationships, nutrient supply and aeration are involved in varying degree in these adaptations to specific soils, but the disentanglement of these phenomena has scarcely begun.

PERENNIALS AND ANNUALS

There has been much debate regarding the need for perennial species in southern Australian pastures. Many workers consider that perennials are highly desirable and that even though an annual legume may be sown it should be associated with a perennial grass. It is pointed out that pastures wholly of annuals show marked and unpredictable changes in botanical composition from year to year, and that they are susceptible to invasion by weeds (see Chapters 12, 23). Proponents of perennials also claim that the growing season of perennials is longer because they will produce foliage earlier in the autumn and carry it later into the spring or summer; they will also respond, though but weakly in the case of typical Mediterranean species, to any rains during the normally dry summer period.

Other workers, point out, however, that perennial grasses, even those from Mediterranean zones (e.g. *Phalaris tuberosa* and *Ehrharta calycina*) may show poor summer survival under grazing and that they are often heavily invaded by annual species. Their production pattern in the autumn, it is affirmed, does not differ appreciably from that of annual species, because the weight of live over-summering tissues (the basal internodes and the roots of perennials, or the seed of annuals) may be of much the same order.

We can, however, see some relationship of climate to the value of perenniality. In the south-east of the continent, where rainfall is more evenly distributed and where summer drought is less prolonged and intense (Fig. 20 : 5), perennials are clearly of value. This applies especially to regions in which northern European perennials can be grown, as in the Gippsland area of eastern Victoria, but also to areas with pronounced though not total summer drought, where Mediterranean perennials such as *Phalaris tuberosa* are valuable.

In the south-west sector of Western Australia the rainfall season is short and the summer drought is of great intensity; here it is established that perennials, or at least the cultivars at present available, are of little value except in the extreme south-west corner, where phalaris is marginally worthwhile.

Lying between these two environments, the south-west of Western Australia and the more favoured south-east of the continent, are many ecotonal areas in which the role of perennials and annuals is undefined—where there seems to be no clear advantage of either annual or perennial habit. A good deal of the sown pasture areas of South Australia are of this uncertain status.

Despite this pattern of experience, we may yet find that the role of perennial grasses will expand as the new 'Mediterranean' cultivars (e.g. Medea ryegrass, Berber cocksfoot, Sirocco phalaris) come into wider use, despite the greater cost of seed and establishment compared with annuals. Meanwhile, over much of southern Australia, pastures of annuals have lost the stigma formerly attached to them by those with the traditional viewpoints of northern Europe. The weakness of many annual pastures lies not in their annual habit but rather in the awned and sharply pointed seeds of so many of the successful species, such as the annual Hordeum, Bromus and Vulpia species. At least part of the success of these grasses is, however, due to these seed characteristics, which assist in their establishment.

The contrast in the role of annuals and perennials in these sown pastures of the temperate and Mediterranean parts of Australia is shown in Table 20 : 6; the importance of annuals in the Mediterranean sectors is clearly indicated.

TABLE 20 : 6 The perenniality of pasture plants sown in southern Australia in 1967

	Perennial	Annual
Temperate plants		
Species	8	3
Cultivars	22	4
Mediterranean plants		
Species	5	9
Cultivars	9	30

Source: Based on the cultivars listed by Barnard (1967 and Supp. 1968).

21

MINERAL NUTRITION OF PASTURES

C. H. WILLIAMS AND C. S. ANDREW

With few exceptions Australian soils, in their natural state, are deficient in both phosphorus and nitrogen. In addition, many are also deficient in other essential elements, notably some of the trace elements, potassium and sulphur. The dual deficiency of phosphorus and nitrogen, coupled with high costs of nitrogenous fertilisers, have had a marked impact upon the development of Australian agriculture in the devising of farming practices aimed at overcoming these two deficiencies.

Superphosphate has always been the dominant fertiliser used and, at the present time, it still accounts for about 88 per cent of all fertilisers used. Nitrogen deficiency and the relative cost of applied nitrogen has meant that the effectively nodulated legume has a distinct and primary role in pasture development and vast areas of Australia have been subjected to ready pasture improvement by the introduction of a suitable legume accompanied by top-dressing with superphosphate. Cropping in Australia has largely depended upon bare fallowing to mineralise soil nitrogen for the growth of the subsequent crop, and these exploitative fallowing practices have led, in the past, to a serious decline in organic matter status of most cropped soils. This, in turn, has led, in more recent times, to the inclusion of leguminous pasture leys in many crop rotations as a means of maintaining, and building, the organic matter and nitrogen status of cultivated soils.

The nutrition of pastures in Australia is thus largely concerned with leguminous pastures sown either directly for animal production or as a ley pasture in a cropping rotation. Many of the soils sown to pastures were those generally found unsuitable for cropping, often because of their poor fertility. The frequency and severity of nutrient deficiencies is thus greater, as a general rule, for pasture soils than for cropped soils.

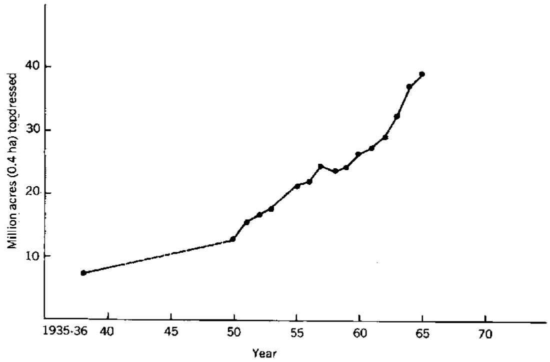


Fig. 21 : 1 Area of pasture top-dressed with fertilisers, 1938–66 (*Year Book of the Commonwealth of Australia* 1939–67)

The importance and the rapid expansion of pasture improvement over the past thirty years is indicated in Figure 21 : 1.

Soils available for pastures are limited to those areas in which the rainfall is adequate or irrigation water is available. Within these areas the development of productive pastures has depended upon the choice of suitable legumes and the recognition of their nutrient requirements.

In southern Australia pasture improvement, as we know it today, commenced in the early 1920s with the recognition of the suitability of Mediterranean species—especially subterranean clover—fertilised with superphosphate. This was later followed by the use of tropical species—especially Townsville lucerne—in northern and north-eastern Australia. The early recognition of the importance of phosphorus was followed by the discovery of potassium deficiency (Anon. 1933) and of the role of trace elements deficiencies in areas where introduced legumes had failed, even when liberally treated with superphosphate. The first demonstration of a trace element deficiency was a response to copper by lucerne and black medic reported by Riceman and Donald (1938). This was followed by responses by subterranean clover to molybdenum (Anderson 1942), zinc (Riceman 1945) and more recently cobalt (Powrie 1960; Ozanne, Greenwood, and Shaw 1963).

The importance of copper and cobalt to animals grazing on certain pastures in southern Australia was recognised somewhat earlier (Underwood and Filmer 1935; Marston 1935; Bennetts and Chapman 1937).

SOIL GENETIC FACTORS AFFECTING NUTRIENT AVAILABILITY

Apart from a wide range of soils arising from considerable diversity of parent material and climatic conditions, as indicated in Chapter 3, the widespread occurrence of nutrient deficiencies in Australian soils stems, to an appreciable extent, from the great age of many of them. Certain geomorphic characteristics of the continent have led to the development of a high proportion of strongly leached, deeply weathered soils of great antiquity which are of exceptionally low fertility (Stephens and Donald 1958). The main factors contributing to this are:

(i) Volcanic activity has been limited mainly to a narrow zone along the east and south-east coasts.

(ii) Limited uplift of the mainland has restricted dissection and the exposure of basement rocks to weathering.

(iii) Only small areas of south-eastern Australia and Tasmania were glaciated in the Pleistocene so that exposure of basement rock by this agency and deposition of morainic material has been limited.

There are large areas of Tertiary soils and many Recent soils which have developed on lower-horizon remnants of these or their colluvial and alluvial residues. All are of low fertility.

In addition, because of high porosity, several soil groups in moderate to high rainfall regions are susceptible to leaching under present-day climatic conditions. Moreover, a high proportion of soils have been formed from coarse-textured sediments high in silica and low in nutrient elements.

The correction of nutrient deficiencies by the use of artificial fertilisers has thus been an essential feature of pasture development in Australian agriculture.

NUTRIENT DEFICIENCIES OF AUSTRALIAN PASTURE SOILS

Nitrogen

The low nitrogen status of Australian soils is a direct consequence of their low organic matter content. Total nitrogen in surface soils generally ranges from 0·01 per cent upwards, with a high proportion of soils containing less than 0·20 per cent. Prescott (1931) showed that a general correlation exists between rainfall and nitrogen content of surface soils. He also indicated further important correlations between the nitrogen and phosphorus contents of surface soils which led him to suggest that the marked phosphorus deficiency in many areas may have exerted some control over the climax associations of the native vegetation. It thus seems probable that a paucity of effectively nodulated legumes in the native vegetation could have been an important factor contributing to this almost universal deficiency of nitrogen. Beadle (1962) has suggested that removal of surface soil and organic matter by erosion could have been an important factor contributing to the generally low phosphorus content of Australian soils. If so, these same factors would have led to corresponding losses in soil nitrogen.

In spite of the poor nitrogen status of most soils relatively little nitrogenous fertiliser is used in Australia. Of that used, most of it is applied to sugar cane and horticultural crops and very little to pastures. Field crops are still largely dependent upon fallow nitrogen and leguminous pasture leys for nitrogen. The almost complete reliance upon the legume for pasture nitrogen is a result of the high costs of fertiliser nitrogen coupled with the adaptability of pasture legumes, particularly subterranean clover, to southern Australian conditions. The more important factors include their relative ease of establishment, their productivity on poor soils, and their nutritive value as dry feed during the dry season.

Donald (1960b) estimated the current rate of addition of nitrogen to soils in southern Australia by pasture legumes to be of the order of 1,000,000 tons of nitrogen per annum. This figure refers only to the soil increment and does not include the nitrogen removed in farm produce or soil losses by volatilisation, leaching or erosion. The actual amounts of nitrogen fixed would thus be considerably in excess of this figure. Allowing also for the increased areas of sown pasture since 1960, it would seem that the current contribution of nitrogen by pasture legumes to soils in Australia must now be of the order of 1,500,000 tons per annum. At current fertiliser prices this is nitrogen equivalent to $300,000,000 worth of fertiliser per annum. While no comparable figures are available for northern Australia, it is clear that important contributions of legume nitrogen are also occurring in these regions. Nitrogen yields ranging from 30 to as high as 300 lb N per acre (approx. 34–336 kg per ha) for various tropical legume species have been reported under field conditions (Norman 1959; Wetselaar and Norman 1960; Wetselaar 1967; Henzell 1968) while increases in soil nitrogen of up to 100 lb per acre (112 kg per ha) per annum have been reported under pastures of Townsville lucerne (Wetselaar and Norman 1960; Wetselaar 1967) and Desmodium (Henzell, Fergus, and Martin 1966).

It seems likely that legumes will continue to be the main source of nitrogen for pastures for some years to come, at least in southern Australia. But, it also seems likely that fertiliser nitrogen may find a place as an adjunct to legume nitrogen either for increasing production at particular seasonal periods, the possibility of which has been demonstrated by Nicholson *et al.* (1960), Strang (1960), Newman, Allen and Cook (1962), Simpson (1965), and Crofts (1965), or for use on winter cereal fodder crops grown in association with leguminous pastures (Crofts 1959). Increasing use of fertiliser nitrogen on cereal crops also seems likely to affect the importance of the pasture ley in crop rotations.

In northern Australia the likely role of fertiliser nitrogen is less clear, but responses have been reported both on grass pastures (Henzell 1963, 1968; Henzell and Oxenham 1964; Bryan and Sharpe 1965; Gartner 1966; Coleman 1966) and on cereal crops in ley systems (Leslie and Hart 1967; Littler 1968).

Simpson (1962) has shown that appreciable seasonal fluctuations in the mineral nitrogen content of the surface soil occur under well-established subterranean clover pastures. Mineral nitrogen remains at low levels during most of the period of active growth (late autumn-winter-spring) but during summer when the pasture is dormant or senescent nitrate may increase to quite high levels (40–50 ppm N). This build-up during summer results mainly from the mineralisation of organic nitrogen in moist soil in the absence of active plant uptake. Apart from fluctuations induced by rainfall the level in the surface soil remains high until the new season's growth exhausts the accumulated mineral nitrogen. Fertiliser nitrogen applied to such a grass-clover pasture in May did not increase pasture yields but when applied in July increased early spring yields (Simpson 1965).

Phosphorus

Phosphorus deficiency. Although individual values vary widely (from less than 0·0001 per cent to over 0·5 per cent P) Australian soils generally have low phosphorus contents when compared with soils overseas (Wild 1958). Indeed, Donald (1964) presents figures calculated from Wild's (1958) data which indicate that 93 per cent of Australian soils have average phosphorus contents of less than 0·03 per cent. Although the total phosphorus content of soils is a poor guide to the actual available phosphorus, the generally low phosphorus status of Australian soils is undoubtedly a reflection, in part at least, of these low values.

Wild (1958) has suggested that the low phosphorus content is the result of leaching of soil phosphorus, particularly during the period of laterisation under poor drainage conditions during the mid-Tertiary period, rather than to a low phosphorus content of Australian rocks. Beadle (1962), however, considers that extensive areas of phosphate-low rocks do occur and that the low phosphorus content of Australian soils is largely due to their formation from these rocks or from unconsolidated parent material derived from them. These are mainly sedimentary rocks that have been formed from the coarse particles remaining after the finer, phosphate-rich, particles were removed by water or wind. He also suggests that significant losses of phosphorus could have resulted from the removal of surface soil and organic matter by erosion.

It seems most likely that each of these processes has been involved in bringing about the generally low phosphorus content of Australian soils.

The soils of higher phosphorus content are mostly black earths and kraznozems, a large proportion of which are located in eastern Australia. Many of these are associated with basalt or basalt-derived alluvium and reflect the higher phosphorus content of their parent material.

In general, the black earths (less than 5 per cent of all soils) are the least phosphate-responsive of Australian soils, some of them showing no response at all. Many of the kraznozems, however, although high in total phosphorus are phosphorus deficient. Many are high in active iron and aluminium and have a high capacity to 'fix' added phosphate in unavailable forms, and in others, much of the inorganic phosphate appears to be present in forms which have extremely low availability to plants. Norrish (1957) has shown that in some of these soils much of the phosphate is present as gorceixite and related minerals which, because of their low solubility, would release little phosphate for plant uptake. Norrish and Sweatman (1962) later examined the occurrence of these minerals in soils of the Barossa Valley, South Australia, and associated their presence entirely with intensely weathered soils on the remnants of an early Tertiary land surface. The presence in these forms of much of the phosphorus in the older soils of the Australian landscape could be a further reason for the low phosphorus status of many soils.

Phosphorus fertilisers. The overriding importance of phosphorus deficiency in Australian soils is indicated in Table 21 : 1 which gives the quantities of fertilisers used in Australia in the year 1965–6. Superphosphate accounted for 89 per cent of all fertilisers used and 96 per cent of those applied to pastures. Of the total fertiliser used 61 per cent was applied to pastures at an average rate of 1·15 cwt per acre (144 kg per ha).

TABLE 21 : 1 Quantities of fertilisers used in Australian States and Territories, 1965–6 (tons)[a]

State or Territory	Crops		Pastures	
	Superphosphate	Other fertilisers	Superphosphate	Other fertilisers
N.S.W.	216,474	49,070	564,762	9,649
Vic.	204,949	49,843	743,062	56,539
Qld	22,959	178,261	10,300	2,967
S.A.	252,301	12,831	295,430	1,400
W.A.	421,071	30,853	512,758	7,750
Tas.	24,200	11,494	121,330	5,901
N.T.	138	92	379	63
A.C.T.	379	54	3,336	8
Aust.	1,143,471	332,498	2,251,357	84,277

[a] 1 long ton = 2240 lb = 1016 kg = 1 metric ton approx.

Source: Year Book of the Commonwealth of Australia.

The importance of phosphorus deficiency and the use of superphosphate for its correction in Australian pasture soils is further indicated in Fig. 21 : 2 which shows the amounts of fertiliser applied to pastures since 1938–9 when the amount of superphosphate applied to pastures made up only 32 per cent of the total fertiliser used.

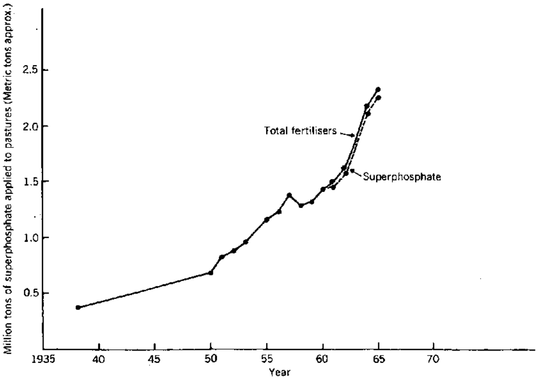


Fig. 21 : 2 Fertilisers applied to pastures, 1938–66 (*Year Book of the Commonwealth of Australia* 1939–67)

Superphosphate is almost invariably surface broadcast on to the pasture and in the past has been applied using a fertiliser drill, spinner, or blower. During recent years increasing use has been made of aircraft for pasture top-dressing and in 1966 approximately 25 per cent of all superphosphate applied to pastures in Australia was distributed in this way (*Year Book of the Commonwealth of Australia* 1968). The rapidly increasing use of aircraft for pasture top-dressing is shown in Table 21 : 2.

Residual phosphorus. The majority of Australian soils show no serious problem of phosphate 'fixation' and there have been numerous reports from all parts of the Commonwealth of good residual effects from past applications of superphosphate both on cropped and pasture lands (Jackson 1966). High phosphate 'fixation' is confined mainly to some kraznozems (Parberry 1946; Hughes and Searle 1964) high in active sesquioxides and to small areas of acid soils showing aluminium toxicity (Munns 1965a).

TABLE 21 : 2 Aerial top-dressing with superphosphate in Australia, 1957–66

Year	Area treated (million acres or approx. 4×10^5 ha)	Superphosphate ('000 tons)
1966	10·13	588
1965	12·54	656
1964	9·53	505
1963	6·13	329
1962	5·13	278
1961	4·35	237
1960	2·31	126
1959	1·15	63
1958	1·38	79
1957	0·90	55

Source: Year Book of the Commonwealth of Australia 1958–67.

The potential for rapid improvement in soil phosphorus status by the accumulation of residual fertiliser phosphorus is generally much greater under pasture than in cropped soils because:

(i) Except for dairy pastures, the removal of phosphorus in farm produce is small compared with that in grain crops.

(ii) The practice of top-dressing pastures by the surface broadcasting of superphosphate leads to the accumulation of the residual fertiliser phosphorus at the soil surface. The effect of this is one akin to fertiliser placement, in that the soil surface becomes a zone of high phosphate saturation and high phosphate availability. Dispersal of this zone throughout the surface 3–4 in. of soil by cultivation can lead to appreciable decrease in phosphate availability (Williams and Simpson 1965).

Operating against the build-up of phosphorus in readily available forms is the fact that under pasture a proportion of the residual phosphorus is converted to organic forms. Organic phosphorus, particularly under pasture conditions, appears to become available to plants at only a slow rate. Thus the accumulation of phosphorus in available forms will depend upon the amounts converted to organic forms as well as upon the chemical properties of the soil governing the availability of the residual inorganic phosphate. The actual amounts of organic phosphorus formed depend upon a number of factors including the rate of fertiliser application, the rate of organic matter accumulation, and the phosphorus content of this organic matter. As might be expected, the proportion of fertiliser phosphorus accumulating in organic forms varies widely and under subterranean clover pastures in southern Australia, Williams (1950) in Adelaide found 12–22 per cent, Donald and Williams (1954) in Crookwell, N.S.W., 52 per cent and Carter (1958) in Kangaroo Island 84 per cent of the residual phosphorus in this form.

In most soils the rate of build-up of available phosphorus is high, and there are many reports of beneficial residual effects of superphosphate top-dressed on to pastures both on ungrazed experimental plots (Trumble and Donald 1938a; Anderson and McLachlan 1951; McLachlan 1960) and on farms (Cullity and Elliot 1949; Donald and Williams 1954; McLachlan and Norman 1962). These results suggest that for virgin phosphorus-deficient soils large initial applications would be worthwhile in order to promote early productivity. It is now clear that reduction in annual rates of phosphate application to lower 'maintenance' levels should eventually be possible even on soils with high capacity to 'fix' phosphate. For example, Newman (1963) found that on a kraznozem with a high capacity for phosphate 'fixation' which had received a total of 30 cwt per acre (3765 kg per ha) superphosphate over a period of 25 years, 0·5 cwt superphosphate per acre (62 kg per ha) per annum was adequate to maintain pasture growth. McLachlan and Norman (1962, 1964) have shown that in soils where the 'maintenance' stage has been reached the time lapse since the last application of phosphate appears to be more important in determining the response to current dressings than the total amount of phosphate applied, suggesting that small annual dressings are more effective than occasional heavy dressings.

Clearly some exceptions are likely. Carter (1958) showed that over a period of four years the residual value of superphosphate applied to the Seddon sandy loam, Kangaroo Island, was considerably higher on the original virgin soil than on the developed soil. These results suggest that changes may have occurred affecting the capacity of soil under pasture to retain phosphate in available forms. Soil pH has been shown to decrease in some soils as a result of pasture improvement (Donald and Williams 1954; Russell 1960a) and it is possible that this decrease in pH could bring about an increase in the capacity of the soil to retain phosphate in unavailable forms.

In a number of sandy soils leaching of phosphate may reduce the rate at which residual phosphorus accumulates. These are soils with a very low capacity to sorb phosphate so that, even under moderate (18–22 in., 457–558 mm) rainfalls, soluble fertiliser phosphate may be leached from the surface soil. Hingston (1959) reported losses from the surface 0–6 in. (0–15 cm) of the order of 74 per cent of the phosphorus applied to grazed pastures at Coolup, W.A., and in one soil it is apparent that only the phosphorus incorporated into the soil organic matter was retained. Ozanne, Kirton, and Shaw (1961) reported losses from the surface 0–4 in. (0–10 cm) of 17–81 per cent of phosphate in single dressings applied to sandy soils in Western Australia. Loss of phosphate from surface soils by leaching has also been reported by Paton and Loneragan (1960) in Tasmania and by Russell (1960b) and Powrie (1963) in South Australia. However, in soils of the Coonalpyn Downs, S.A., Powrie (1963) found that although phosphate was leached from the surface soil it was not leached from the root-zone. It remained in the subsoil and was readily available to plants in the following season. Thus appreciable loss of phosphate from these soils by leaching seems only likely in years of particularly high rainfall.

Sulphur

Although not nearly so widespread as nitrogen and phosphorus deficiencies, sulphur deficiency has been reported in a wide range of Australian soils and is particularly common on the tablelands of New South Wales and the coastal sand plains of Western Australia.

Because of the extensive use of ordinary superphosphate (11 per cent S) the deficiency has been only of minor agronomic importance up to the present time, and, also because of the wide use of superphosphate, the full extent of sulphur deficiency is not yet known.

The high incidence of sulphur deficiency in Australian soils is partly a reflection of their generally low organic matter contents but, to a much greater extent, it is due to a generally low accession of sulphur in rainfall. This low sulphur accession, often only of the order of 1 lb per acre (1·1 kg per ha) S per annum, is due to the concentration of heavy industry in Australia at relatively few localities on the coast. Accession of sulphur from industrial sources, so important in Europe and North America, is thus small in many Australian agricultural areas. Sulphur accession from cyclic salts is limited to areas immediately adjacent to the coast. In Victoria, for example, Hutton and Leslie (1958) found values of 3 to 7 lb S per acre (3·4–7·8 kg per ha) per annum at the coast, but these fell off rapidly with increasing distance inland so that the annual rate of accession was less than 2 lb per acre (2·2 kg per ha) for most of the State. McArthur and Spencer (1963) found that the severity of sulphur deficiency on the Dorrigo Plateau increased rapidly with distance from the coastal scarp and that this could be associated with decrease in rainfall.

Sulphur deficiency is more likely under leguminous pastures and this increases the frequency of its occurrence in Australia. The non-legume is dependent upon the soil (or fertilisers) for both its nitrogen and sulphur requirements and in most instances this involves mineralisation of the soil organic matter. Because of the difference between the relative nitrogen and sulphur requirements of the plant (N : S about 15 : 1) and the N : S ratio in soil organic matter (about 8 : 1) nitrogen usually becomes limiting to plant growth before sulphur. The legume, however, is independent of the soil for nitrogen but is entirely dependent upon it, or external sources, for sulphur.

The incidence of sulphur deficiency, however, is lower than that of nitrogen because, although most well-drained soils in good rainfall areas contain little free sulphate in the surface soil, some contain appreciable amounts of sulphate, either free or adsorbed in the subsoil. This is often readily available to growing plants, particularly deep-rooted species. In addition, some acid soils, particularly kraznozems, contain adsorbed sulphate even in the surface soil. Thus plants are not always entirely dependent upon the mineralisation of organic matter for their sulphur requirements as is the case with non-legumes for nitrogen.

As would be expected, the majority of soils showing sulphur deficiency are also phosphorus deficient and relatively few soils have been re-

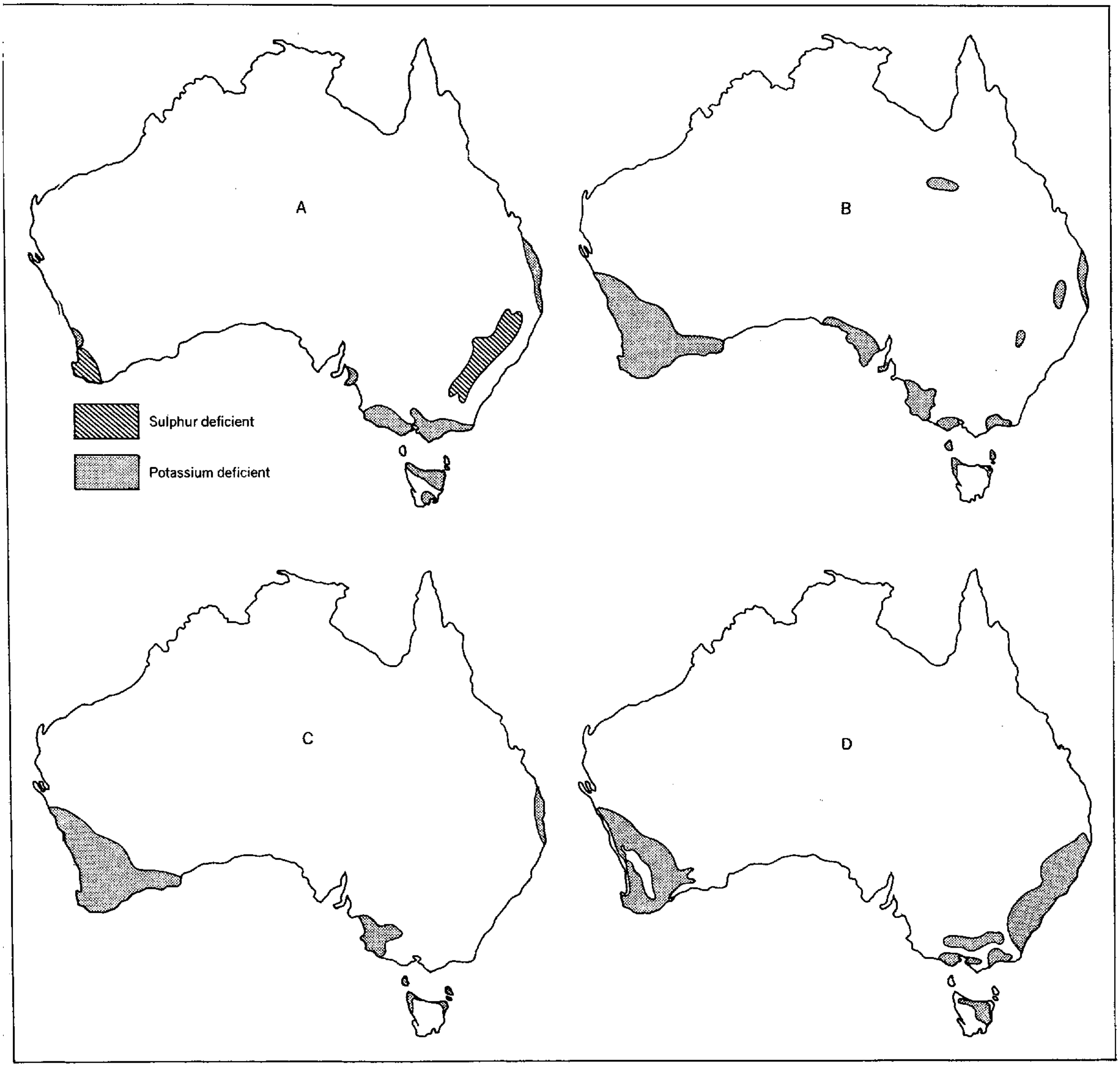


Fig. 21 : 3 The distribution of the major occurrences of (A) sulphur and potassium, (B) copper, (C) zinc, (D) molybdenum deficiencies

ported which are deficient in sulphur only. These are mainly soils of basaltic origin, many of them black earths, on the tablelands of New South Wales (Hilder 1954; Hilder and Spencer 1954; Spencer and Barrow 1963; Spencer 1966) and the Darling Downs of Queensland (Andrew, Kipps, and Barford 1952; Littler and Price 1967).

In general, ordinary superphosphate has continued in use as the most satisfactory fertiliser to meet both phosphorus and sulphur deficiencies. However, the areas of sulphur deficient soils in New South Wales with only low phosphorus deficiency or no phosphorus deficiency at all have led to appreciable use of 'sulphur-fortified' superphosphate (superphosphate enriched to a 26 per cent sulphur content by the addition of ground elemental sulphur) and gypsum. The area of pasture top-dressed with gypsum in New South Wales has increased from a few thousand acres in 1958–9 to over 1,300,000 acres (520,000 ha) in 1965–6. Similar acreages are now probably also top-dressed with 'sulphur-fortified' superphosphate.

Seasonal fluctuations in sulphate sulphur have been observed in the surface soil under subterranean clover pastures similar to those found for nitrogen (Williams 1968). It is of interest to note that readily available sulphur naturally accumulates to its highest level in the soil at the time of the year when, according to usual farming practice, pastures are top-dressed with superphosphate—a practice dictated by the phosphorus requirements of the pasture.

The main known regions of sulphur deficiency in Australia are shown in Fig. 21 : 3a.

Potassium, Calcium, and Magnesium

Potassium. Although potassium deficiency is widespread in Australian soils and pasture responses to potassium have been reported in all states, potassium fertilisers have played only a small part in the improvement of pasture in both southern and northern Australia. The deficiency is most prevalent in the south-west of Western Australia and in Tasmania, Victoria, and the southern coastal region of Queensland. It was first recognised in Victoria as early as 1933 (Anon. 1933). The deficiency occurs both on virgin soils as a result of naturally low potassium status and, commonly, on soils in which the potassium reserves have been depleted as a result of exploitative removal of potassium in hay or potash-demanding crops such as potatoes (Paton 1956a; Drake and Kehoe 1956; Fitzpatrick and Dunne 1956).

The deficiency is almost invariably associated with phosphorus deficiency and is also commonly associated with trace element deficiencies.

Even at the present time potassium fertilisers account for only about 1·5 per cent of the fertilisers applied to pastures. Their use on pastures, however, is increasing rapidly, as shown in Fig. 21 : 4. Over the past ten years the amounts used have increased seven-fold to a level where pasture usage now accounts for 37 per cent of all potassium fertiliser used.

Table 21 : 3 shows the usage of potassium on pastures for the years 1964–6 in each state. These figures show increasing consumption in all states except Western Australia and indicate the importance of potassium deficiency in Victoria—70 per cent of the potassium applied to pasture is used in Victoria.

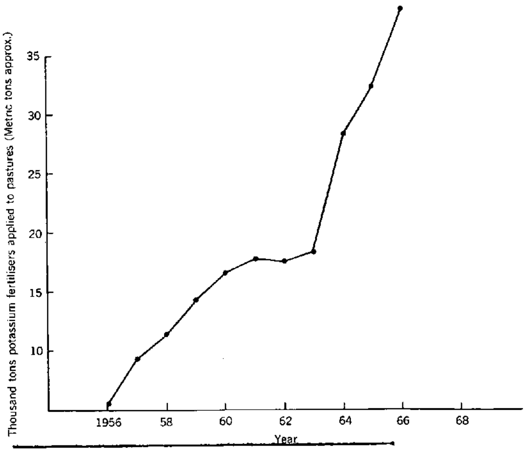


Fig. 21 : 4 Potassium fertilisers applied to pastures, 1956–66 (Potash Australasia Pty Ltd)

TABLE 21 : 3 Potassium fertilisers (chloride + sulphate) applied to pastures, 1964–6 (tons)

State	1964	1965	1966
N.S.W.	35	485	560
Vic.	19,657	22,781	27,539
Qld	—	610	810
S.A.	1,051	974	1,857
W.A.	4,730	4,464	4,349
Tas.	3,016	3,110	3,833
Aust.	28,489	32,424	38,948

Source: Potash Australasia Pty Ltd.

The importance of potassium fertilisers for Australian pastures is likely to increase at least for several years to come. The main reasons for this are:

(i) On many potentially potassium deficient soils an incipent potassium deficiency may have been masked by the more severe phosphorus deficiency. As the phosphorus status of more and more soils is raised nearer a level of adequacy by frequent superphosphate applications the likelihood of potassium limiting pasture production may increase.

(ii) Potassium deficiency is often associated with more severe trace element deficiencies and as these are recognised and corrected the need for potassium may increase.

(iii) Hay-making and the cropping of pasture soils may continue to induce potassium deficiency by removal of potassium from the soil.

(iv) Potassium deficiency is not always easily recognised. Plant symptoms are often only evident in cases of severe deficiency and yields can be appreciably depressed without visible symptoms being shown by the plants. The rapidly increasing interest in soil testing in Australia at the present time and the use of potassium soil tests in the near future seem most likely to reveal many cases of unsuspected potassium deficiency where this has not been severe enough to induce plant symptoms.

Under pasture conditions, particularly sheep pastures when wool is the principal product, removal of potassium in farm produce is small and residual effects can be expected from potassium fertilisers in most soils. Paton (1956b), for example, reports residual effects from 112 lb per acre (125 kg per ha) of potassium chloride lasting 4–5 years. The residual effects vary with locality but further maintenance dressings are usually required. Newman (1956), for example, suggests that after the initial application of 1–2 cwt potassium fertiliser per acre (125–250 kg per ha) subsequent dressings of 0·25–0·5 cwt per acre (31–62 kg per ha) in alternate years are usually sufficient to maintain pasture production in Victoria.

The major areas of potassium deficiency are shown in Fig. 21 : 3a.

Calcium (*lime*). The use of lime on Australian pastures is relatively small compared with overseas. This is somewhat surprising in view of the widespread sowing of legumes requiring high calcium levels and the extensive areas of acid podzolic and solodic soils involved.

Many of the early responses to lime have been shown to be due to greater molybdenum availability resulting from the higher soil pH following liming (e.g. Paton 1956b) and in these cases lime has been replaced by the less expensive molybdenum.

Although lime is used directly to overcome calcium deficiency, to correct soil pH and ameliorate associated aluminium and manganese toxicities (Munns 1965a; Kipps 1947) its main use in Australia is to aid pasture establishment on acid soils. Here lime is important for ensuring satisfactory nodulation and establishment of legumes. Spencer (1950) showed that both soil pH and adequate calcium supply were involved in nodulation and growth of subterranean clover. Anderson and Moye (1952) showed that good nodulation and establishment of the clover could be achieved on acid podzolic soils of the Southern Tablelands of New South Wales by the use of as little as 2 cwt per acre (250 kg per ha) of lime, if this were drilled with the seed. Loneragan *et al.* (1955) later showed that comparable success could be achieved with much smaller quantities of lime by localising the lime around the seed in a pellet. Superphosphate-lime mixtures (1 : 1) are now commonly drilled with the seed for pasture establishment on acid soils. Lime-pelleting or low rates of lime can only be successful on soils in which the calcium status is sufficient to meet the plants' requirements. On soils of extreme calcium deficiency such as those on the coastal lowlands of Queensland (Andrew and Bryan 1955; Bryan and Andrew 1955) and acid peaty sands in Western Australia (Fitzpatrick 1958) larger amounts of lime are required for both nodulation and plant growth.

Magnesium. Australian soils frequently contain an unusually high proportion of magnesium in the exchangeable metal ions (Prescott 1931) —often magnesium and calcium are present in similar proportions—and there are few cases of deficiency. Prescott suggests that the high proportion of magnesium is probably related to the accession of magnesium in cyclic salt or to the reweathering under semi-arid conditions of clays containing non-replaceable magnesium. The relatively rare occurrence of magnesium deficiency in Australian soils is undoubtedly a partial reflection of this high proportion of magnesium on the exchange complex.

Trace Elements

Trace elements, particularly copper, zinc, and molybdenum have played a vital part in pasture development in southern Australia. Stephens and Donald (1958), for example, estimate that in South Australia the area to which trace elements have been applied may well exceed one-third of the total area fertilised, while Burvill (1965) estimated that the total area treated with copper and zinc in Western Australia probably exceeds 10,000,000 acres (4,000,000 ha). The

TABLE 21 : 4 Trace element-containing superphosphates (SP) used in Australian States, 1965–6

	S.A.	N.S.W.	W.A.	Vic.[a]	Tas.[a]
Trace element SP per cent of total SP used	10·6	5·2	14·2	7·8	11·5
Trace element SP per cent of SP applied to pastures	14·2	7·3	15·5	8·2	13·9
Per cent of trace element SP applied to pastures	71	96	61	82	96
Total SP applied to pastures (tons)	295,430	564,760	512,760	743,060	146,530

[a] Calculated from quantities of trace element raw materials used (Anon. 1967b).

TABLE 21 : 5 Trace element-containing superphosphates (SP) used in Australian States, 1965–6. Individual mixtures as percentages of total trace element superphosphate applied to pasture.

Mixture	S.A.	N.S.W.	W.A.	Vic.[a]	Tas.[a]
SP + Cu	14·2	<0·2	7·8	20·5	23·8
SP + Zn	1·2				<1·0
SP + Mo	11·5	99·8	48·8	45·9	62·4
SP + Co	4·4	<0·01	2·8	1·1	2·8
SP + Mn	1·2		0·2		
SP + B		<0·2			2·1
SP + Cu Zn	23·8	<0·01	18·5	13·1	
SP + Cu Mo	7·1			14·8	
SP + Cu Co	0·6			4·6	8·9
SP + Cu Mn	1·2				
SP + Cu Zn Mo	11·3		21·9		
SP + Cu Zn Co	3·0				
SP + Cu Zn Mn	1·0				
SP + Cu Zn Mo Co	13·4				
SP + Cu Mn Mo	1·0				
SP + Cu + other mixtures	5·2				
SP containing Cu	81·8	<0·2	48·2	53·0	32·7
SP containing Cu + others	67·6		40·4	32·5	8·9
SP containing Zn	53·7		40·4	13·1	
SP containing Zn + others	52·5		40·4	13·1	
SP containing Mo	30·9	99·8	70·7	60·7	62·4
SP containing Mo + others	19·4		21·9	14·8	
SP containing Mn	4·4		0·2		
SP containing Mn + others	3·4		0·0		
SP containing Co	21·4		2·8	5·7	11·7
SP containing Co + others	17·0		0·0	4·6	8·9
SP containing B		<0·2			2·1

[a] Calculated from trace element raw materials used 1965–6 (Anon. 1967b).

trace element deficiencies are almost invariably associated with phosphorus deficiency, in many cases severe phosphorus deficiency, so that it has proved a relatively simple matter to correct them by application as additives in superphosphate. Almost 10 per cent of the superphosphate now used in Australia contains trace elements and 70–80 per cent of these trace element-containing fertilisers is applied to pastures (see Table 21 : 4). In Western Australia about 15·5 per cent of the superphosphate applied to pastures contains trace elements while the percentages for South Australia, Victoria, and New South Wales are 14, 8, and 7 per cent respectively.

In South Australia, the only State for which detailed figures are available (Anon. 1967a), the percentages of trace element-containing superphosphate shown in Table 21 : 4 have remained essentially unchanged over the past six years, and probably for the last ten years at least. This is probably true also for the other States with the exception of Western Australia. For most States it is likely that the relative percentages of the various trace elements in the mixtures used (as shown for 1965–6 in Table 21: 5) have changed little over this period. In Western Australia, however, marked changes have occurred following recent recognition of molybdenum deficiency over large areas of the State previously thought to be deficient only in copper and zinc (Doyle *et al.* 1965). As a result, the percentage of trace element mixtures containing molybdenum have increased from about 3·5 per cent of the total in 1963–4 to almost 70 per cent in 1966–7.

The deficiencies frequently occur as multiple deficiencies of two or more trace elements, as indicated in Table 21 : 5, and are sometimes associated with potassium deficiency. These deficiencies are widespread throughout the Commonwealth, most deficiencies having been reported in each State. With the possible exception of manganese and cobalt there is, as yet, no clear understanding of the chemical nature of the trace elements in Australian soils or of many of the factors affecting their availability to plants.

Although some clear geographical groupings of the major occurrences of the deficiencies can be made, as shown in Fig. 21 : 3, the individual deficiencies often occur over a range of apparently unrelated soil types. For example, in pot experiments on pasture soils from eastern Australia, which included soils from Victoria, New South Wales, and southern Queensland, McLachlan (1952) obtained responses to molybdenum on 12 of 32 soils. The responsive soils included kraznozems, red and yellow podzolic soils, and a red-brown earth, and their parent materials included basalt, granite, and sedimentary rocks. Each of these soils was also phosphorus deficient. McArthur and Spencer (1963) in a pot culture study of pasture soils of the Dorrigo Plateau, New South Wales, obtained responses to molybdenum on 44 of 48 soils. The responsive soils included kraznozems, chocolate soils, alpine humus soils, red podzolic soils, and red earths and the parent materials included basalt, trachyte, granite, and sedimentary rocks.

Table 21 : 6 indicates soil types on which some important occurrences of molybdenum, copper, and zinc deficiencies of pasture soils have been reported in various Australian States. For each nutrient the deficient soils vary considerably in character.

It thus seems likely that several soil genetic factors have contributed to such widespread occurrence of trace element deficiencies. Possibly the more important of these includes the prevalence of old soils and of soils developed on remnants of them, the effects of leaching which have given rise to large areas of solodic and podzolic soils and, in some cases, the high calcium carbonate contents of many calcareous aeolian sands.

The concentration of molybdenum with iron in ironstone gravels (Oertel and Prescott 1944), of trace elements in minerals of the gorceixite group (Norrish and Sweatman 1962), and of cobalt and other elements in manganese minerals (Taylor, McKenzie and Norrish 1964; McKenzie 1967; McKenzie and Taylor 1968), are examples of chemical processes possibly contributing to trace element deficiencies, particularly in old soils.

Copper. Copper deficiency affecting both animals and plants occurs over large areas of southern Australia (see Fig. 21 : 3b). Recognition of copper deficiency, associated with that of cobalt, as the cause of 'coast disease' (Lines 1935; Marston *et al.* 1938) and of simple copper deficiency as the cause of enzootic ataxia of lambs (Bennetts 1937) preceded its recognition as a deficiency affecting plants (Riceman and Donald 1938).

As indicated in Table 21 : 6, it has been recorded on a wide variety of soils and is often associated with other trace element deficiencies. Its importance in South Australia is indicated by the fact that copper is included in over 80 per cent of the trace element-containing fertilisers applied to pastures in that State while in Victoria and Western Australia it is included in approximately 50 per cent.

The main regions of copper deficiency are the Coonalpyn Downs (Ninety Mile Desert) of South Australia, the 'sand plain' area of southwestern Western Australia, the Gippsland region of Victoria, the Cloncurry-Hughenden area, Queensland, and the southern coastal area of Queensland.

Zinc. Like copper, zinc deficiency is widespread in southern Australia, as shown in Fig. 21 : 3c. Most commonly it is associated with other trace element deficiencies, usually copper,

TABLE 21 : 6 Soil types on which field responses to trace elements have been reported in Australian States

Deficiency	Soil type	State	Reference
Molybdenum	Lateritic podzolic	S.A.	Anderson (1942)
	Podzolic	Vic.	Newman (1955)
	Solodic		
	Lateritic podzolic		
	Podzolic	W.A.	Fitzpatrick (1957)
	Humic gley	Qld	Andrew and Bryan (1955)
	Podzolic	N.S.W.	Strang (1955)
	Podzolic	N.S.W.	Anderson and Moye (1952)
	Podzolic	Vic.	Drake and Kehoe (1956)
	Kraznozem	Tas.	Fricke (1945)
	Podzolic		
	Lateritic podzolic	W.A.	Doyle *et al.* (1965)
Copper	Aeolian calcareous sand	S.A.	Riceman and Donald (1938)
	Solodised solonetz	S.A.	Riceman (1948a)
	Neutral-alkaline fen	S.A.	Anderson (1946)
	Groundwater podzol	W.A.	Teakle, Morton, and Turton (1941)
	Humic gley	Qld	Andrew and Bryan (1955)
	Podzolic	Vic.	Newman (1956)
	Podzolic		Drake and Kehoe (1956)
	Podzolic		McLachlan (1953)
	Calcareous solonised	W.A.	Bennetts (1959)
	Red-brown earth		
	Podzolic		
	Aeolian calcareous sand	S.A.	Lee (1951)
	Rendzina		
	Terra rossa		
	Podzolic		
	Solodised solonetz		
Zinc	Solodised solonetz	S.A.	Riceman (1948a)
	Neutral-alkaline fen	S.A.	Anderson (1946)
	Lateritic podzolic	W.A.	Dunne, Smith, and Carriss (1949)
	Aeolian calcareous sand	W.A.	Dunne and Throssell (1948)
	Humic gley	Qld	Andrew and Bryan (1955)
	Podzolic	Vic.	Newman (1956)
	Lateritic podzolic	W.A.	Dunne and Elliott (1950)
	Grey soil of heavy texture	Vic.	Millikan (1938)
	Rendzina	S.A.	Tiver (1955)

and does not often occur as a single deficiency although it does occur as such in wheat in the Wimmera district of Victoria.

The most important regions of zinc deficiency are the Coonalpyn Downs of South Australia where it is associated with copper deficiency, in the south-west of Western Australia where it is associated with both copper and molybdenum deficiencies, and in Queensland where it occurs as a single trace element deficiency on the Darling Downs and in association with copper deficiency in the southern coastal areas.

Molybdenum. Molybdenum deficiency in pastures is possibly even more widespread than copper deficiency—particularly in eastern Australia (see Fig. 21 : 3d). In New South Wales molybdenum accounts for nearly all trace element-superphosphate mixtures used, while in Victoria, Western Australia, Tasmania, and South Australia the percentages of trace element superphosphates containing molybdenum are 70, 60, 62, and 30 per cent respectively (Table 21 : 5).

The deficiency (apart from an almost invariable association with phosphorus deficiency) often occurs as a single deficiency and is also frequently associated with potassium, copper, and zinc deficiencies. Response of deficient pastures to applications of molybdenum are invariably in the legume component which requires larger quantities for nitrogen fixation by nodule bacteria than for its own needs (Anderson and Thomas 1946) (Pl. 42).

The main areas of molybdenum deficiency are the tablelands regions of New South Wales and the central highlands of Victoria and Tasmania where it usually occurs as a single deficiency, parts of the Gippsland region of Victoria where it commonly occurs in association with copper deficiency, the south-west of Western Australia where it is associated with copper and zinc deficiencies, and Queensland where it occurs on a wide range of soils.

Most of the deficient soils are acid and the deficiency in many of them is one of unavailability. Liming, by raising the pH, often releases sufficient molybdenum to meet the plant requirements, and, as mentioned above, most of the early reports of lime responses in Australian pastures were due to improved molybdenum availability rather than to a direct response to lime.

Cobalt. An insufficiency of cobalt in some Australian pastures for the needs of animals has long been recognised (Underwood and Filmer 1935; Lines 1935) but responses by pasture plants were not reported until recently (Powrie 1960; Ozanne, Greenwood, and Shaw 1963). As with molybdenum, the cobalt improves the growth of legumes in deficient pastures by increasing nitrogen fixation by nodule bacteria.

In ruminants cobalt deficiency is expressed either as a dual disease in association with copper ('coast disease') or as a simple cobalt deficiency, a wasting disease ('Denmark wasting disease') with symptoms of gradual starvation. A constant daily intake of cobalt of 0·1–1·0 mg per day is required by rumen flora for the synthesis of vitamin B_{12} and other compounds vital to the welfare of the animals.

Cobalt deficiency is largely confined to coastal regions in Western Australia, South Australia, and Tasmania. The dual copper-cobalt deficiency occurs largely on coastal aeolian calcareous sands but the simple cobalt deficiency is found over much wider areas including many of the soils adjacent to the calcareous sands. These soils include a wide range of soil types such as terra rossas, rendzinas, podzolic soils, and kraznozems (Lee 1951; Bennetts 1959). The occurrence of cobalt deficiency on coastal soils suggests that it may be associated in some way with high accession of cyclic salts.

Manganese. Compared with copper, zinc and molybdenum, manganese deficiency is only of minor importance in pastures in Australia. Table 21 : 5 shows that only a little over 4 per cent of the trace element superphosphates used on pastures in South Australia in 1965–6 contained manganese and in Western Australia the percentage was only 0·2.

The main region of manganese deficient soils is in the south-east of South Australia where the deficiency occurs on a range of alkaline soils including rendzinas, calcareous aeolian sands, terra rossas, solonetz soils, and grey calcareous soils (Tiver 1955). It also occurs on calcareous sands and grey calcareous soils of York Peninsula (Higgs and Burton 1955). Toms (1958) has reported manganese deficiency in subterranean clover on sands near Bremer Bay in Western Australia. The deficiency has not been reported in pastures in Victoria (Newman 1956).

Practically all of the pasture soils on which manganese deficiency has been recorded are alkaline, many of them calcareous, and in general the deficiency is one of unavailability rather than low manganese content.

Boron. Field responses to boron have been reported on several podzolic soils on the tablelands of New South Wales (Anderson 1952; McMullen 1966) and in Tasmania (Paton 1956c). Andrew and Bryan (1955) have shown boron to be marginally deficient in the coastal sands regions of Queensland. Boron deficiency has not been widely reported in Victoria, South Australia, or Western Australia.

The deficiency has assumed sufficient importance on the tablelands of New South Wales and in Tasmania to warrant the manufacture and use on pastures of small amounts of boron-containing superphosphate (Table 21 : 5).

Iron. The only notable report of an iron deficiency in Australian pastures is by Marrett (1963) on groundwater podzols in the lower south-east of South Australia.

Selenium and iodine. Selenium deficiency in lambs has been reported on some of the light soils in the south-west of Western Australia (Gardiner *et al.* 1962; Gardiner 1963) and on the Northern Tablelands of New South Wales (Setchell *et al.* 1962). An iodine deficiency on the Southern Tablelands was recorded by Setchell *et al.* (1960).

Residual values of trace element fertilisers. In general the residual effects of the application of trace element fertilisers to Australian soils appear to be good.

Fitzpatrick (1962) found that copper applied to certain soils, including peaty sands in the south-west of Western Australia, may be 'held' in unavailable forms. On these soils copper applications to crops need to be repeated every 3–4 years but the residual effects on pastures are much better and repeat applications are only required at intervals of 6–7 years. Most Australian soils, however, show good residual values for copper and, in many areas, applications need only be repeated at intervals of 6–8 years (Newman 1956; Anon. 1961b).

Zinc and molybdenum also have good residual effects and a single application is often sufficient to meet pasture requirements for at least 10 years (Newman 1955; Anon. 1961b). However, there is a suggestion that on certain Queensland soils more frequent applications of molybdenum may be necessary ('t Mannetje, Shaw, and Elich 1963). In Western Australia it has been found that the normal zinc impurities in superphosphate are often adequate fully to meet pasture requirements after an initial application (Ozanne, Shaw, and Kirton 1965).

For cobalt in Western Australia it is generally held that dressings should be repeated every three years (Anon. 1961b).

The residual value of manganese fertilisers is generally poor and for crops it is usually necessary to apply manganese with each crop, but the residual effects on pastures are somewhat better.

DIFFERENCES IN SPECIES RESPONSE TO APPLIED NUTRIENTS

All of the species used for sown pastures in Australia have been introduced from overseas. It is not surprising therefore that differences in degree of response to added nutrients should occur between species, particularly if the countries of origin are considered in relation to environment and soil type. This is particularly so with respect to the two latitudinal groups of pasture species, temperate and tropical.

Phosphorus

Although minor differences have been demonstrated between the phosphorus requirements of temperate Medicago and Trifolium species, little differentiation is made in practice. However, in northern Australia species of Stylosanthes and Lotononis give maximum yields at lower levels of applied phosphate than do Phaseolus, Desmodium, and other tropical genera. In the case of *S. humilis* this has been attributed to greater efficiency of phosphate uptake (Andrew 1966b) and a lower phosphorus requirement (Andrew, unpublished).

Lime

The response of pasture species to the application of lime may be compounded of several factors which include the correction of calcium deficiency, low pH, molybdenum deficiency, and aluminium or manganese excess. Differential response to lime may thus result from differences in tolerance to one or more of these factors.

In general terms grasses are less sensitive to acid soil conditions than legumes. Within the temperate legume group Medicago species are more sensitive than the Trifolium species. For this reason Medicago species are usually sown on calcareous or high fertility soils, although there are now examples of their establishment on poorer soils of medium pH by the use of lime-pelleted seed. Even within the Trifolium species the use of lime-pelleted seed has enabled their establishment in areas which hitherto had required moderate to heavy applications of lime. On the Southern Tablelands of New South Wales Munns (1965a) showed that lucerne was more sensitive to acid soil conditions than subterranean clover. On soils with pH values in the range 5·5–6·0 the effect of lime on lucerne growth was primarily through its effect on nodulation but on soils of pH 5·0–5·5 the effect was also through the suppression of aluminium toxicity. Subterranean clover, however, although it took up more, was more tolerant to aluminium (Munns 1965b).

The tropical legumes appear to be much more tolerant of acid soil conditions than the temperate legumes (Andrew and Norris 1961). This is particularly so with respect to low calcium availability, high acidity, and aluminium toxicity. With the exception of the Phaseolus species, tropical legumes are also relatively tolerant of manganese excess (Andrew 1963b).

There are thus few areas in northern Australia where application of lime has proved necessary for the growth of tropical pasture species. An important exception is the southern coastal lowlands region of Queensland (Andrew and Bryan 1955; Bryan and Andrew 1955). *Glycine wightii* syn. *G. javanica*, however, appears to require a higher soil calcium status and pH than other commonly used tropical species.

Copper and Zinc

On some soils lucerne appears to be less susceptible to zinc deficiency than many other species. On the soils of the Ninety-mile Desert of South Australia, for example, it has been found that lucerne responds to copper but not to zinc, whereas on the same soils subterranean clover requires both copper and zinc (Riceman 1945, 1948a). Similar differences between these two species have been observed on other soils in pot culture (Trumble and Ferres 1946) and in water culture (Millikan 1953a).

Andrew and Thorne (1962), in pot culture, showed that white clover gave a smaller response to copper than did berseem clover, lucerne, or barrel medic on a copper deficient soil from the southern coastal region of Queensland and, on the same soil, showed similar differences in the responsiveness of tropical legumes—Stylosanthes, Indigofera, and Centrosema responding to a greater degree than Desmodium or Phaseolus.

Molybdenum

There have been indications in some areas of southern Australia that the Medicago species in general have a higher molybdenum requirement than the Trifolium species, particularly subterranean clover (Anderson and Thomas 1946; Andrew and Milligan 1954). In practice the differences have not proved great enough to require differential rates of molybdenum.

Molybdenum responses have been obtained with all of the tropical legumes currently used in northern Australia. Luck and Douglas (1966) have shown that *G. wightii* has a considerably higher requirement than the others and for this reason a double strength molybdenum-superphosphate mix is now available for use on this species.

Boron

Studies on the Southern Tablelands of New South Wales have indicated that lucerne has a higher boron requirement than subterranean clover (Moye and Spencer 1962) or white clover and red clover (Simpson, Lipsett, and Fisher 1968).

Potassium

Shallow-rooting species of pasture legumes usually respond to potassium to a greater degree than deeper-rooting species. Thus white clover generally requires more potassium than lucerne and *Lotononis bainesii* more than *Phaseolus atropurpureus*. This almost certainly reflects advantages of the deeper root system in the uptake of potassium leached into the subsoil.

Competition between the grass and legume components of the pasture for soil and fertiliser potassium occurs in Australian pastures in much the same way as in Europe and North America.

DIAGNOSIS OF NUTRIENT DEFICIENCIES

The recognition and delineation of the present known regions of nutrient deficiency and the determination of appropriate corrective fertiliser rates have largely been achieved by extensive fertiliser field trials aided by pot culture experiments. In the case of nutrient disorders of stock, such as copper, cobalt, selenium, and iodine deficiencies where no effect of a deficiency is evident in pasture plants, the regions have been defined by observation of animal symptoms.

Visual plant symptoms have also been used extensively as aids in the diagnosis of nutrient disorders. Symptoms have been confirmed by water culture techniques and described accurately for many of the more important pasture species, particularly the legumes (Samuel and Piper 1929; Piper 1942; Millikan 1953b, 1958; Andrew 1963a).

Until quite recently little use has been made of soil or plant tissue testing techniques or of plant analysis in the diagnosis of nutrient disorders in pastures (Skene *et al.* 1965). However, with the realisation that the phosphorus status of many pasture soils may be approaching satisfactory levels and of the likely limitation of pasture yields in some areas by 'marginal' deficiencies not severe enough to induce plant symptoms, interest in more precise methods of diagnosis has increased rapidly.

Satisfactory correlations between various soil test values and pasture response have been reported for phosphorus (McLachlan 1963; Spencer and Barrow 1963; Ozanne and Shaw 1967; Spencer, Bouma, and Moye 1969) and potassium (Vimpany 1967). These results have indicated the potential value of soil tests in predicting likely pasture fertiliser needs, and limited commercial soil testing services for both phosphorus and potassium are now available in several States.

A number of plant tests have also been developed which show considerable promise either for the prediction of fertiliser requirements or for precise diagnosis of limiting nutrients. Reliable 'critical' values for potassium in subterranean clover (Rossiter 1955b) and for phosphorus, potassium, and calcium in white clover (Andrew 1960) have been derived from plant response studies and foliar analysis, while field studies on subterranean clover pastures (Bouma, Spencer, and Dowling 1969) have shown high correlations between final pasture yield and both the total sulphur and the sulphate contents of young subterranean clover plants. Bouma and Dowling (1962, 1966a and b) have proposed a physiological assessment of nutrient status which involves the transfer of the test plants to nutrient solutions. These solutions include one with all nutrients and others lacking various elements. Subsequent plant response patterns are then defined by leaf area measurements. A proposal for the measurement of nitrogen deficiency in grass swards based on measurement of relative growth rates has also been made by Greenwood, Goodall, and Titmanis (1965).

NUTRIENT DEFICIENCIES IN SOILS OF AUSTRALIAN PLANT COMMUNITIES

The main nutrient deficiencies occurring in agriculturally important soils of the plant communities discussed in Chapters 7–15 are indicated in Table 21 : 7.

TABLE 21 : 7 Nutrient deficiencies in soils of Australian grasslands

Community	Characteristic soil deficiencies
Tropics and sub-tropics	
Coastal grasslands, N.T.	N, P
Heaths (incl. wallum)	N, P, K, S, Mo, Cu, Zn, B
Rainforests	N, P, (K), Mo
Wet sclerophyll forests	N, P, (K), Mo
Woodlands	N, P, (K), Mo
Grasslands	N, S
Brigalow	N, (P), (Mo)
Temperate	
Wet sclerophyll forests	N, P, (K), *S*, Mo, *Cu*
Dry sclerophyll forests	N, P, S, Mo
Heaths	N, P, (K), S, *Mo*, Cu, *Zn*
Mallee heaths	N, P, (*K*), Cu, Zn, *Mn*
Mallee	N, P
Woodlands and grasslands	N, P, (*K*), *S*, *Mo*, (*Zn*)
Alpine and sub-alpine woodlands	P, *S*, *Cu*

Note: Figures in parentheses indicate marginal deficiency; those in italics are limited to certain soils.

FERTILITY BUILD-UP

As already stated the majority of leguminous pastures in Australia have been established on soils of low initial fertility. The original intention when pasture improvement first commenced was to provide better grazing and to increase animal carrying capacity. It was soon realised that these pastures, especially those with subterranean clover, were fulfilling a secondary function of raising the fertility of the soil. This function is now recognised as an important corollary to pasture improvement and, where cereals are grown, soil fertility building is now the major function of the pasture.

The build-up in fertility depends firstly and most importantly on the alleviation of the almost universal dual deficiencies of phosphorus and nitrogen. The first of these is met by the use of phosphatic fertilisers, almost without exception superphosphate or a modification of it, and the second by the fixation of nitrogen by legumes. The rate and extent of the fertility build-up thus depends to a considerable extent upon the accumulation in the soil of residual fertiliser phosphorus in plant-available forms, and upon the build-up of soil organic matter, or humus.

The major elements of organic matter are carbon, nitrogen, sulphur, and phosphorus. Accumulation of organic matter increases the total amounts of nitrogen and sulphur in the soil but the amounts of organic phosphorus formed affect the overall availability of residual phosphorus. An increase in organic matter increases the cation exchange capacity of the soil, which may in turn increase exchangeable calcium, potassium, and magnesium and decrease pH. Organic matter also improves the structure and water retention properties of soils.

The rate of organic matter accumulation and fertility build-up are influenced by many factors, the relative importance of which will vary from soil to soil. The more important of these include soil type, initial organic matter content, pasture yield and management, the rate and frequency of superphosphate application, temperature, rainfall, leaching intensity, and removal of nutrients in farm produce. Under most conditions in Australia the loss of nutrients in farm produce is small (Williams 1962).

Appreciable increases in soil fertility and organic matter content have now been reported from various parts of the Commonwealth (Hingston 1959; Watson 1963 (W.A.); Cook 1939; Russell 1960a (S.A.); Donald and Williams 1954; Rixon 1966 (N.S.W.); Davies and Andrew 1964 (Qld)). It is to be expected that with time accumulating organic matter will approach a new equilibrium value in a curvilinear fashion. In most of the studies so far, rates of accumulation of organic matter with time have been linear, or near linear, probably reflecting only the earlier stages of accumulation. Accession rates of 50–90 lb of nitrogen per acre (56–100 kg per ha) per cwt (125 kg per ha) of superphosphate applied have been recorded (Cook 1939; Donald and Williams 1954; Hingston 1959; Russell 1960a) although Russell (1960a) has shown that the rate of fertiliser application can influence this rate appreciably.

Following the build-up in organic matter in yellow podzolic soils at Crookwell, N.S.W., there were marked increases (Table 21 : 8) in available phosphorus, nitrogen, sulphur, and potassium as well as in water-holding capacity (Donald and Williams 1954; Williams and Donald 1957; Williams and Lipsett 1960). Cation changes will depend upon the nature of soil and of its cations. The Crookwell soil referred to in Table 21 : 8 contained non-exchangeable potassium which could be utilised by plants, and this probably provided most of the potassium for the increase in the exchangeable form (Williams and Lipsett 1960). Russell (1961) found no increases in exchangeable potassium and magnesium and increases in calcium which were equivalent only to a portion of the total calcium applied in fertilisers.

The increase in fertility possible under subterranean clover pastures is indicated in Table 21 : 9. This table, taken from Donald and Williams (1954), shows the yield of oats sown immediately after cultivation, without fallow, on a virgin and on a nearby 'improved' soil in the Crookwell district of New South Wales.

TABLE 21 : 8 Changes in soil nutrients and soil properties in the surface 4 in. (10 cm) of soil for each cwt of superphosphate applied per acre (125 kg per ha) to subterranean clover pasture on a yellow podzolic soil at Crookwell, N.S.W.

Nutrient	Increase, lb per acre (approx. kg per ha) from fertiliser	from plant or soil
Nitrogen		86
Phosphorus	10·3 (4·9 inorganic) (5·4 organic)	
Sulphur	13·4	
Exchangeable calcium	22·0	3·5
Exchangeable potassium		6·5
Exchangeable magnesium		5·2
Carbon		1300
Organic matter		2300
Cation exchange capacity[a]		0·4
pH[b]		−0·06

[a] m.e. per 100 g soil.
[b] pH units.

EFFECTS OF MANAGEMENT

In southern and western Australia particularly, the trend towards heavier stocking rates in recent years has posed questions of fertiliser requirements. Removal of phosphorus and sulphur from pastures by sheep is small compared with the input from superphosphate, even at low rates of application (Donald and Williams 1954). Thus except where appreciable leaching occurs it would seem likely that some increases in stock numbers should be possible without raising fertiliser requirements. In Western Australia Parkin (1966) in the Chapman Valley and White, Lightfoot, and Glencross (1966) at Avondale found that stocking rates could be increased without increasing the rates of superphosphate. However Lightfoot and McGarry (1966) at Wongan Hills, applying

TABLE 21 : 9 The yield of oats (hay) grown, with and without fertiliser, on 'unimproved' and 'improved' soils at Binda, N.S.W.: cwt per acre (kg per ha)

	Fertiliser treatments		
Paddock history	No fertiliser	Superphosphate 1·5 cwt/acre (187 kg/ha)	Superphosphate 1·5 cwt (187 kg per ha) and ammonium nitrate 0·6 cwt/acre (75 kg/ha)
Unimproved grazing land	8·6 (1079)	12·3 (1544)	18·8 (2359)
Approx. 20 years clover and superphosphate 7 cwt per acre (878 kg per ha)	33·8 (4242)	51·2 (6426)	56·6 (7103)

Min. sig. diff. $P < 0{\cdot}05 = 3{\cdot}0$ (376)
$P < 0{\cdot}01 = 13{\cdot}0$ (1631).

superphosphate annually at 90 lb per acre (101 kg per ha), found that animal production declined if the stocking rate was increased beyond 1·5 sheep per acre (3·7 per ha). Mann *et al.* (1966) at Mt Barker found that 1 cwt per acre (125 kg per ha) of superphosphate was inadequate to maintain wool yields at stocking rates of 5 and 6 sheep per acre (12–14 per ha). At 2 and 3 cwt per acre (250 and 375 kg per ha) wool yields were greater at high than at low stocking rates.

On the Southern Tablelands of New South Wales McLachlan and Norman (1966) indicated that the high utilisation of pasture at high stocking rates did not appear to increase the fertiliser requirement above that of standing unused herbage. They suggested that the greater nutrient re-cycling at high stocking rates might reduce the need for additional nutrients. McLachlan (1968) further indicated that pastures that had been grazed at high stocking rates for fifteen years responded less to applied phosphorus and had higher available soil phosphorus contents than otherwise similar pastures grazed at lower stocking rates.

Grazing intensity may also influence pasture nutrition through the transfer of plant nutrients into 'camp' sites by the grazing animals. Hilder and Mottershead (1963) demonstrated a substantial transfer of nitrogen, phosphorus, potassium, calcium, and magnesium into small camp site areas on pastures in northern New South Wales. On a soil of low initial potassium status, Hilder (1964) showed that the resultant transfer of potassium into small camp site areas was sufficient to create a severe potassium deficiency on the rest of the paddock.

FUTURE TRENDS

Davies and Eyles (1965) have estimated that the total area of land available for development in Australia is of the order of 430 million acres (174 million ha), and, of this, approximately 360 million acres (146 million ha) still await development. Of this 360 million acres about 85 million (34 million ha) (compared with 65 million (28 million ha) already developed) are in southern Australia and the remainder in northern Australia.

Pasture development in southern Australia seems likely to follow the pattern already established, at least for many years to come. Ordinary superphosphate is likely to remain an important phosphatic fertiliser, but with more accurate recognition of sulphur requirements and better prediction of sulphur deficiency the use of 'triple' superphosphate and 'sulphur-fortified' superphosphates are likely to assume far greater importance—particularly if the present trends evident in the increasing use of aerial top-dressing (see Table 21 : 2) continue.

The trends likely in northern Australia are not yet clearly defined. During the past decade or so great increases in the range of pasture species available have been made and it seems likely that legumes will be as important as they have been in southern Australia. Similar nutritional problems to those already encountered in the south are likely and similar fertiliser practices are likely for their solution.

The role of nitrogen fertilisers is less clear. Donald (1960b) suggests that fertiliser nitrogen could have an important place in pasture development in northern Australia.

22

NODULATION OF PASTURE LEGUMES

D. O. NORRIS

The key to the spectacular success of pasture improvement in Australia lies underground in the shape of legume nodules. The realisation that this is so has in the past twenty years resulted in the fact that the focus of endeavour in the field of legume bacteriology has moved from the U.S.A. (where it was in turn inherited from Europe) to Australia and New Zealand. More acres of legume-based pastures have resulted not only in more sheep and cattle, but in more legume bacteriologists and grassland scientists, and an output of new ideas on origins, functioning, and practical application of the symbiosis.

THE HISTORY OF LEGUME INOCULANTS IN AUSTRALIA

The early beginnings have been reviewed by Roughley (1962). Greig-Smith (1899), a Sydney bacteriologist, published a dissertation on the nodule bacteria before it was finally agreed that the organisms were bacteria. The potential use of inoculant cultures was first mentioned in 1896 in the *Agricultural Gazette of New South Wales*, by Guthrie, but the first field trial of an inoculant was not recorded in the *Gazette* until 1905. According to Roughley (1962), this was done with an imported American culture by Marks, a bacteriologist at Hawkesbury Agricultural College, New South Wales. The Department of Agriculture of New South Wales first distributed agar cultures to farmers in 1909. At first free, these cultures were ultimately charged for at cost because of the increasing demand. Distribution of agar cultures from Departments of Agriculture in other States began in the 1930s (e.g. Pittman 1935). Some agar cultures, particularly those for less commonly used legumes, are still available to farmers at cost from State Departments of Agriculture, but most inoculants in Australia and New Zealand are now supplied as peat-based cultures by commercial interests.

Peat cultures were first issued by the New South Wales Department of Agriculture in 1953, but demand soon overtook capacity and commercial firms were invited to enter the field in 1954. At present four companies (one operating in Melbourne, two in Sydney, and one in Brisbane) supply the Australian market, and one company (operating in Auckland) supplies the New Zealand market. The Brisbane company specialises in inoculants for tropical species. For a short time in the 1950s a freeze-dried product, needing reconstitution before use, was marketed in Sydney, but it was withdrawn following poor field performance. New Zealand cultures are the wet type, in which sticker in solution is premixed with the peat, but all Australian cultures are the 'dry' peat type (approximately 40 per cent moisture, but friable). Some are prepared by the open mixing of broth with autoclaved peat, and others by injection of broth into pre-packaged peat sterilised in the packet, either by autoclaving (N.Z.) or by gamma irradiation (Australia).

As a very recent development in Australia—since the advent of tropical pasture species—some merchants now automatically supply specific inoculant culture with the seed, especially when they receive orders from foreign countries where inoculant supplies are unlikely to be available.

The U-DALS Organisation

The first commercial production of cultures in Australia coincided with, and of course was primarily stimulated by, extensive development of legume pastures on grazing land previously carrying native pasture largely devoid of legumes, or on land newly broken from native bush. Being devoid of the specific bacteria that such species as subterranean clover require, these lands provided critical testing conditions for inoculants, and deficiencies in many of the early commercial inoculants were strikingly revealed. Faced with serious production control problems, manufacturers and scientists, under the leadership of Professor J. M. Vincent, then at the University of Sydney, pooled information and experience at a conference in 1955. They agreed upon minimum standards for inoculant cultures, and the University of Sydney began to assist manufacturers by advising them and by checking the quality of broths used for peat culture preparation.

In 1957 the unique organisation known as U-DALS (University—Department of Agriculture Laboratory Service) was formed. It is a three-sided union comprising the University of Sydney, the Department of Agriculture of New South Wales, and manufacturers. It draws on both University and Department of Agriculture staff, as well as having employees of its own, and receives voluntary financial support from inoculant manufacturers and from various industry research funds, such as the Wheat Research Fund. U-DALS maintains stock cultures of tested bacterial strains and supplies these to manufacturers; it checks broths forwarded by manufacturers for purity and bacterial count before adding to peat; it checks the peat cultures immediately after manufacture, and by periodically sampling retailers' stocks; it receives and collates reports from workers throughout Australia on the performance of inoculant strains and periodically recommends changes to manufacturers; and it conducts research on factors affecting quality and survival of bacteria in inoculants. In addition it is associated with, though not directly responsible for, the publication of *Rhizobium Newsletter*, which since 1956 has served as an informal exchange of information on all aspects of Rhizobium research, inoculant culture preparation, and field performance of inoculants. The *Newsletter* began as an Australian domestic circular and it may not be quoted as a publication, but it has increasingly found its way overseas and now receives many contributions from outside Australia.

U-DALS is an entirely voluntary body. There is no statutory control of legume inoculants in any State of Australia, and no compulsion on a manufacturer to belong to U-DALS. Nevertheless the standards laid down and supervised by the organisation are so high that non-members are obliged to ensure a high quality in their own product to survive in a strongly competitive market. Because of this the Australian pastoralist is fortunate in having available at all times a source of high-quality inoculants, a situation very different from that of fifteen years ago.

THE COURSE OF AUSTRALIAN RESEARCH IN LEGUME BACTERIOLOGY

The Australian contribution to this field has been fully reviewed by Vincent (1954, 1956, 1958, 1962a, 1965, and 1967), himself a prolific contributor to the work. His 1962 review lists 140 references. At the beginning in the 1930s, little more was attempted than the maintenance of a small range of strains, mostly imported, and their issue as agar cultures to farmers on request. The work was usually a sideline to the activities of a plant pathology service in a State Department of Agriculture. The research phase in Australia may be said to date from the paper by Strong (1937) in which he clearly demonstrated that Rhizobium strains from subterranean clover are ineffective on red and white clovers and vice versa. It may be fairly said that this launched the pastoral revolution based on subterranean clover that has transformed the southern half of Australia. A rapid tide of investigation on all aspects of inoculant preparation and field performance set in during the 1940s. Great emphasis was placed in this phase on the interrelations of the Rhizobium symbiosis and the mineral nutrition of the plant host, and research is still active in this field.

Such early fundamental research on Rhizobium as was done clearly related to practical needs of field work, for instance the work of Vincent (1941, 1942) on serology of clover and medic strains. Subsequently, during the 1950s, a rising interest in the fundamental functioning of the symbiosis became apparent. Strong schools of fundamental research on Rhizobium-host relations have arisen in the Division of Plant Industry of CSIRO at Canberra and in the Universities of Sydney and Western Australia.

Work on tropical legume bacteriology began in Queensland with isolated studies by Steindal (1941) and McKnight (1949). The work of Norris (1956–67) was the direct outcome of the need to do for northern Australia what had been done for the south over the previous fifteen years. When the drive to develop legume-based pastures for the monsoonal north began in the early 1950s it was apparent that accumulated knowledge of inoculants for temperate clover and medic species had little relevance to the summer-growing tropical species of genera such as Phaseolus, Desmodium, Glycine, and Stylosanthes. Knowledge of the Rhizobium requirements of these species was almost non-existent, as were suitable inoculant strains. The situation called for radical re-thinking, and in this process there emerged a fundamentally new philosophy on the origins and development of the legume-Rhizobium symbiosis (Norris 1956, 1965), which in turn has had a strong practical impact on tropical pastures, and which will be dealt with again later.

In retrospect it is to New South Wales, the eldest State of Australia, that most of the credit for beginning and fostering legume bacteriology belongs. From there, active work has developed in all States of Australia (as well as the A.C.T.), with the notable exception of Victoria.

SOME CONTRIBUTIONS TO PASTURE LEGUME BACTERIOLOGY RESULTING FROM THE IMPACT OF THE AUSTRALIAN ENVIRONMENT

The Molybdenum Story

Although the function of molybdenum in plant growth or even in the functioning of leguminous nodules is not an Australian discovery, the appreciation of the vital role of this element in legume pasture development is largely due to the initiative of Anderson (1942, 1956a and b). In the Meadows district of South Australia, subterranean clover pastures on ironstone soils remained very poor despite liberal application of superphosphate. It was noticed that improved growth occurred where timber had burned, and the application of wood ashes reproduced this effect. Patient elimination of other nutrients led to molybdenum, and finally the application of 1 lb of ammonium molybdate per acre (1 kg per ha) gave spectacular yield increases. Subsequent work (Anderson and Moye 1952; Anderson and Oertel 1946; Anderson and Thomas 1946) clearly established the basic facts that molybdenum affects the functioning of the symbiosis within the nodule, not the formation of nodules, and that its availability in soils is a function of pH, the effect of lime being to release molybdenum.

While not directly a matter of legume bacteriology, this work has had an incalculable effect on the subsequent testing and use of inoculants. For want of knowledge of poor molybdenum status of the soil, the best inoculant might be rated a failure, since it will not produce any improvement in the legume. Beginning about 1951, superphosphate premixed with molybdenum has been available on the Australian market for pasture development, the present consumption being estimated to lie between 300,000 and 500,000 tons per annum.

The Roles of Calcium and Magnesium in Rhizobium Nutrition

A complete reappraisal of this subject has resulted from Australian research. The traditional view, based largely on the work of McCalla (1937), was that Rhizobium is a calcium-hungry organism. It was challenged by Loneragan and Dowling (1958) and Norris (1959). Norris concluded, after studying 96 strains by a variety of techniques, that Rhizobium must require calcium in trace amounts only and that, by contrast, it is very sensitive to magnesium supply. He showed that McCalla's results, which appeared to indicate enhanced growth of Rhizobium with increasing degree of calcium saturation of a clay colloid, were basically due not to the calcium enriching the clay, but to the small amounts of magnesium—the true limiting nutrient—that it displaced from the clay. Norris also pointed out that the traditional addition of calcium carbonate to nutrient agar for Rhizobium growth is pointless except to neutralise acidity, and 'cowpea' type bacteria (the majority) do not produce acid. The calcium needs of the bacteria for nutrition are adequately met by the calcium occurring as impurities in the ingredients of the medium, and on an agar medium these needs are grossly oversupplied since agar is itself a calcium compound.

Doubt of the validity of these findings led both Bergersen (1961) and Vincent (1962b) to make careful quantitative studies of Rhizobium growth in relation to calcium; their results nevertheless substantiated those of Norris. Calcium was shown to be a required nutrient for growth, but the amount involved is so small that it can become a limiting factor only in ultra-purified defined media. Vincent (1962b) demonstrated that the bacteria require a Ca : Mg ratio of 1 : 8, a result in agreement with the Brazilian workers Ruschel, Alvahydro, and Penteado (1962), and has since gone on to a valuable series of studies of the function of calcium in the cell of Rhizobium principally as a constituent of the cell wall.

The demonstration of the unimportance of calcium and the overriding importance of magnesium to Rhizobium has had little effect on practice in Australia, other than to secure better growth in culture by omitting calcium salts and enhancing magnesium supply in the medium. Despite the unequivocal results of Fulmer (1918), who demonstrated great increases in Rhizobium numbers after adding magnesium salts to soil already well served for plant nutrient purposes, the idea has had no effect on field practice in Australia, possibly because of the antagonistic attitude of Loneragan (1960), who suggested that 'a response of Rhizobium to magnesium will only be obtained under conditions where the plant can't grow anyway'. In New Zealand, however, improved field nodulation of clovers has followed the use of dolomite instead of lime in pelleting clover seed (Hastings and Drake 1962), and a mixture of equal parts of dolomite and Gafsa phosphate is the standard material recommended for pelleting.

The Effect of High Soil Temperature on Rhizobium

The importance of this subject to Australia is twofold: in southern temperate areas because of the necessity to ensure that bacteria survive the hot dry summer to nodulate regenerating annual species, and in tropical northern areas because most legume sowings are made into hot moist soils in mid-summer.

In the south-west of Western Australia, which has a Mediterranean climate, Marshall, Mulcahy, and Chowdhury (1963) studied over-summering of subterranean clover inoculant. Subterranean clover was successfully nodulated and established in the first year, but failed in the second year because of lack of nodulation. Most trouble occurred in grey sands (80 per cent nodulation failure) and yellow sands (50–70 per cent failure), but there were no failures on red sandy, brown solonetzic, or red-brown earths. Wherever an abrupt change of texture from sand to heavier soil occurred there was an abrupt cessation of the problem. Lupin Rhizobium was apparently not affected, only clover Rhizobium. Since the trouble seemed to be related to absence of clay fractions from the soil, Marshall and Roberts (1963) made a field experiment on a deep grey sand near Perth. The soil was amended with (1) a finely ground silica, (2) montmorillonitic clay, or (3) fly ash from a power house (mostly burnt clay). The percentages of subterranean clover plants nodulated in the various soils the following season were control 28 per cent, silica 21 per cent, montmorillonite 54 per cent, and fly ash 73 per cent. The magnitude of the survival problem involved may be gauged from their quoted figures of soil temperature readings for January in a yellow sand near Perth:

Mean maximum temperature at 1 in. (25·4 mm) 50·5°C (highest 65·5°C)

Mean maximum temperature at 4 in. (101·6 mm) 37·8°C (highest 47·2°C).

Marshall (1964) then made laboratory studies with the amended soils, inoculated with bacteria, dried, and subjected to temperatures of 50°C and 70°C for varying periods. He noted remarkable differences in protective power between the different materials. Kaolinite had no protective effect at all but montmorillonite and illite protected strongly. Of the two iron oxides occurring in soils, geothite had no protective value, but haematite was strongly protective. Lupin and soybean bacteria, that is the slow-growing cowpea type, survived these high-temperature treatments even in untreated sand, in contrast to the clover and lucerne bacteria. Although few improved pastures are likely to encounter a survival problem equal to that in Western Australian sands during a Mediterranean-type summer, these results may apply elsewhere, possibly in pelleting or culture storage.

Brockwell and Phillips (1965) demonstrated the remarkable ability of lucerne Rhizobium to survive heat and desiccation. Lucerne seed inoculated with peat and a sticker of 10 per cent sucrose was sown in dry soil devoid of native lucerne bacteria at Katherine, Northern Territory, on 2 August and lay dormant in the soil until 1 October (59 days). When germinated by irrigation, 77 per cent of plants sown at 0·5 in. depth (12·7 mm) and 82 per cent of plants sown at 1 in. depth (25·4 mm) nodulated. During this time soil temperatures as high as 61°C at 0·5 in. (12·7 mm) and 56°C at 1 in. (25·4 mm) had been recorded. Subsequent laboratory studies of survival at 40°, 50°, and 60°C showed that broth inoculum did not survive more than 72 hours even at 40°C, broth culture applied with sucrose survived to 72 hours at 50°C and 360 hours at

40°C, but peat culture survived to 504 hours (4 weeks) at 40°C, to 72 hours at 50°C, and to 20 hours at 60°C.

Remarkable tolerance of some Rhizobium to heat in dry soil was also demonstrated by Wilkins (1967). Medicago, Acacia, Psoralea, and Lotus Rhizobium survived 5 hours exposure to 100°C. In three soils, Medicago Rhizobium survived 32 hours continuous exposure to 50° and 60°C, and 20 consecutive daily exposures for 8 hours to 50°, 60°, and 70°C, alternating with 16 hours at 30°C. In moist soil, however, survival rates were much lower, medic Rhizobium surviving 50°C, but not 55°C, for 5 hours, though some Psoralea Rhizobium still survived 60°C. Both medic and Psoralea Rhizobium strains could withstand a regime of 10 daily exposures in moist soil to 40° and 45°C for 8 hours, followed by 16 hours at 30°C, conditions comparable with what might be expected in the field.

Philpotts (1967), working with cowpeas in a moist black chernozemic soil in northern New South Wales, found that the higher the soil temperature at sowing depth, the lower was the percentage of plants with nodules and the number of nodules per plant, as though the inoculum were being adversely affected. She also recorded temperatures between 40° and 45°C over a period of 5–6 hours from 12.00 to 18.00 hours at a depth of 1 in. (25·4 mm).

The data of Bowen and Kennedy (1959) in Queensland perhaps illustrate most strikingly the difference between the behaviour of cowpea Rhizobium and specialised types of Rhizobium under moist conditions and their behaviour in dry soil. The following maximum temperatures for growth on agar were recorded:

	Maximum temp. for growth		
	Lowest	*Highest*	*Mean*
8 strains ex *Medicago* spp.	36·5°C	42·5°C	41·0°C
9 strains ex *Trifolium* spp.	31·0°C	38·4°C	33·2°C
68 strains cowpea type	30·0°C	42·0°C	35·4°C

When bacteria added to a moist sandy soil were incubated at 40°C, two strains from clover died within 10 hours and three out of four cowpea strains within 12 hours (the fourth surviving to 24 hours), and two strains from Medicago survived to 24 hours. Concurrently with these studies, temperature records were made in the field at Coolum, Queensland, in the same moist sandy soil on a typical cloudless summer day in February. Maxima of 47·5°C at 1 in. (25·4 mm) and 42·5°C at 2 in. (50·8 mm) were reached, and the temperature at 1 in. remained above 40°C for 6 hours. The implications for shallow sowings of summer species into cultivated soils are obvious.

Two features of this subject warrant special stress: the advantages of using a peat culture, and the strong ecological implications, which suggest the possibility of selecting Rhizobium for specific temperature environments. More research is needed into this subject, which is relevant to all tropical and warm temperate areas.

Antibiosis as a Factor in Pasture Establishment on New Land

Hely, Bergersen, and Brockwell (1957) reported a failure of subterranean clover to nodulate on yellow podzolic soil newly broken from native grassland on the New England Tableland region of New South Wales. Normal inoculation of the seed completely failed to produce nodulation. An exhaustive investigation of nutritional and microbiological aspects produced clear evidence that prior establishment in the rhizosphere of an antibiotic-producing agent was responsible for the inoculant failure, but no causal organism was identified. Bergersen, Brockwell, and Thompson (1958) subsequently developed a pelleting technique in which the incorporation of the inoculant in nutrient pellets containing bentonite and dried blood, or bentonite and milk powder, both of which allowed extensive multiplication of the bacteria within the pellet, largely overcame the problem.

The subject arose again in Western Australia during attempts to bring under pasture large areas of lateritic podzolic soil bearing a dense cover of dwarf 'Tamma scrub' (*Casuarina humilis*). When inoculated subterranean clover was sown immediately after clearing, nodulation failed, the plants were severely stunted, and a pasture could not be established. If the land was allowed to lie fallow for two or three years before sowing, clover establishment was successful. Cass Smith and Holland (1958) found that sterilisation of the soil with fungicides solved the problem. Holland then began a classical series of studies (Holland 1962, 1966; Holland and

Parker 1966) that clearly showed the role of saprophytic antibiotic-producing fungi in the problem. The soil after clearing is left with 10 per cent by weight of the surface 2 in. (50·8 mm) composed of plant tissue, principally roots, from *Casuarina* sp. On this medium flourishes a dense population of fungi, which shows a marked succession of species during decomposition of the roots. *Penicillium* spp. dominate in the early phases, when toxic effects are acute, but by the time the succession has moved through to Ascomycetes and Basidiomycetes the nodulation problem disappears. It was clearly demonstrated both in artificial culture and in soil that antibiotics produced in the Penicillium phase by numerous organisms are toxic to both plant and Rhizobium. Some of the fungal flora isolated occur in the rhizosphere in both problem and non-problem areas, but the antibiotic-producers occur only in the problem areas. The simplest way to overcome the problem is to allow the soil to lie fallow for a season before attempting pasture establishment.

In New Zealand, Beggs (1961, 1964) obtained strong evidence that a long-standing failure of white clover to establish in the Wither Hills, Blenheim, North Island—in the face of intensive nutrient and inoculant treatments and investigation—was due to a growth inhibitor in the soil. Sterilisation of the soil with formalin led to spectacular nodulation and establishment of white clover, as did elimination of the native Notodanthonia tussock grass by chemical turf killers such as sodium dichlorpropionate. Parle (1964) obtained experimental evidence that the problem was associated with the presence of living Notodanthonia grass. A heat-stable water-extractable toxin was obtained from the rhizosphere of living plants, but not from the roots themselves, and the evidence strongly suggested that antibiotic production by an organism or organisms living in the grass rhizosphere was the cause of the trouble.

These instances are now sufficiently numerous to sound a strong note of caution in pasture establishment on new land, particularly where it is being cleared from native tussock or scrub. Much time may be wasted in exhaustive checking of inoculants and fertilisers that are not related to the trouble at all.

The Story of Lime Pelleting

The origin of lime pelleting for promoting legume nodulation on acid soils appears to be the work of Snieszko (1941) in Maine, U.S.A., who coated field pea seed with lime after inoculation and obtained greatly improved nodulation on acid potato land. The development of the process as a practical field technique for establishing species of Trifolium, Medicago, and Vicia on acid soils without applying lime to the soil was begun by Loneragan *et al.* (1955) in Australia. The additional potential of the technique as a means of pre-inoculation was probably first indicated in the New Zealand work of Hastings and Drake (1960), who obtained excellent nodulation of white clover after holding pelleted seed for 92 days. Others have subsequently obtained similar results (Brockwell 1962; Brockwell and Whalley 1962; Goss and Shipton 1965; Murguia and Date 1965).

While all of the early work and much of the commercial and farmer pelleting done at the present time uses a 40–45 per cent solution of gum arabic as an adhesive for the pellet, Cass Smith and Goss (1958) in Western Australia developed the use of 5 per cent methyl ethyl cellulose (Cellofas A—now no longer manufactured), and Hastings and Drake (1960) in New Zealand developed the use of 5 per cent methyl cellulose. These latter workers at the same time exploited the stimulating action of magnesium on Rhizobium by using a mixture of dolomite and Gafsa rock phosphate as a pellet coat instead of lime. Hely (1965) in Canberra developed an advanced pelleting technique called the 'three-step process' in order to overcome excessive mortality of bacteria on the seed coat during aerial seeding of exposed hilly terrain several weeks before germinating rains occurred. Up to 800,000 bacteria per seed were stuck to the seed by first soaking it in a bacterial broth, then adding a pellet incorporating a heavy inoculation with peat culture, and finally applying a tough outer coat of clay + lime + gum arabic sticker. The work of Brockwell and Dudman (1968) has now revealed this technique as unnecessarily elaborate. Serological typing of the resultant nodules has proved that, independent of the Rhizobium strains used, the only bacteria that contribute significantly to nodulation are those incorporated in the peat culture. This necessity for peat culture to be used in pelleting accords with the experience of many workers.

'Lime pelleting' is now a firmly established commercial practice carried out by many seed suppliers on a contract basis in both Australia and New Zealand. Gum arabic, various cellulose derivatives, and certain animal glues are known to be used as adhesives. However, a wave of enthusiasm produced a strong tendency to recommend universal lime pelleting of legumes, regardless of species. This is illogical. Norris (1967) recently discussed the pros and cons of lime pelleting in an attempt to halt the indiscriminate application of the procedure to tropical species. He pointed out that with many of these species there is a distinct possibility that lime will do more harm than good, since the species are naturally adapted to acid soils and some strains of the cowpea Rhizobium may be intolerant of the high alkalinity of the lime coat. What they need is a pellet coating of an inert material that will protect the bacteria when seed is dropped on to the surface of the soil but will itself have no deleterious effect on them. Rock phosphate dust is a compromise in this direction, but there must be many other substances awaiting exploitation. Where the synthetic cellulose derivatives are available, they are preferable to gum arabic from an economic point of view, since 5 lb (2·2 kg) of these materials will do the job that requires 40–45 lb (18–20 kg) of gum arabic.

THE BALANCED APPROACH ACKNOWLEDGES TROPICAL ORIGINS

In 1956, Norris published a critical review of the state of legume bacteriology in relation to the phylogeny of the legumes, acting on the assumption that to understand a symbiosis one must know something of both partners. A completely new philosophical approach to the subject was incorporated in this paper, which has been discussed and amplified in several subsequent publications (Norris 1956, 1958b, 1959, 1964, 1965, 1966a and b, 1967). In brief, it suggests that the legumes probably evolved under conditions closely approximating those of the modern tropical rainforest, which are characterised by low soil nutrient status and high acidity. The majority of the legumes (in diverse genera of all three great subdivisions of Leguminosae) that still inhabit acid tropical soils possess the slow-growing cowpea type of Rhizobium, which, according to this evidence, presumably is the archetype of Rhizobium. The broad lines of evolution of the symbiosis are suggested to have been:

By the host legume:

1. Invasion of temperate and arid zones of the earth.
2. Reduction of growth form from tall rainforest trees to shrubs and woody lianas to perennial herbs to annual herbs.
3. Progressive loss of the ability to establish symbiosis unspecifically with cowpea Rhizobium, which is another way of saying progressive development of strain specificity or physiological selectivity for adapted strains of bacteria.

By the symbiont bacteria:

1. Progressive loss of ability to tolerate acid soil conditions where the host legume adapts itself to alkaline soil environments.
2. Development of peritrichate flagellation from the primitive condition of a single subpolar flagellum, accompanied by a change from alkali-producing to acid-producing habit in culture media.
3. Development of physiological selectivity for the host legume, parallel to that developed by the plant itself. This occurs in two stages, ability to fix nitrogen within the nodule being lost before ability to invade the root and form a nodule.

Some of the implications of this view of the development of the symbiosis follow.

Cross-inoculation Groups

The concept of the cross-inoculation group, as originally advanced, supposed that all legumes belonged to one group or other. Those that did not belong to a group were 'exceptions'. In fact, the cross-inoculation group is the exception, not the rule. From the basic unspecialised tropical legume in symbiosis with the cowpea type of Rhizobium, every degree of specificity has developed, sometimes in a single isolated species, sometimes in a group of species. The existence of a cross-inoculation group then simply means that we are dealing with a recently developed cluster of species sharing a common degree of physiological specialisation. The Medicago-Trigonella-Melilotus complex is a good example.

The 'cowpea cross-inoculation group' is not a group at all, being merely the assemblage of the majority of the legumes retaining the primitive unspecialised form of the symbiosis.

The Classification of Rhizobium

Traditionally based on the cross-inoculation groups, classification has given us a number of species such as *R. trifolii.* The 'cowpea' type has never been accorded specific rank, although a strain-specific variant associated with the soybean has been designated '*R. japonicum*'. Clearly, the archaic cowpea type associated with the majority of legume species should form the basis of the genus Rhizobium. However, the view has received no consideration by recent workers concerned with forming a new classification for Rhizobium (Graham 1964; De Ley and Rassel 1965; Moffett and Colwell 1968), who have proceeded strictly on Adansonian principles, using bacteriological data and ignoring symbiotic evidence. Only 't Mannetje (1967b) in Queensland has shown that the symbiotic evidence for cowpea Rhizobium as the archetype accords perfectly with the bacteriological data of these other workers. Failure to understand that the classification of a symbiont must start from the phylogenetic evidence of the symbiosis and be supported by bacteriological data has resulted in the launching of an unacceptable proposal to remove all slow-growing cowpea Rhizobium to a separate genus Phytomyxa (Graham 1964).

All Rhizobium bacteria should stay in the genus, but to what extent species can be erected on the basis of specialised forms associated with strain-specific legumes is a thorny problem. A veritable infinity of intergrading types must exist, bridging the gap from the primitive tropical legume to an extremely advanced form like *R. meliloti* associated with the lucerne cross-inoculation group.

The Field Approach to Inoculating Tropical Species

Since legume development has followed the path from non-specialisation to strain specificity, every degree of adaptation will exist in the vast assemblage of some 14,000–15,000 species. Among tropical species, many like cowpea and siratro (*Phaseolus atropurpureus*) will retain the primitive condition to a marked degree and rarely need inoculation. Many others in various degrees of specificity, while retaining the basic cowpea type of Rhizobium, will require a specific strain of this type. Those that have not gone far along this path may be satisfied by the use of a wide-spectrum cowpea inoculant, for example *Dolichos lablab.* Eventually species are encountered that need a group-specific inoculant. Thus the *Desmodium* spp. in common pastoral use usually require inoculant strains derived from *Desmodium* spp., and even within the genus some are more exacting than others. *D. intortum* will usually nodulate quite well from cowpea Rhizobium in the soil, but *D. uncinatum* does so only poorly and tardily, and *D. heterophyllum* so far has shown effective symbiosis only with strains actually derived from *D. heterophyllum* (Diatloff 1968). Finally, some tropical species like *Leucaena leucocephala* and *Sesbania* spp. have followed the same path as the clovers, developing specialised, fast-growing acid-producing Rhizobium strains and requiring a highly specific inoculant. These specificities may only be determined by experiment, observation, and experience.

In Australia the wide-spectrum cowpea strain CB756, derived originally from *Dolichos africanus,* is serving as a commercial inoculant for many tropical species in the genera Phaseolus, Glycine, Vigna, Dolichos, Stylosanthes, etc. Other inoculant strains for more specific legumes are available from inoculant manufacturers on request. Unusual specifics for species rarely in use are usually available on request from one or other of several research laboratories. In several instances in the past, new legume cultivars, for example the Woogenellup cultivar of subterranean clover in Western Australia, have been launched before it has been checked that they will function effectively with available inoculants. This has resulted in field failures and the necessity to prepare special inoculants. In future, no species or cultivar of legume will be marketed commercially in Australia until a satisfactory inoculant strain is known to be available for it.

The Feedback from Tropical to Temperate Legume Bacteriology

The continuing study of the symbiosis of tropical legumes in Australia is some sixteen years old. It has been iconoclastic in its impact, and has usually been ignored by the establishment (e.g. Vincent 1967; Alexander 1961;

Burton 1965; Stuart 1966; De Ley and Rassel 1965) although on one occasion attacked with more vigour than exactitude (Parker 1968). It has nevertheless been productive of new ideas, some of which are relevant to the temperate world of clovers and medics.

The obvious feedback to a new classification of Rhizobium resulting from a sensible view of cross-inoculation groups has been mentioned above. Norris (1966a) has developed another useful application of systematised cross-inoculation studies, based on a study of the strain specificity of African species of clover by Norris and 't Mannetje (1964). Called 'Symbiotaxonomy', it provides a tool for determining the relative evolutionary status of species within a symbiotically specialised group such as *Lotus* spp. clover, or *Medicago* spp. It depends on the principle that, as species diverge during evolution, the ability of the Rhizobium symbiont to fix nitrogen is lost before the ability to form nodules, that is effectivity is lost before infectivity. Cross-reacting species with a spectrum of Rhizobium strains known to be effective on each homologous host, and determining whether the reaction of the cross-reactors is effectiveness, ineffectiveness, or failure to nodulate, may reveal the taxonomic status of a species when orthodox morphological taxonomy sheds little light on its status. Uncontrolled cross-inoculation studies such as those of Saubert and Scheffler (1967a and b), in which no account is taken of the effectiveness of a strain on the homologous host, shed no light on group affinities.

The concept developed by Norris (1965) to explain the repeated development of the acid-producing habit in Rhizobium associated with unrelated groups of legumes, and the fact that the majority of legumes possess Rhizobium with alkali-producing habit, has several applications to temperate legume bacteriology. One of these is in the seed pelleting procedure already mentioned. Although most temperate crop and pasture legumes are of specialised type, possessing fast-growing acid-producing Rhizobium, for example clovers and *Medicago* spp., some have retained the more primitive slow-growing alkali-producing Rhizobium and are adapted to acid soils, for instance species of Lupinus and Ornithopus and Lotus major. For these the practice of pelleting with lime has no more relevance than it has for unadapted tropical species. Harmful effects of lime pelleting on Lupinus and Serradella have already been demonstrated by Parker and Oakley (1965) and Shipton and Parker (1967) in Western Australia.

Another application of the acid-alkali hypothesis is in the potential development of acid hill country to clover pasture in situations where the amendment of the soil with lime is not economic or practical. Back selection of the advanced acid-producing clover Rhizobium towards the primitive alkali-producing habit, naturally adapted to an acid environment, is a potential approach. It is almost certain, however, that such selection must be accompanied by parallel selection of acid-adapted ecotypes of the host for success to be achieved, because the combination of acid-adapted Rhizobium with alkali-adapted clover is very likely to be ineffective. Brockwell, Asuo, and Rea (1966) in Canberra have shown a highly significant correlation between the amount of acid production in culture by clover and lotus Rhizobium strains and the pH of the soil from which they were derived, those strains from the most alkaline soils being the strongest acid producers and vice versa. This provides strong evidence both for the soundness of the original hypothesis and for the potential of the suggested approach. It is possibly no accident that three of the highly successful commercial inoculant strains for clovers in use in Australia, TA1, UNZ29, and WA67, are mild acid producers. If calcium carbonate is incorporated in the nutrient agar on which they are grown, they do not change the colour of brom thymol blue inoculator. Blair (1967) in New Zealand began a program of selection for alkali-producing strains of white clover Rhizobium, but the unusually high proportion of his strains isolated from hill soils that showed this character conflicts with the evidence of Brockwell *et al.* (1966) and suggests that technique should be carefully standardised.

It is ironic that on the continent of Australia, where our limited survey indicates that most of the abundant native legumes have cowpea-type Rhizobium (McKnight 1949; Bowen 1956; Lange 1961; Norris, unpublished), the majority of studies have been made with Rhizobium from *Trifolium* spp. and *Medicago* spp. The genus Trifolium did not exist in Australia before European settlement and its Rhizobium must have been brought in as a contaminant with early settlers. The Medicago-Melilotus-Trigonella complex was represented in Australia by one species only, *Trigonella suavissima* (Cooper's Creek clover), occurring along the inland rivers draining to Lake Eyre as an ephemeral following flooding. Its Rhizobium apparently cannot nodulate effectively on introduced species (Brockwell and Hely 1966), so useful types of *R. meliloti* must also be casual introductions to Australia. The reason for the paucity of studies of 'cowpea' bacteria is largely economic, but we may hope that in a prospering community more effort will be devoted in future to studies with this ubiquitous cowpea organism, and particularly to ecological studies designed to shed light on the effectiveness of Rhizobium from native species on the increasing number of new pasture legumes possessing cowpea Rhizobium. If full effectiveness of native cowpea strains on these species can be combined with their great adaptation to heat and desiccation, the prospect of very 'durable' inoculants is presented.

What needs to be avoided in future Rhizobium studies in Australia is the attitude that might be expressed as 'East is East and West is West and never the twain shall meet'; in other words that tropical legume bacteriology and temperate legume bacteriology are two separate disciplines that concern the north and the south of the continent respectively.

23

WEEDS OF GRASSLANDS

P. W. MICHAEL

Accurate estimates of the cost of weeds to the pastoral industry in Australia are difficult to obtain. The poisoning of livestock by many native and introduced plants is frequent but irregular. In 1963–4, 74 per cent of the wool produced in New South Wales contained vegetable fault, but only 16 per cent was so badly contaminated with burrs as to necessitate carbonising (Webster and Whan 1967). Although heavy infestations of annual and biennial thistles certainly lower pasture production and at times prevent livestock from gaining access to useful pasture species, there is a wide range of densities of thistles which does not affect pasture yield. The weediness of old stands of subterranean clover (*Trifolium subterraneum*) adds to the cost of subsequently establishing perennial pastures. To obtain pure seed of subterranean clover, additional costs to maintain weed-free stands of clover or in the cleaning of the seed are necessary, as, for example, in the elimination of barley grass (*Hordeum leporinum*) which is prohibited in seed exported to New Zealand (Blackwood 1967). The costs involved in the clearing of land for new pastures vary considerably. In the brigalow (*Acacia harpophylla*) lands of southern Queensland (Pl. 34), recent estimates range from $4 to $7 an acre ($10–$17.50 per ha) for initial clearing followed by $2.50 to $3.50 per acre ($6.20–$8.65 per ha) for subsequent removal of suckers, while in medium forest country in Victoria it may cost up to $78 an acre ($195 per ha) for clearing, packing, burning, ploughing, picking up and cultivation (Watson 1967) (Pl. 37). It may cost $40 an acre ($100 per ha) to convert country infested by serrated tussock (*Nassella trichotoma*) to useful grazing land.

In Australia, as elsewhere, certain plants may be described as weeds at one time or in some situations but as useful plants at another time or in other situations. In southern Australia, barley grass, though of poor nutritive value and troublesome to sheep in the spring, provides useful feed over vast areas in the autumn and winter; tussocks of Poa and Lomandra are useless for grazing but offer useful shelter for sheep and lambs; saffron thistle (*Carthamus lanatus*) may make wool very unpleasant to handle but its seeds provide useful feed for sheep in late summer and in dry autumn periods; in the annual pastures of large parts of southern Australia, Wimmera ryegrass (*Lolium rigidum*) is a good pasture grass but it hinders the establishment of lucerne (*Medicago sativa*) in the south-west slopes region of New South Wales; annual Medicago species are important pasture legumes in southern Australia but the burrs of many species are difficult to remove from wool.

Weeds may often be useful indicators of soil fertility. Thick stands of variegated thistle (*Silybum marianum*) are found essentially on rich alluvial soils or on soils of igneous origin; harestail grass (*Lagurus ovatus*) occurs only on coastal heath soils deficient in copper and zinc in the southern States. Areas infested with spear thistle (*Cirsium vulgare*) have previously had their fertility raised by the application of superphosphate and the sowing of subterranean clover. Such areas are often found adjacent to thistle-free areas which have not been sown to subterranean clover. The invasion of subterranean clover pastures by thistles, various annual grasses, and herbaceous species has usually been attributed to the accumulation of nitrogen (Cook 1930; Trumble 1935; McTaggart 1936; Trumble and Donald 1938a; Cook 1939; Morley 1961; Moore and Biddiscombe 1964). Areas infested with serrated tussock in New South Wales and onionweed (*Asphodelus fistulosus*) in the mallee areas of South Australia, are of very low fertility, either natural or induced.

The following treatment of weeds of Australian grasslands includes a brief discussion on their origin and history, a practical classification, and an account of work on their control.

ORIGIN AND HISTORY OF AUSTRALIAN WEEDS

Native Weeds

Although most Australian weed species are of alien origin, many native plants are of considerable importance. The latter are more common as weeds in the arid and sub-tropical or tropical parts of Australia than in the temperate regions of Australia which have been subject to grazing by sheep, cattle, and rabbits since the early days of European settlement. They include a large number of trees and shrubs which cause problems in clearing or which regenerate on grazing lands, many plants poisonous to livestock, galvanised burr (*Bassia birchii*), an undesirable prickly perennial especially in the semi-arid woodlands of north-western New South Wales and southern Queensland, and bracken (*Pteridium esculentum*), common in cleared land in a large proportion of the wet sclerophyll forest areas of Australia.

Introduced Weeds

The introduction of aliens to Australia has been both accidental and intentional. Some of the worst weeds in the history of agricultural development in Australia were introduced, at one time or another, as ornamental or medicinal plants. They include Paterson's curse or Salvation Jane (*Echium lycopsis* syn. *E. plantagineum*), Harrisia cactus (*Eriocereus martinii*), one-leaf Cape tulip (*Homeria breyniana*) and two-leaf Cape tulip (*H. miniata*), St John's wort (*Hypericum perforatum*), *Lantana camara* sens. lat., cotton and Illyrian thistles (*Onopordum acanthium* and *O. illyricum*), the prickly pears (*Opuntia* spp.), soursob (*Oxalis pes-caprae*), and variegated thistle. Mesquite (*Prosopis juliflora*), introduced both for ornamental and fodder purposes, has become a serious weed between Carnarvon and Geraldton in Western Australia.

The success of aliens, contrasted with native plants, is due to their greater adaptability to environments altered by disturbance and/or to the absence of their native pests and other plant competitors. Many of these aliens had been preadapted, before introduction to Australia, to disturbed sites by evolutionary histories in areas long disturbed by man and his domestic animals in Europe, Asia, or North Africa (Moore 1967b). Doing (1966) has drawn attention to the greater aggressiveness of many weed species—for example St John's wort, Paterson's curse, capeweed (*Arctotheca calendula* syn. *Cryptostemma calendula*), and serrated tussock—in Australia than in their countries of origin.

In the few attempts which have been made to fit the climatic distribution in Australia of weeds of European or Mediterranean origin to their distribution in Europe and the Mediterranean region a number of inconsistencies have been found. Moore (1967b) has drawn attention to the occurrence of *Echium plantagineum* in lower latitudes in Australia than in the northern hemisphere, Doing, Biddiscombe, and Knedlhans (1969) to the occurrence of nodding thistle (*Carduus nutans*) in areas in Australia with higher winter temperatures and lower relative humidities than in Europe. *Onopordum acanthium*, of more northern distribution in Europe, and *O. illyricum* of more southern distribution respectively, show a tendency to occupy colder and warmer parts in southern New South Wales, but, again, winter temperatures in areas infested with *O. acanthium* are much higher in Australia than in Europe. The presence of different associated species in Australia than in Europe has been noted by Doing *et al.* (1969) in relation to *Carduus nutans*.

On the other hand, the distribution of weeds originating from the Cape Province of South Africa shows in both Australia and South Africa essentially the same climatic pattern, for example *Oxalis pes-caprae* (Fig. 23 : 1) and the Cape tulips and capeweed. Soursob and capeweed have become more widespread and noticeable in southern Australia than in the Cape Province, at least partly because of the presence of more fertile soils in Australia and the much greater areas of similar climate.

It is possible that the weeds introduced from Europe and the Mediterranean region have a much greater adaptability to different environments after centuries of disturbance than those originating from the Cape Province which has been subjected to disturbance by man for a much shorter period.

Taking a wider view, however, as Moore (1967b) has stated, 'the common naturalized aliens of southern Australia are European and North African (and from the Cape Province) and those of northern Australia are sub-tropical and tropical in origins. However many temperate European plants have become naturalized

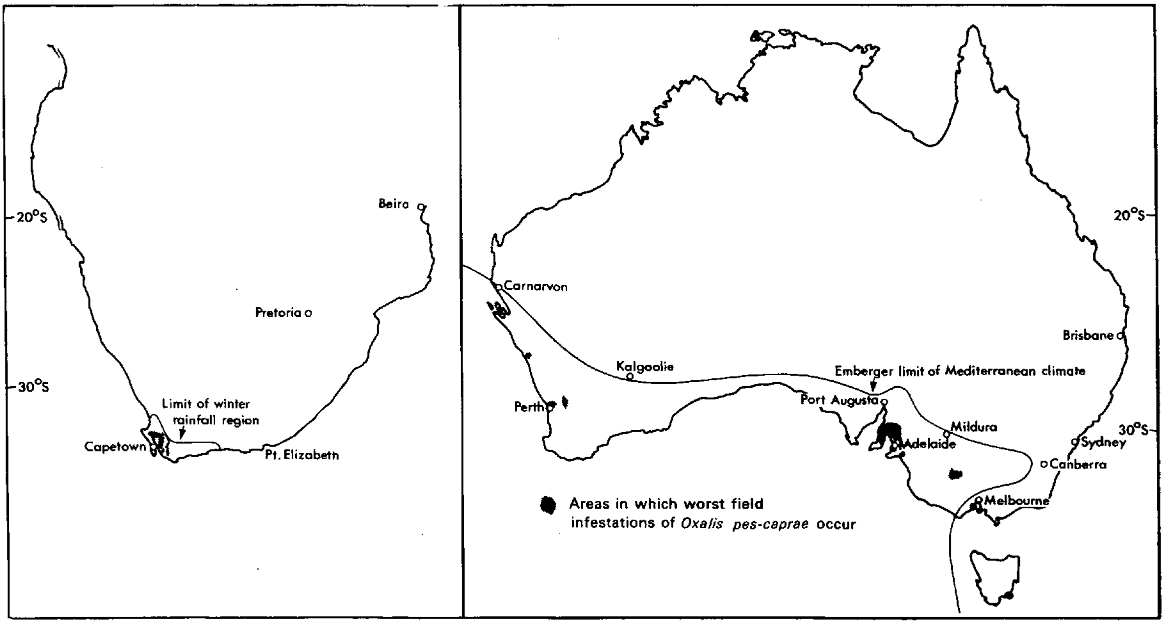


Fig. 23 : 1 Comparative maps of *Oxalis pes-caprae* in Australia and South Africa (Emberger's limit of Mediterranean climate in Australia from Moore (1967b) and limit of south-western Cape climate (hot, dry summers and cool, rainy winters) from Cole (1961))

in sub-tropical areas'. He quotes the data given by Everist (1959) where, of the plants naturalised in Queensland, 40 per cent were from Europe, West Asia and North Africa, 3 per cent from East Asia, 13 per cent from the Old World tropics, 3 per cent from South Africa, 8 per cent from extra-tropical North America, 20 per cent from the New World tropics, 9 per cent from extra-tropical South America, and 3 per cent were cosmopolitan or of uncertain origins.

> The large proportion of European plants in a State which is largely tropical and subtropical is thought to be due to the fact that Australia is settled by Europeans and its communications are largely with the European continent. The inference is that the naturalization of exotic plants in Australia is influenced by history as well as by climate and other factors.

Opportunity, a term used by Moore (1967b), is important, too. Infestations of *Oxalis pes-caprae* in southern Australia are mainly of a pentaploid form which is quite uncommon in South Africa where tetraploid forms occur in endless variety. Evidence suggests that this pentaploid form was collected around Cape Town because of the greater showiness of its flowers, grown in Europe as an ornamental and sent from Europe to various parts of the world. Other varieties, all tetraploid, were apparently introduced to Australia, especially Western Australia, directly from South Africa (Michael 1964, 1965a). Michael suggested on the basis of bulb production at different moisture levels that the tetraploids may have an even greater potential in Australia than the pentaploid.

Viper's bugloss (*Echium vulgare*) was presumably introduced to Australia earlier than its close relative *E. lycopsis*, and while the former is associated with many of the older settled places in south-eastern New South Wales, the latter is more likely to be found in more recently settled areas. The distribution of cotton and Illyrian thistles mentioned earlier is in part determined by what particular species was originally grown as 'Scotch' thistle in the areas concerned.

A PRACTICAL CLASSIFICATION OF AUSTRALIAN WEEDS

Weeds of Australian pastures and grazing lands may conveniently be grouped as follows:

1. Weeds of established pastures or lands used for grazing

  - (a) Plants which are harmful to livestock or which lower the value of livestock products.
  - (b) Plants which occupy ground which could be utilised by more useful pasture species.

2. Weeds which interfere with the establishment of pastures
  - (a) Plants which interfere with the development of new land or the establishment of pastures on new or unimproved land, or the redevelopment of old land which has been neglected or over-grazed. 'Unimproved land', in the Australian context, is land which has not been fertilised with superphosphate and/or sown to legumes. Many of the plants in this group may be described as weeds of low fertility.
  - (b) Plants which interfere with the establishment of better pastures on improved land. Many of these plants may be described as weeds of high fertility.

The more important weeds belonging to each of these groups are given below with brief mention of their importance and distribution in Australia. The groups are not necessarily mutually exclusive.

Group 1(a) includes a wide range of poisonous plants, both native and introduced. Many of these have been discussed in Anon. (1956, 1957, 1959a) and by Hall (1964), Aplin (1967, 1968) and McBarron (1967). The toxic principles of these plants include alkaloids of various types, fluoroacetate, oxalate, nitrate, hydrocyanic acid, and selenium, but in many cases they are unknown. It is not possible to give an exhaustive treatment here, but the magnitude of the problem will be made clear. Many of the poisonous plants of Australia occur along water courses, the most productive parts of the arid regions.

Pyrrolizidine alkaloids occur in the rattle pods, *Crotalaria retusa* and *C. novohollandiae*, prevalent along water courses in north-west Queensland, Northern Territory, and north-west Western Australia, common heliotrope (*Heliotropium europaeum*) and Paterson's curse in temperate woodland regions of south-eastern Australia, and cotton fireweed (*Senecio quadridentatus*) in the Hunter Valley region of New South Wales, south-eastern South Australia, and the Esperance region of Western Australia. The alkaloid, erythrophleine, occurs in ironwood (*Erythrophloeum chlorostachys*) on sandstone country in tropical Australia (see Chapter 16). Other alkaloids are present in the Cape tulips, which occur especially in the wetter temperate woodlands of Western Australia and South Australia.

Fluoroacetate occurs in Georgina gidyea or gidgee (*Acacia georginae*) growing in the Georgina River basin of western Queensland and the Northern Territory, in desert poisonbush or heart leaf (*Gastrolobium grandiflorum*) on poor sandstone country in tropical woodlands of Queensland, Northern Territory, and Western Australia, in York Road poison (*G. calycinum*) and many other species of Gastrolobium, and in box poison (*Oxylobium parviflorum*) in dry sclerophyll forests of Western Australia.

Oxalate occurs in a large range of plants belonging to the families Aizoaceae, Chenopodiaceae, Oxalidaceae, Polygonaceae, and Portulacaceae. Soursob, commonly toxic to sheep and of greatest importance in the woodland and adjacent mallee regions of South Australia, is perhaps the best known. Nitrate may occur in high quantities in many plants and may induce nitrite poisoning in stock grazing on, for example, giant pigweed (*Trianthema portulacastrum*), pigweed (*Portulaca oleracea*), mint weed (*Salvia reflexa*), variegated thistle and many grasses. The presence of other toxic compounds in these plants may influence the reaction of stock grazing them. Hydrocyanic poisoning is common and may be caused by, for example, *Eremophila maculata* and spider grass (*Brachyachne convergens*) in northern Australia and caustic weed (*Euphorbia drummondii*) which is widespread in southern Australia. Selenium poisoning has been reported in *Morinda reticulata*, *Neptunia amplexicaulis*, and boree (*Acacia cana*) in Queensland (see Chapter 25). These plants either accumulate selenium from soils of low selenium content or grow on highly seleniferous soils, for example, between Hughenden and Julia Creek.

The toxic effects of many other plants are well known, for example photosensitisation caused by St John's wort which occurs in dry temperate forest regions principally in New South Wales, Victoria, and South Australia, and haemorrhage in cattle caused by ingestion of bracken.

Many useful pasture species may also cause poisoning, for example *Phalaris tuberosa* due at least partly to the presence of tryptamine alkaloids and cultivated sorghums caused by the presence of hydrocyanic acid. Burr medic (*Medicago polymorpha*) may cause photosensitisation and lucerne and other pasture legumes may be responsible for bloat. The oestrogenic activity of subterranean clover is well known (see Chapter 26).

Many plants cause mechanical injuries (external or internal) to livestock. These include spiny emex or double gee (*Emex australis*) which extends from south-western Western Australia to southern Queensland, and caltrop (*Tribulus terrestris*) and khaki weed (*Alternanthera repens*), especially in north-western New South Wales. The spikelets of many grasses, especially the native Stipa and Aristida and introduced barley grass and Bromus may cause trouble. Skeleton weed (*Chondrilla juncea*), especially abundant in south-western New South Wales, may cause choking in cattle, and ingestion of stinkwort (*Inula graveolens*) may predispose sheep to enterotoxaemia.

Group 1(a) includes also many plants, the fruits (or burrs) of which adhere to wool, for example, Noogoora burr (*Xanthium pungens*) and Bathurst burr (*X. spinosum*), prevalent along water courses in New South Wales, Queensland, and South Australia and annual *Medicago* spp. and *Erodium* spp., occurring in large areas of southern Australia. Many more plants, both native and introduced, are recorded by Milthorpe (1943).

Group 1(b) includes the annual and biennial thistles—slender thistle (*Carduus pycnocephalus*), winged slender thistle (*C. tenuiflorus*), spear thistle, cotton and Illyrian thistles and variegated thistle especially in New South Wales, Victoria, and South Australia; the perennial artichoke thistle (*Cynara cardunculus*) of rather restricted distribution on heavy soils near Melbourne and Adelaide; Paterson's curse or Salvation Jane especially in South Australia and southern New South Wales and adjacent areas in Victoria. This group also includes the many annual weeds occurring along water courses in the arid regions and barley grass in dry land and irrigated pastures. Annual grass weeds lower the value of hay cut from lucerne pastures in southern Australia and grasses like summer grass (*Digitaria adscendens*) lessen the productivity of Townsville lucerne (*Stylosanthes humilis*) in northern Australia.

The introduced perennial shrubs, blackberry (*Rubus* spp.), African boxthorn (*Lycium ferocissimum*), and briar (*Rosa* spp.), all widespread in southern Australia, and Lantana, Crofton weed (*Eupatorium adenophorum*), and groundsel bush (*Baccharis halimifolia*), all of coastal areas of northern New South Wales and southern Queensland, belong here. The Chinee apple (*Zizyphus mauritiana*), has invaded grazing lands of tropical woodlands in north Queensland; Harrisia cactus, established in several localities in Queensland, is causing increasing concern. Bracken and many native shrubs and trees presenting regrowth problems in newly cleared land belong here as well as in group 2(a).

Group 2(a)—the most important woody plants presenting difficulties in clearing and subsequent operations—are essentially native species. These include both trees and shrubs that regenerate from seed, roots, or stem bases after ringbarking or felling and are major economic problems, particularly in areas of summer rain. They include brigalow (*Acacia harpophylla*) which produces suckers from roots (Pl. 36), poplar box (*Eucalyptus populnea*) which regenerates from seed and from stem and lignotuber buds, lime bush (*Eremocitrus glauca*) and sandalwood or budda (*Eremophila mitchelli*), all important in southern Queensland. Many other species of Eucalyptus and Acacia may cause problems in clearing throughout southern Australia. In the semi-arid regions of New South Wales and Queensland, Cassia, Eremophila, Ellangowan poison bush (*Myoporum deserti*), Dodonaea, and Callitris may more or less completely occupy land which was once well grassed, and present great economic difficulties in the restoration of land for useful grazing.

Group 2(a) includes also useless plants like serrated tussock, which is at its worst in the central and southern tablelands of New South Wales, and large tussocky *Poa* spp. in similar situations in New South Wales, Victoria, and Tasmania. *Sorghum intrans* is an important annual grass weed in areas suitable for the sowing of Townsville lucerne in open eucalypt forests and woodlands in the higher rainfall region of the Northern Territory.

Perhaps the most important weeds in Group

2(b) are the annual grasses (barley grass, *Bromus* spp., Wimmera ryegrass and others in southern Australia), thistles and many other alien weeds which accompany the improvement of pasture land in southern Australia.

ECOLOGICAL CONTROL OF AUSTRALIAN WEEDS

The rest of this chapter is concerned with ecological aspects of the control of some of the weeds listed in the previous section. It is not intended to give an exhaustive treatment of herbicidal work, the main emphasis being placed on the use of herbicides as ecological 'tools'. However, when dealing with native trees and shrubs the use of herbicides must be given due emphasis.

Only brief references will be made to biological control of weeds in Australia and for further information the reader is referred to two recent publications (Waterhouse 1967; Huffaker 1967). The well-known success of biological control of Opuntia by the insect *Cactoblastis cactorum* continues to give hope to graziers and scientists for further successes on other species.

Relevance of Germination, Dormancy, and Life History Studies in Control

Few detailed studies of the germination and dormancy characteristics of seeds of pasture weeds have been made in Australia, despite their direct relevance to weed control methods. It is, however, difficult to relate the results of experiments in the laboratory to field conditions. Temperature relationships alone are not sufficient to explain behaviour in the field because dormancy and moisture relationships are also involved. Smith (1968a) showed that large differences in percentage germination of barley grass and Wimmera ryegrass occur under a range of temperature conditions with or without diurnal fluctuations and that the viability of barley grass seed differed depending on storage conditions. The presence or absence of cover and the depth of burial of seed also affect germination and emergence of weed seedlings.

Field observations may have important practical implications. Variegated thistle, for example, germinates only from late summer through the autumn and winter in southern New South Wales so that it can be avoided in the establishment of lucerne stands by sowing in the spring. The main germination of barley grass in the Southern Tablelands of New South Wales is in the autumn-winter period and it can also be largely avoided in the establishment of perennial pastures by spring sowing. Barley grass seed under field conditions is unlikely to remain viable for more than 12 months so that if setting of seed is prevented by cultivation or chemical means in the preceding year, establishment of perennial pasture species such as lucerne or *Phalaris tuberosa* should be made much easier.

In the Northern Territory wet season burning of *Sorghum intrans* before sowing of Townsville lucerne leads to excellent control. At this time the dry grass of the previous season makes it possible to burn the new stand of the weed, which germinates with the first heavy rains (Stocker and Sturtz 1966).

Pearce (1963) has shown variable dormancy in corms of one-leaf Cape tulip. Dormancy decreases with lowering temperatures but this process is accelerated by the burning of surface cover in the summer months. This enables control by cultivation or by herbicides to be more effective. Cashmore (1938) studied the life history of one-leaf Cape tulip and was able to demonstrate three main periods of growth—the first about 8 weeks after planting when leaf and root production occurs at the expense of corm reserves; the second when photosynthesis and mineral uptake become effective, culminating 6 or 7 weeks later at flowering; the third when dry matter accumulation and the organisation of stem, seed, and new corms proceed. Cashmore suggested that the second stage would be the best at which to exercise control measures but later work (Walker 1954 and Pearce 1963) showed that adequate results could only be obtained by cultivating at the first stage and following it with later cultivations.

Michael (1965b), in studies on the pentaploid form of soursob, also pointed to various stages, the first about 8 weeks after planting (or sprouting) of bulbs, corresponding to the stage of old bulb exhaustion, followed by a considerable growth of tubers and associated roots; flowers and bulbs begin to develop after about 11 weeks, with bulbs increasing greatly after 15 weeks. Michael suggested that the first stage would be the best stage to attempt control by cultivation, but in field experiments it became evident that a second cultivation some weeks later was necessary to achieve great reductions in bulb production. This second cultivation was necessary because of the great capacity of soursob to shoot from injured crowns and broken stems. The dry weight of bulbs was reduced from 51 cwt to 6·3 cwt per acre (6400 to 791 kg per ha) on a heavy soil and from 22 cwt to 1·1 cwt per acre (2761 to 138 kg per ha) on a light calcareous soil (Michael 1965c).

Cultivation for control of Cape tulip and soursob is often impracticable because conditions are too wet, and chemical control may be indicated. 2,4-D (2,4-dichlorophenoxyacetic acid) and 2,2-DPA (2,2-dichloropropionic acid) have been used successfully against Cape tulip and 2,4,5-TP (2,4,5-trichlorophenoxypropionic acid) against soursob. The timing of herbicidal treatment may not be so critical as the timing of cultivation.

The control of soursob, which is of greatest importance in the cereal-growing areas of South Australia, is most conveniently geared to the cropping phase of the rotation. The effect of reductions in bulb production on the subsequent establishment of subterranean clover or barrel medic (*Medicago truncatula*) has yet to be tested.

Seed production may or may not be of importance in perennial weeds. Campbell (1960a) has calculated that serrated tussock, covering 10 per cent of the surface area of soil, produces more than 200,000,000 seeds per acre (494 million per ha). The seeds are easily spread by wind and readily colonise new areas. Two-leaf Cape tulip reproduces only by corms; soursob in nearly all of its infestations in Australia only by bulbs, and bracken, at least in Australia, essentially by shoots from its rhizomes. In St John's wort spread is mainly by seed but limited local spread may occur from the thick rootstocks, particularly in cultivated land.

Control by Sown Pasture Species

The greater part of experimental work on the control of weeds by sown pasture species has been done in southern Australia. It is convenient, indeed, that many pasture weeds can be controlled by the sown pasture species themselves. This applies particularly to areas suitable for the growth of subterranean clover and perennial grasses.

Moore and Cashmore (1942) demonstrated unequivocally that St John's wort could be controlled by subterranean clover aided by superphosphate. Results of a harvest taken in the fourth summer following sowing of six pasture mixtures are given in Table 23 : 1. Moore and Cashmore ascribe the competitive effect of pasture species on St John's wort as probably due to a reduction in light intensity under the sward. The decumbent winter growth of St John's wort is susceptible to shading by the strongly winter-growing subterranean clover. The perennial white clover (*Trifolium repens*), which grows most actively in the spring and summer, is not so effective in control. The more erect Wimmera ryegrass does not shade the wort sufficiently. The presence of a perennial grass—*Phalaris tuberosa* or perennial ryegrass (*Lolium perenne*)—adds to the effectiveness of control.

TABLE 23 : 1 Control of St John's wort by subterranean clover

Pasture species	Yield of St John's wort lb per acre (approx. kg per ha) in 4th season after sowing pastures
Perennial ryegrass—cocksfoot—white clover	590
Perennial ryegrass—cocksfoot—subterranean clover	1
Phalaris tuberosa—white clover	568
Phalaris tuberosa—subterranean clover	4
Wimmera ryegrass—white clover	848
Wimmera ryegrass—subterranean clover	98

Source: Moore and Cashmore 1942.

Campbell (1960b) has shown the effectiveness of subterranean clover in suppressing serrated tussock and emphasises also the importance of a perennial grass, notably *Phalaris tuberosa*. Of the other clovers tried, red clover (*Trifolium pratense*) was successful in shading serrated tussock in the first and second years.

Subterranean clover has also been used with success in the suppression of skeleton weed, which although a very useful plant in pastures of southern New South Wales, causes much trouble in cereal crops. Control is associated with shading and raising soil nitrogen levels (Moore and Robertson 1964).

Annual grasses are not often intentionally used for weed control but they may exercise their own seasonal control of other species. Wimmera ryegrass and barley grass, abundant in annual pastures in southern Australia, reach some kind of balance. As Smith (1968b) points out they explore mainly separate soil layers—ryegrass the surface, and barley grass the deeper layers. Cashmore (1938) suggested that in the management of pastures infested with Cape tulip, Wimmera ryegrass might respond more to added fertiliser than the tulip. Annual grasses appear to keep down annual and biennial thistles in so-called 'grass' or 'poor clover' years. On the other hand, subterranean clover and thistles grow well together in 'good clover' years. Rossiter (1966b) has given an account of between-year variation in species composition of Mediterranean annual-type pastures in southern Australia. Species composition is largely influenced by the time of the opening rains. In the thistle-infested areas of southern New South Wales good rains in January and February are followed by good germination and establishment of subterranean clover and thistles. Later opening rains seem to favour the annual grasses.

Roark and Donald (1954) demonstrated the effectiveness of lucerne and a pasture mixture containing lucerne in the control of onion weed, contrasted with the relative ineffectiveness of annuals, including volunteer pasture (Table 23 : 2). Michael (1968a) has demonstrated that lucerne and *Phalaris tuberosa* give excellent control of variegated thistle (Table 23 : 3) and suggests that competition for moisture by the sown perennials is of great importance in control of the thistle. But other factors are undoubtedly important too. Annual pasture species, namely Wimmera ryegrass and subterranean clover, give very poor control. *Phalaris tuberosa* has been shown to give excellent control of Salvation Jane or Paterson's curse in south-eastern South Australia.

TABLE 23 : 2 Control of onion weed by lucerne

Pasture species	Plants of onion weed per m² in 3rd season after sowing pastures	
	Perennating plants	Seedlings
Volunteer annuals	7·4	938
Wimmera ryegrass	5·0	575
Perennial veldt grass (*Ehrharta calycina*)	3·6	600
Lucerne	0·1	150
Mixed, including lucerne	0·9	113

Source: Based on Roark and Donald 1954.

TABLE 23 : 3 Control of variegated thistle by perennial pasture species

Pasture species	Yield of variegated thistle lb per acre (approx. kg per ha) in 2nd season after sowing pastures	
Phalaris tuberosa	4,144	(5·3)[a]
Phalaris tuberosa—subterranean clover	2,800	(3·7)
Wimmera ryegrass	23,968	(15·3)
Wimmera ryegrass—subterranean clover	28,112	(17·7)
Subterranean clover	27,440	(17·0)
Lucerne[b]	0	
No sown species	16,018	(13·0)

[a] Square root transformations (lb per acre) in brackets.
[b] Lucerne not included in analysis.
Least difference for significance (P = 0·05) between transformed values is 5·4.
Source: Michael 1968a.

Michael (1968b) used a range of perennial grasses in the control of Onopordum and showed that *Phalaris tuberosa* and demeter fescue (*Festuca arundinacea* cv. Demeter) were the best grasses in long-term control (Table 23 : 4). There were great seasonal fluctuations in the relative merits of the grasses in thistle control. Perennial ryegrass was not successful in thistle control. The seasonality of the thistles was also apparent. The reasons for the large fluctuations in thistle numbers and growth seen in southern Australia from season to season are not yet properly understood, but their occurrence is undoubtedly influenced by climatic variations, such as those mentioned earlier, and previous paddock history.

Thistles may re-invade *Phalaris tuberosa* or lucerne pastures in southern Australia after heavy stocking by sheep. In these cases, on arable soils, a cropping phase may need to be introduced to make better use of the high induced fertility.

TABLE 23 : 4 Control of Onopordum by perennial grasses

Perennial grass	Yield of Onopordum lb per acre (approx. kg per ha)		
	1st season	5th season	8th season
Bromus inermis	414	134	1658
Dactylis glomerata	168	11[a]	2081
Festuca arundinacea (cv. Demeter)	358	11[a]	470
Lolium perenne	381	381	1613
Phalaris tuberosa	459	112	829
No sown grass	616	314	1725
L.S.D. P = 0·05	179	90	728

[a] Not included in statistical analysis.
Source: Michael 1968b.

Prunster (1940) reported the effectiveness of pasture mixtures (perennial ryegrass, cocksfoot (*Dactylis glomerata*), and white clover), with adequate fertiliser, in the control of blackberry, *Watsonia meriana*, bracken, and ragwort (*Senecio jacobaea*) in high rainfall (more than 30 in., 762 mm) areas in Victoria which could be cultivated for sowing. In non-arable areas, however, there are many difficulties in the control of blackberry and bracken. Bracken, in particular, shows great resistance to defoliation and herbicides. O'Brien (1964) has related this to its complex system of rhizomes.

Everist (1954) has indicated that the perennial grasses, guinea grass (*Panicum maximum*), and molasses grass (*Melinis minutiflora*) and the perennial legume, calopo (*Calopogonium mucunoides*) may be very useful in controlling lantana in parts of coastal Queensland. Guinea grass may be sown through standing lantana.

Annual clover-perennial grass mixed pastures have been developed to give pastures greater stability and potential for weed control. But in vast areas of southern Australia rainfall is insufficient to support perennial grass species and weed species are always likely to volunteer in an annual pasture. In northern Australia, annual weeds will almost certainly occur in Townsville lucerne pastures unless suitable companion perennial grasses are found. In some of the areas with an extended dry season annual pastures may alone be possible.

In the many examples of successful control of pasture weeds by sown pasture species, the end results are clear, but there are many problems to overcome in the attainment of such results. Most of the experimental work described for southern Australia has been done on arable land, but more recently emphasis has been given to the vast areas of non-arable land.

In arable land it would be profitable to examine further the best methods for the preparation of seedbeds for the sowing of pasture species. The few studies already made include those of Moore and Cashmore (1942) in connection with the control of St John's wort, Campbell (1963) concerning the use of the chisel plough in the control of serrated tussock, and Hutchings (1967) concerning the use of the mouldboard and chisel plough in the spring establishment of *Phalaris tuberosa*. In addition, the relative merits of autumn- and spring-sowing must be examined in detail.

Is it advantageous to use chemicals like diquat (6,7-dihydrodipyrido [1,2-a : 2′,1′-c] = pyrazidinium salt) or paraquat (1,1′-dimethyl-4,4′-bipyridinium salt) before sowing pasture or to use other herbicides in the early stages of pasture development? The use of diquat aids in the establishment of perennial ryegrass and *Phalaris tuberosa* (Cocks 1965), but the use of herbicides in the early stages of pasture establishment in the control of thistles may not be economic in the long term, except where initial thistle density is high.

The use of 2,4-DB (2,4-dichlorophenoxybutyric acid) or bromoxynil (3,5-dibromo-4-hydroxybenzonitrile) for broad-leaved weed control in lucerne may be profitable, because the density of lucerne, unlike that of perennial grasses, does not increase with time.

Campbell (1960b) has pointed out that, in the control of serrated tussock, it is important to spare from grazing the first year's growth of subterranean clover to enable it to exert its full competitive effect.

In the establishment of pastures on non-arable land aerial techniques of application of herbicides and fertilisers and sowing of seed are likely to become more important. Campbell (1968) has shown in experiments on serrated tussock control that subterranean clover can be established easily by surface sowing, provided that the seed is inoculated with Rhizobium. On the other hand, establishment of *Phalaris tuberosa* in surface sowings is difficult; perennial ryegrass and cocksfoot are somewhat easier. Prior herbicidal treatment with 2,2-DPA assisted in the establishment of the grasses.

CONTROL OF NATIVE TREES AND SHRUBS

In recent years in Australia, much attention has been given to the clearing of the brigalow lands of Queensland for pasture production. A map showing the extent of these lands, roughly between the 20 in. (508 mm) and 30 in. (762 mm) rainfall limits, has been given by Johnson (1964) after Isbell (1962). An account of the studies already made on brigalow will highlight some of the problems concerned with the control of native trees and shrubs in general.

Johnson (1964) distinguished three main types of brigalow:

1. Sucker brigalow of low branching habit up to 12 ft (3·7 m) high. These suckers occur in groups and are produced following damage or stimulus to roots or aerial pests. After about thirty years these may give rise to—
2. whipstick brigalow, with straight and slender trunk, branched in its upper half. It is thought that these may grow eventually to—
3. tall or virgin brigalow, trees of 40 to 60 ft (12 to 18 m) with rounded crown.

The root suckers appear to be the most important means of spread and become especially prominent on deep clay soils showing moderate to strong melon-hole (gilgai) development.

Early techniques of clearing included the cutting down of trees with the axe or ringbarking. The former stimulated suckering to a greater extent than the latter. The trees were then burnt and Rhodes grass (*Chloris gayana*) was sown in the resultant ash. Now, with the use of heavy machinery, the suckering problem has become worse. It has been shown by Johnson (1964) that a reasonable delay (at least 8 or 9 months) between pulling and burning is advantageous in that fewer suckers are likely to appear.

In the ploughing of land for sucker control before sowing, shallow ploughing (4 in., 10 cm) appears to be adequate (Coaldrake 1967b). Sheep are useful in destroying young suckers on newly prepared lands. Sucker regrowth after sowing of pastures may be handled by burning, chemicals (mainly 2,4,5-T), and mechanical methods. Aerial spraying with 2,4,5-T is most successful against suckers in their first year of growth.

Both Coaldrake (1964) and Johnson (1964) draw attention to the irregularity of the rainfall in brigalow lands. This is in no small measure responsible for the large variability in the success of control methods used. Age of trees or suckers is also important. These variables also affect the reaction of brigalow to 2,4,5-T.

Rhodes grass is by far the most common grass used in the development of these lands and is certainly the most successful in sucker control. Other grasses which may be useful include green panic (*Panicum maximum* var. *trichoglume*), *Sorghum almum*, and buffel grass (*Cenchrus ciliaris*). The introduction of legumes might perhaps be considered as a secondary phase in the development of these pastures. Lucerne is successful in parts of the brigalow lands, while centro (*Centrosema pubescens*) and Phasey bean (*Phaseolus lathyroides*) have shown some promise.

In semi-arid parts of southern and western Queensland work is being directed towards the control of poplar box in stands of which the growth of grass and other herbaceous species is greatly reduced. The killing of the trees by chemical injection of 2,4,5-T (Robertson 1966) has an immediate stimulating effect on grass production (Anon. 1967c). Chemical injection appears to be a feasible method of killing trees on grazing lands, trees being thinned to the desired density with no disturbance of the soil. Where successful, chemical thinning has considerable advantages over pulling with its consequent suckering problem.

Budda or sandalwood may be controlled by 2,4,5-T (Robertson 1965). Limebush is much more difficult to control by chemicals. There has been some experimental success using pelleted picloram (4-amino-3,5,6-trichloropicolinic acid) but drought reduces its effect.

In the southern parts of Queensland cleared of poplar box and other associated species like the above, lucerne, barrel medic, buffel grass, *Panicum coloratum* var. *makarikariensis*, birdwood grass (*Cenchrus setigerus*), blue panic (*Panicum antidotale*), and hybrid phalaris (*Phalaris tuberosa* × *P. arundinacea*) are being tested in pasture sowings.

In southern Australia, the establishment of pastures on land cleared of various species of

Eucalyptus is aided by the good knowledge of suitable pasture mixtures but woody regrowth problems may often necessitate the use of chemicals, like 2,4,5–T or picloram. It is difficult to envisage control of trees without chemicals, except for those species which are small and can be readily handled by big cultivating machinery.

In the drier regions, the problems of tree and shrub regeneration are much more difficult to solve. The suggestions made by Carn (1938), in reference to areas troubled by puntee (*Cassia* spp.) and turpentine (presumably *Eremophila sturtii*), still apply. They include greater subdivision of properties with more watering points, the use of cattle as well as sheep rather than sheep only, and the prevention of overstocking. Chemical control can scarcely be expected to be economic but pulling, cutting, and burning may be helpful in small areas.

OTHER PROBLEM WEEDS

Harrisia Cactus

Harrisia cactus which is prevalent in brigalow scrub country in the Collinsville and Rockhampton districts of Queensland has been described by Mann (1967). There are no hopeful signs of biological control and chemical control is not really satisfactory. Cultivation, followed by the sowing of suitable pasture species, assists in control. The main protection against a weed like this is to encourage the growth of pastures in susceptible lands which are not yet infested.

Galvanised Burr

This troublesome native weed of southern Queensland and north-western New South Wales appears to become prominent after the breaking of droughts, probably in response to overgrazing. Germination occurs throughout the year but winter establishment appears to be more general than summer establishment. However, if summer rains are of sufficient magnitude seedlings will persist. In areas of suitable rainfall galvanised burr could perhaps be replaced by barrel medic. In lower rainfall areas, studies on the effect of burning and the intentional introduction of native grass species (almost entirely neglected in this country) might lead to useful results. Though galvanised burr is susceptible to some forms of 2,4-D (Cuthbertson 1951), chemical control is unlikely to be economic, even if it is effective, except in the better rainfall areas. Seasonal factors seem to override any control measures which have been suggested against this weed.

Poisonous Plants

The importance of recognition of these plants by landholders and their avoidance, wherever possible, must be stressed. Chemical control may be economic and effective in some cases. Cultural control is the most satisfactory way to deal with southern Australian weeds like Cape tulip and St John's wort. Grazing of poisonous plants by animals not affected by them may be a useful control measure, as in the case of *Indigofera enneaphylla*, which is poisonous to horses and mules but may be safely grazed by sheep. Soursob is not so harmful to cattle as to sheep. Dick *et al.* (1963) suggested that it may be possible to protect sheep and cattle from chronic intoxication by pyrollizidine alkaloids in Heliotropium, Senecio, and Crotalaria by the deposition of heavy pellets containing cobalt in the rumen-reticulum, just as in the case of protection from phalaris staggers. Many poisonous plants occurring on stock routes, like mintweed in southern Queensland, for example, are not so important as formerly, due to the present greater use of road transport for moving stock.

CONCLUSION

In this chapter, the importance of useful pasture species in the control of weeds, both introduced and native, has been stressed. Successful weed control rests largely on the proper establishment and maintenance or management of such species. Grazing management studies designed specifically for weed control have as yet barely begun in this country and are much needed, especially in relation to thistle and annual grass control. Many weed problems have arisen because of overgrazing, resulting in the elimination of useful native species.

In Australia, much emphasis has been placed on the principle that weeds occur where they do because the environment suits them and that to control them the environment must be altered in some way. It is useless to kill thistles by chemical means unless conditions are made favourable for the growth of useful plants which can replace the thistles. Variegated thistle, for example, can be easily controlled by 2,4-D but without the sowing of a perennial grass, notably *Phalaris tuberosa* or lucerne, its control is only temporary or seasonal. In the absence of a suitable perennial species its place could be taken by the much more tenacious thistle, cotton thistle, as in the Crookwell region of New South Wales. It is of no avail to have a Chrysomelid beetle kill St John's wort if useful pasture grasses or subterranean clover are not encouraged to replace the weed. The control of lantana, important in parts of coastal Queensland and the north coast of New South Wales, by an insect such as the lace bug, *Teleonemia scrupulosa*, will be of little use if pasture improvement is not carried out at the same time.

24

INSECTS OF GRASSLANDS

M. M. H. WALLACE

Most of the insect pests of pastures and grazing lands in Australia are indigenous. Populations of some native insects have increased enormously as agricultural and pastoral activities have modified their environments and raised their food levels. Small numbers of introduced insects have also found the changed conditions favourable and, in the absence of some or all of their natural enemies, have reached pest proportions in some places.

In the tropics and sub-tropics, where the establishment of highly productive pastures is relatively recent, insects are not generally deleterious to grassland production. But new species of grasses and legumes are being introduced and it would be surprising if some of the native insects and mites now able to sustain only low numbers in the near-original environment do not increase as a result of higher levels of pasture production.

This chapter describes the ways insects or mites affect botanical composition and growth of pastures and attempts to show how man's agricultural activities create and aggravate insect pest problems. Only the commoner and more important species are discussed.

TEMPERATE AND MEDITERRANEAN REGIONS

The greater part of the agricultural areas of southern Australia has a Mediterranean-type climate characterised by a cool, moist, winter growing season and a hot, dry summer period when the predominantly annual herbage dries off (see Figs. 1 : 7, 1 : 8, 1 : 16, and 17 : 1). In these regions, a number of insects and mites have been introduced accidentally from other parts of the world with a similar climate, such as the Mediterranean itself and South Africa (Cape Province). In the humid temperate climate of the remaining south-easterly areas, chiefly in New South Wales, rainfall is more or less uniform throughout the year and the pastures contain a high proportion of perennial species. Here insect pests are all native species that have responded to agricultural development and these are discussed first.

Native Species

Webworm, a complex of species belonging to the genus Hednota (Lepidoptera; Crambidae) is now considered among the worst pests of pastures and cereal crops (oats excepted) in south-western Australia. In recent years, with a change in emphasis from fallow to ley pasture, these moths have become more prominent as pests in the State of South Australia. There is also some evidence that they may become pests in south-eastern regions, especially in southern New South Wales and Victoria.

Hednota spp. in their natural environments inhabit temperate woodlands, where they live among the tussocks of grasses such as *Danthonia* spp., *Stipa* spp., and *Poa* spp., which are common throughout. In such environments their numbers remain low. Development of these lands for agriculture has changed the situation. When annual grasses such as barley grass (*Hordeum* spp.), silver grass (*Vulpia* spp.), and brome grass (*Bromus* spp.) were introduced, the webworms found them palatable and so the stage was set for a rapid increase in insect numbers (Button 1963). Serious outbreaks now occur every few years in Western Australia. Wheat crops suffer the most obvious damage and may have to be treated with insecticide or even re-sown. Barley is also attacked, but oats appears to be completely immune. Less obvious, but probably just as serious, is the damage done to pastures. In some localities, insects may consume up to 85 per cent of the grass in a pasture and reduce the total production by 50 per cent (see Table 24 : 1). Loss of the grass component increases the proportions of subterranean clover and of weeds such as capeweed (*Arctotheca calendula*, formerly *Cryptostemma calendula*) and long

TABLE 24 : 1 Influence of *Hednota* spp. larvae on yield and botanical composition of an ungrazed pasture in Western Australia

Treatment	Yield of dry matter—lb per acre (approx. kg per ha)				
	Sub. clover	Volunteer grasses[a]	Capeweed	Misc. spp.[b]	Total
No treatment—heavily infested with Hednota	1088	582	643	211	2524
Treated with DDT—Hednota larvae virtually eliminated	697	3905	391	540	5533

[a] Mainly *Vulpia myuros*, *Hordeum leporinum*, and *Bromus* spp.

[b] Mainly *Erodium botrys* and ryegrass (*Lolium* sp.).

Source: Wallace and Mahon 1952.

storksbill (*Erodium botrys*) (Wallace and Mahon 1952). An attack of this magnitude may reduce the carrying capacity of a pasture by as much as 1 sheep per acre (2·5 sheep per ha) (Wallace and Mahon 1963).

Typically, an area infested with webworm shows a mosaic of grassy areas interspersed with areas from which all or most of the grass has been removed.

Hednota is not yet looked upon as a serious pest in eastern Australia, although clearly large numbers of larvae must be present in the winter months in order to produce the dense swarms of adult moths observed in the autumn. Up to 2500 moths have been collected in one night in a light trap in Canberra. This is equivalent to the numbers caught in Western Australian light traps in regions where the webworm is a serious pasture pest. Surveys show that larvae are widely scattered in northern Victoria and southern New South Wales. Possibly damage is not as evident in New South Wales and Victorian pastures because of their relatively high content of perennial grasses. Newly germinated annual grasses provide most of the food at the time when the larvae are active (May to September), and Hednota may not find perennial grasses as palatable.

Less important, but often occurring in high numbers in association with Hednota, are the brown pasture looper (*Ciampa arietaria* (Lepidoptera: Geometridae)) and the pasture day moth (*Apina callisto* (Lepidoptera: Agaristidae)). Both of these feed almost exclusively upon weed species, especially capeweed and long storksbill. *Ciampa arietaria* may at times form dense masses on the ground and advance on a distinct front selecting these weed species as food. Mass insect deaths may occur at these high densities, perhaps through a virus infection, causing fouling of the soil surface, which in turn kills large patches of pasture. Alternatively, a combined infestation of Hednota and Ciampa may result in an almost pure sward of subterranean clover.

Philobota spp. (Lepidoptera: Oecophoridae) are widely distributed throughout southern Australia but damage to pastures has been reported only in the eastern States. Feeding habits vary. Some species are known to feed exclusively upon

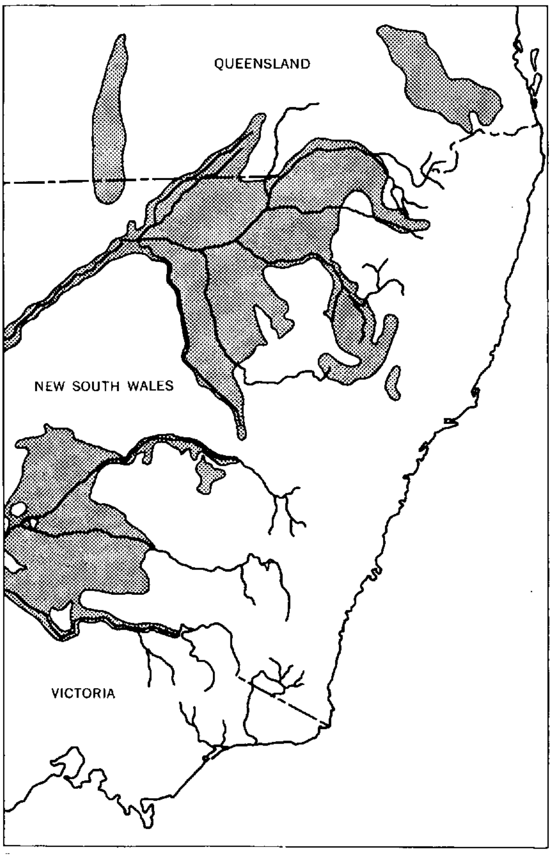


Fig. 24 : 1 Map of south-eastern Australia showing the chief areas of self-mulching soils which appear to be the most important breeding grounds of *Agrotis infusa* (after Common 1954)

Eucalyptus leaf litter while others appear to favour living grass. The latter construct web-lined tunnels in the soil from which they forage on the surface, cutting off blades of grass for later consumption in much the same was as Hednota larvae.

Larvae of native noctuid moths occur in all pastures in southern Australia. Most are relatively unimportant but a number of species cause sporadic damage to grazing lands and sown pastures. Cereal crops may at times suffer severe damage. The southern army worm (*Persectania ewingii*) and the common army worm (*Pseudaletia convecta*), the most abundant, concentrate their attack on the grass component of the community. They sometimes form dense masses, eating all of the grass as they advance along a front.

Less conspicuous, the various cutworms rarely form dense masses as larvae. One of the most interesting is the bogong moth (*Agrotis infusa*), which breeds over a wide area of self-mulching soils in New South Wales and southern Queensland (see Fig. 24 : 1). Before pupating, the larvae feed on annual species of plants during the winter and spring. Moths emerging in late spring migrate southwards to the mountains, where they aestivate gregariously in crevices and small caves in rock outcrops at or near the mountain summits. Many of these moth camps are occupied annually from early November until early April. In the late summer and autumn, the moths return to their breeding grounds in the pastures. This migration enables most of the adult population to avoid the breeding grounds during summer, when perennial grasses unpalatable to the larvae dominate the grazing lands (Common 1954).

The underground grass grub (*Oncopera fasciculata* (Lepidoptera: Hepialidae)) was until recently a rare species in South Australia (Madge 1958). Now this and other species of Oncopera abound not only in that State but also in Victoria, Tasmania, and New South Wales. Like the webworm, this pest eats the grasses of sown pastures in southern Australia. It may also eat legumes, but only in patches where grub numbers are particularly high.

Before agricultural development, excessive wetness restricted Oncopera to the higher, drier portions of poorly drained soils, while dryness confined it to the lower, moister portions of the well-drained soils. Artificial drainage has reduced the chances of excessive wetness, and pasture improvement with clovers and grasses has not only protected the eggs and larvae from excessive evaporation but also provided the larvae with an almost unlimited supply of high-quality food (Madge 1958). Severe damage usually occurs in the spring, producing bare patches that allow various weeds to invade the pasture. When this occurs full recovery of the pasture is often a long, slow process (Martyn 1958).

Other species of Oncopera occur on the Northern Tablelands of New South Wales, including *O. alboguttata*, *O. rufobrunnea*, and *O. tindalei*. Populations of these species declined rapidly in 1964–5, when a severe drought began in eastern Australia. Subsequently, increased numbers of Crambid and Oecophorid webworms replaced Oncopera and defoliated many pastures (R. J. Roberts, unpublished).

Characteristically, a pasture infested with Oncopera becomes a mosaic of damaged areas which are invaded by weeds such as thistles. Damage thus resembles in general appearance that caused by Hednota in Western Australia.

The pasture scarab (*Aphodius howitti* (Coleoptera: Scarabaeidae)) infests sown pastures in south-eastern Australia. The great expansion in areas of improved pasture and in stocking rates within the last 25–30 years has favoured a rapid increase in its numbers (Carne 1956; Maelzer 1962). Unlike Hednota and Oncopera, this insect has a strong preference for the legumes of sown pastures, especially subterranean clover (*Trifolium subterraneum*). Consumption and burial of herbage results in loss of carrying capacity and, on higher ground, where serious infestations often occur, increases the risk of erosion. Furthermore, burrowing larvae throw up the topsoil, and the resultant contamination of the pasture may affect the stock grazing it. On the other hand, if the infestation is light, turning over the topsoil may have beneficial effects (Carne 1956).

Rainfall plays a major part in regulating numbers of Aphodius in pastures. Below-average falls tend to favour increases. The four years preceding outbreaks in South Australia were noticeable for the unusual prevalence of dry winters and wet summers (Carne 1956; Maelzer 1964). Density-induced larval combat and associated invasion of the injured tissue by the fungus, *Cordiceps aphodii*, play a significant role in density regulation (Carne 1956).

Other indigenous species of the pasture scarab complex occur sporadically, occasionally reaching high numbers. They include the pasture white grubs (*Rhopaea morbillosa* and *R. verreauxi*) common on the Northern Tablelands of New South Wales. *R. morbillosa* reaches the eastern limit of its range at about the 44 in. (1117 mm) isohyet, where it is replaced by *R. verreauxi* on the red basaltic loams of the higher rainfall regions. The pruinose scarab (*Sericesthis geminata*) and the other native scarabs *S. nigrolineata*, *S. micans*, and *S. ocularis* are all widely distributed. *S. nigrolineata* may reach average densities of up to 100 larvae per square metre over 20–30 acres (8–12 ha) (Roberts, unpublished). Such populations completely destroy sown pastures, which will be invaded by weeds unless re-sown. Fortunately pastures are not usually heavily reinfested the year following damage. The black soil scarab (*Othnonius batesii*) is common on the heavy black soil areas of northern New South Wales and southern Queensland (Map 2, Fig. 24 : 1), while the red-headed pasture cockchafer (*Adoryphorus couloni*) is common in Victoria and Tasmania. Adult Christmas beetles (*Anoplognathus* spp.) eat new Eucalyptus foliage, and sometimes almost defoliate the trees.

One or more of these scarabs can usually be found in pastures or grazing lands throughout the temperate regions of eastern Australia, although in any locality not more than two to four species are abundant in the same physical niche at any given time (Roberts, unpublished).

Basically, scarabs feed on grass roots, at least in the larval stages, although several of the adults feed exclusively upon Eucalyptus foliage. As a rule, a pasture containing a high proportion of clover is less liable to severe attack. Comparative studies with the larvae suggest that there is a gradation in feeding habits from Anoplognathus and Rhopaea, which appear to be relatively unspecific feeders living primarily on dead organic matter, to more specialised feeders like Sericesthis, which select living roots. Short-term experiments have shown that pastures can lose up to 50 per cent of their roots before foliage growth is depressed, which suggests that some larval feeding, at least by the general soil ingestors such as Rhopaea, is not necessarily damaging and, by aerating the soil, may even be beneficial.

None of these native scarabs has yet been

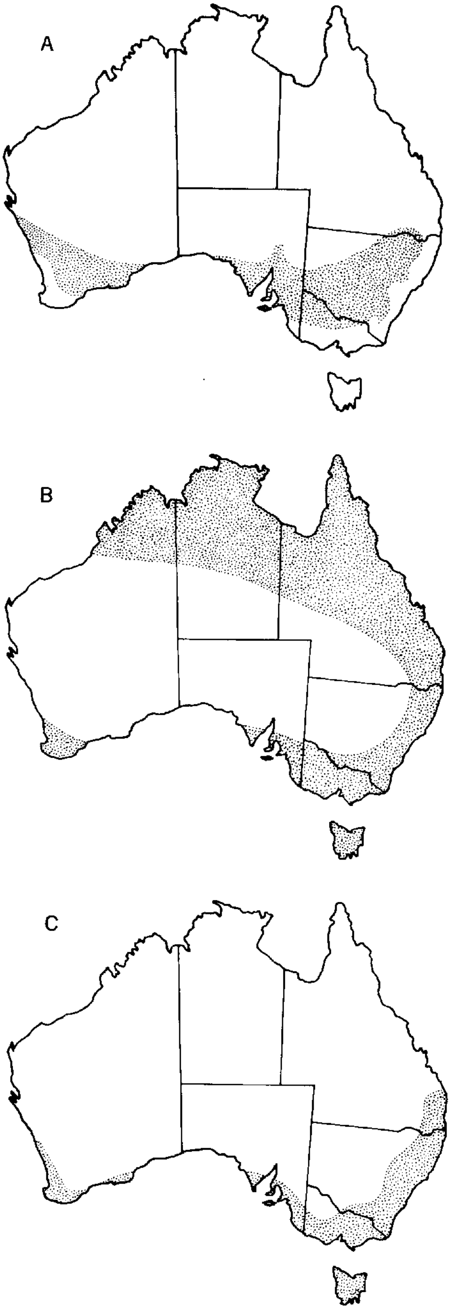


Fig. 24 : 2 Distribution of three grasshoppers within Australia: A. *Austroicetes cruciata*; B. *Gastrimargus musicus*; C. *Phaulacridium vittatum* (after Key 1938)

reported from Western Australia, where there is a relatively poor fauna of Scarabaeidae. The only indigenous species so far observed in high numbers is an undescribed species of Colpochilodes, which severs roots in subterranean clover pastures and cereal crops, causing dead patches to appear (Jenkins 1958). The Tenebrionidae are the dominant pasture beetles in Western Australia, but nothing is known of their feeding habits or their importance in pasture ecology.

The Australian plague locust (*Chortoicetes terminifera*) and the small plague grasshopper (*Austroicetes cruciata*) cause extensive damage to pastures and grazing lands in southern Australia. *C. terminifera* is found throughout the continent, but serious damage is restricted mostly to natural or disclimax grassland areas, as well as to wheat crops, from southern Queensland to northern Victoria. Outbreaks have occurred periodically since the first record in 1844, and there are indicators that the occurrence of swarms is associated with sequences of above-average rains, specially following dry periods.

A. cruciata is frequently a pest in the wheat belts of South and Western Australia, where its one generation per year is well adapted to the winter rainfall regime. However, swarms have also been noted in southern New South Wales and Victoria (see Fig. 24 : 2).

Swarms of *C. terminifera* originate in extensive outbreak areas, most of which occur in New South Wales and Queensland. These areas are characterised by a combination of food-shelter habitats that favour hopper and adult survival and oviposition habitats. The food-shelter habitat consists of a mosaic of tall, tussocky vegetation interspersed with low cover, while the oviposition habitat contains bare, compact ground. The most favourable areas for *A. cruciata* have somewhat similar characteristics, except that the vegetation of the food-shelter habitat is shorter. This species is not strongly migratory.

Land development and grazing by stock have increased the number of habitats that favour both species and thus the opportunities for swarm formation. Both species require grasses in a succulent condition in order to mature (L. R. Clark 1947; D. P. Clark 1965). *A. cruciata* is active during the winter and spring (July to November) when the annual pasture species in winter rainfall regions make their maximum growth. *C. terminifera*, with several generations per year, is most active in the summer months when perennials are growing vigorously under the influence of summer rains (Key 1938; Clark 1947).

The wingless grasshopper (*Phaulacridium vittatum*) abounds in pastures on the tablelands of New South Wales and southern Queensland, and in eastern Victoria and Tasmania. The young nymphs feed almost exclusively on prostrate and rosette-forming plants. They especially favour subterranean clover, but not in continuous sward, so the maintenance of sown pastures

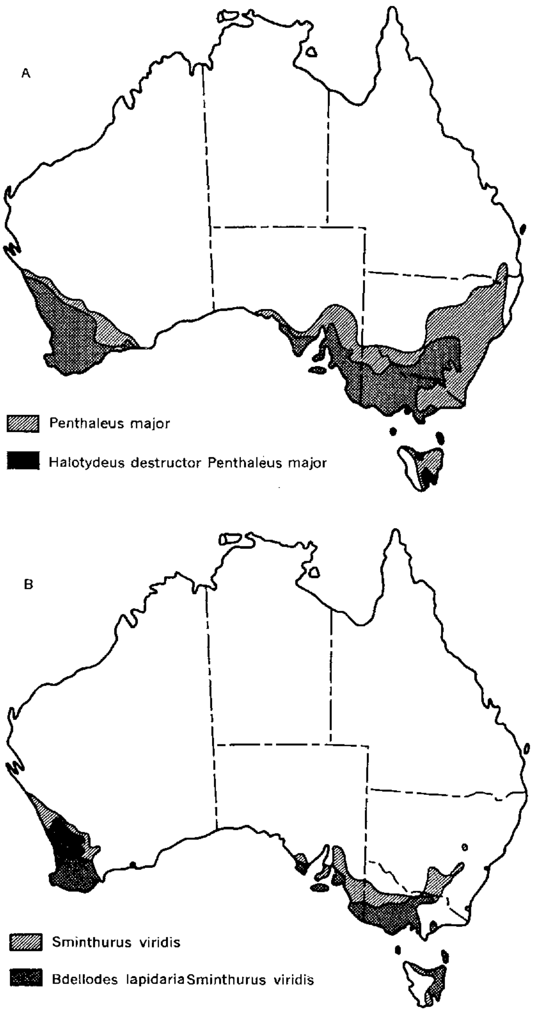


Fig. 24 : 3 Maps of southern Australia showing the present known distributions of (A) *Penthaleus major* and *Halotydeus destructor* and (B) *Sminthurus viridis* and the predatory mite, *Bdellodes lapidaria*

in top condition fully protects against infestation by this insect. Nymphs are unable to locate favourable food plants when grasses dominate the plant cover as they often do after heavy spring rains (Clark 1965).

The Australian field cricket (*Teleogryllus commodus*), a herbivorous cricket indigenous to southern Australia, has occasionally increased to pest proportions in recent years (Browning 1954).

Introduced Insects and Mites

Three exotic species exhibit interesting distribution patterns in southern Australia (see Fig. 24 : 3). These are the lucerne flea (*Sminthurus viridis* (Collembola)) introduced from Europe and first recorded in South Australia in 1884; the red-legged earth mite (*Halotydeus destructor* (Acarina: Eupodidae)) introduced from South Africa and first recorded in Western Australia in 1917; and the blue oat mite (*Penthaleus major* (Acarina: Eupodidae)) introduced from Europe and first recorded in New South Wales in 1921.

H. destructor is restricted to areas of predominantly Mediterranean-type climate with an annual rainfall of 11 in. (279 mm) or more, at least 8 in. (203 mm) of this falling in winter, from May to October inclusive. Its extension into the moist temperate areas is limited to those regions in which the amount of rain falling during the two hottest consecutive months is less than 2 in. (51 mm). *S. viridis* cannot penetrate as far as *H. destructor* into regions with dry Mediterranean-type climates and is not found beyond the 12 in. (305 mm) isohyet, except in isolated pockets of higher soil moisture. On the other hand, *S. viridis* can tolerate higher summer rainfall and infestations have persisted in some coastal areas of New South Wales beyond the zone of Mediterranean climate. *P. major* not only tolerates drier Mediterranean climates, with an annual rainfall as low as 9 in. (229 mm), but also occurs in northern New South Wales and southern Queensland, where the rain falls mostly in the summer.

The climatic limits of these insects and mites in Australia appear to agree reasonably well with those in their countries of origin (Wallace, unpublished).

There are very few pastures containing introduced legumes and weeds in southern Australia in which one or more of these three pests cannot be found. *S. viridis* and *H. destructor* basically feed on broad-leaved plants, especially legumes, whereas *P. major* appears to favour grasses and cereal crops, although all three have an almost unlimited range of food plants. They inflict the greatest damage in the early autumn, when the seeds of these plants germinate and the over-summering diapause eggs hatch more or less simultaneously. Vast numbers of young mites and lucerne fleas attack the emerging seedlings and may cause substantial losses (Norris 1948) (see Table 24 : 2). Attack later in the season is seldom as damaging, since the plants are then large enough to withstand it. Nevertheless some losses may still occur, especially from lucerne flea which, unlike the two sucking mites, consumes plant tissues.

TABLE 24 : 2 Influence of *Halotydeus destructor* on yield and botanical composition of an ungrazed sown pasture in Western Australia

Treatment	Yield of dry matter—lb per acre (approx. kg per ha)			
	Sub. clover	Cape-weed	Other spp.[a]	Total
Attacked by *H. destructor*	164	2671	435	3270
Protected by insecticide	1101	2354	708	4163

[a] Mainly *Erodium botrys* and grasses such as *Vulpia myuros.*

Source: Norris 1948.

It has been estimated that control of severe infestations of *H. destructor* and *S. viridis* could allow stocking rates to be increased by from 0·25 to 0·5 sheep per acre (approx. 0·5 to more than 1 sheep per ha) (Wallace and Mahon 1963). Even so, these authors believe that the economic importance of these pests may have been exaggerated in the past because, in general, existing pastures are understocked. Consequently, the additional herbage resulting from pest control by insecticides is largely wasted. However, set stocking at high rates is now increasingly prevalent and these pests could well become more significant in animal production in the future.

Attempts are now being made to establish biological control agents in Australian pastures. A predatory mite *Anystis* sp., which feeds upon

P. major in the south of France, has been established in Western Australia and may exert some control not only on *P. major* but also on the closely related *H. destructor*.

S. viridis is already preyed upon by a bdellid mite, *Bdellodes lapidaria* (Acarina: Bdellidae), accidentally introduced into Australia, probably from Europe, prior to 1930. This mite is an excellent biological control agent, but has a restricted distribution (see Fig. 24 : 3), and entomologists are now attempting to establish a related mite, *Neomolgus capillatus*, which attacks *S. viridis* in European and north African pastures. If this second predator can be established, the lucerne flea should be under effective biological control throughout its range in Australia. Only local, spot applications of insecticides should then be required.

An important introduced pasture pest is the black beetle (*Heteronychus arator*) from South Africa. This was first found in New South Wales in 1920 but is now common in most high rainfall areas of southern Australia near the coast, especially in dairying areas. Both adults and larvae feed on roots, and in heavily infested pastures the dead herbage can often be rolled up like a carpet because all the roots have been severed. The beetle favours predominantly grass pastures, and seldom attacks severely those containing a high proportion of legumes (Jenkins 1965).

REGIONS OF UNIFORM RAINFALL

Two of the major pasture pests of coastal New South Wales and southern Queensland are weevils. The amnemus or clover root weevil (*Amnemus quadrituberculatus*) is indigenous, but the white fringed weevil (*Graphognathus leucoloma*) is an introduction from South America and was first seen at Scone, N.S.W., in 1932.

A. quadrituberculatus is widespread in this region, both in pastures containing volunteer clovers and in those sown with subterranean clover. There appears to be a close association between the weevil and white clover (*Trifolium repens*), which may be the natural host plant of the insect. The weevil attracted little attention until grazing lands were replaced with pastures of introduced legumes such as subterranean clover. Amnemus feeds almost exclusively on legumes. The adult being a foliage eater is relatively unimportant, but the larvae feeds on roots, causing damage in the autumn and winter months. The effects of injury are more apparent in clovers with a well-defined tap-root, such as subterranean clover. White clover, having a stoloniferous habit, is better able to withstand attack. Even so, plants in heavily infested stands, although appearing healthy, usually make little growth even when well supplied with moisture and nutrients (Braithwaite, Jane, and Swain 1958).

G. leucoloma feeds mainly on legumes, but also attacks other broad-leaved plants. It is at times a serious pest in lucerne crops. Like the amnemus weevil, it exerts the greatest effect on clovers, and recently germinated plants may be killed by larvae feeding upon their tap-roots. In older, well-established pastures, most of the plants survive although there is usually some production loss (Braithwaite 1959).

The sitona weevil, *Sitona humeralis*, was first recorded in New South Wales in 1958 in lucerne. This appears to be its preferred host, but it also attacks other pasture legumes. The adults feed on the aerial parts of the plants and the larvae on the root nodules. Over-wintering adults can cause quite severe damage in spring and early summer (Greenup 1967).

The black beetle (*H. arator*) described earlier is common in flat country along the coastal rivers. Dry conditions in spring and early summer seem to favour an increase in numbers, with resulting damage to pastures during the late summer months. Kikuyu grass (*Pennisetum clandestinum*), common in these areas, attracts the beetles and often supports high numbers (Braithwaite 1959).

In the dairying areas of the tablelands and some coastal areas of northern Queensland (see Fig. 6 : 3), the funnel ants, *Aphaenogaster pythia* and *A. longiceps*, can be troublesome. These ants damage the introduced pasture grasses paspalum (*Paspalum dilatatum*) and kikuyu grass by removing soil from around the roots to form loose mounds, which may smother a closely-grazed sward. Inferior grass species and deep-rooted weeds are encouraged, and affected areas may become almost useless for dairying (Saunders 1967).

The natural habitat of *A. pythia* is wet sclerophyll forest, which mostly occurs in belts fringing the rainforest (see Map 3). In some areas, *A. pythia* has become a pest in the pastures that have replaced the forest after clearing. Similarly, *A. longiceps* has invaded the drier woodlands and dry sclerophyll forests (less than 50 in., 1270 mm rainfall). However, as these contain few sown pastures the ant is as yet only a minor pest.

Two caterpillars, *Oncopera mitocera* and *O. brachyphylla*, occur in Queensland coastal pastures. In the spring and early summer months, they consume debris and grass flag at and near ground level and deposit mounds of dung pellets and excavated soil. Prostrate grasses such as kikuyu and paspalum are most often damaged, since the caterpillars are reluctant to travel far from their burrows or to climb for their food. They eat almost any organic matter, although they appear to favour live grass and grass debris (Elder 1965).

The sod webworm (*Psara licarsisalis*) and a number of noctuid moth larvae (Spodoptera, Pseudaletia, and Agrotis) periodically damage grasses in pastures. Infestations may occur at any time in late summer and autumn, usually on river flats rather than on the drier hillsides (Braithwaite 1959).

ARID AND SEMI-ARID REGIONS

The hot, dry regions of Australia (see Fig. 9 : 1) are as yet almost entirely undeveloped and much of the area is either arid shrubland, grassland, or shrub woodland (see Map 3). Insect pest problems are unknown. However, termites (*Drepanotermes* spp.) have denuded grazing lands in south-western Queensland. The combination of harvesting and the building of hard, smooth slabs over the nest, which cause rapid runoff and prevent seeds from lodging, appears to have contributed to denudation in some areas, especially on mulga ridges (F. J. Gay, unpublished). The Australian plague locust (*Chortoicetes terminifera*) and the migratory locust (*Locusta migratoria*) are both present in arid communities, and their populations could well increase in response to any improvement in their food supplies. Similarly, the spur-throated locust, *Austracris guttulosa*, is a more or less regular minor pest in the drier summer rainfall regions of Australia (Key 1938).

TROPICAL REGIONS

Northern Australia has a tropical climate, with dry winters and wet summers (Figs. 1 : 7, 1 : 8). Where rainfall exceeds 25 in. (635 mm) annually, the area under sown pastures is rapidly increasing (see Chapter 8).

A number of intensive insect-collecting expeditions have been made, but no detailed studies, as yet, of the insects and mites associated with particular grazing lands. No doubt some of those present could multiply rapidly with the advent of large-scale sowing of pastures, but at this stage it is not possible to predict which will become important.

One of the most common insects feeding upon grasses in tropical woodlands is the yellow-winged locust (*Gastrimargus musicus*) (Common 1948). This locust is distributed in moist coastal areas throughout Australia, and often well inland, but is seldom recorded from areas with an annual rainfall of less than 20 in. (508 mm) (see Fig. 24 : 3). The insect swarms in northern tropical areas, but elsewhere occurs only as isolated individuals that do not inflict any significant damage. In the northern areas most grasses and legumes, both native and introduced, are attacked late in the wet season and experimental plots have sometimes been damaged. This locust may well increase in importance when pasture plants are sown on a large scale.

The giant termite (*Mastotermes darwiniensis*) is widespread in tropical Australia. It does not build a mound, but nests mostly in stumps and logs, and in roots below the ground. It may sometimes damage or even kill plants by feeding upon their roots, and may eat seed in the ground. This attack has occasionally proved troublesome in experimental plots, but its significance in grazing lands is unknown.

Other tropical termites forage on the surface of the soil and consume large quantities of dry grass herbage. Their economic effect is difficult to assess, but is probably minor. The many mounds must contain a very large quantity of grass, but the termites harvest it during and immediately after the wet season, a time of excess production on the northern grazing lands, for use during the less productive winter.

CONTROL MEASURES

The relatively low value per unit area of pastures and grazing lands makes it difficult to control insects effectively and economically by insecticides, except in local, severely damaged patches. Moreover, it is often difficult to decide whether control of the pest is really necessary. Low-cost treatments are therefore essential so, since costs of application may be substantial, the quantity and cost of the insecticide must be small.

Modern methods of low and ultra-low volume application have made it possible to obtain effective control of insects with very small quantities of insecticide. This has reduced both costs and the risks of undesirable residues. Where insecticides are deemed necessary for pasture pest control, most treatments involve the use of non-persistent chemicals applied as low-volume sprays, either from the ground or from the air.

Chlorinated hydrocarbons, such as DDT, now discouraged or even banned, have been replaced by the less persistent organophosphorus compounds. However, both DDT and lindane are still widely used if stock can be withheld from the pasture for a sufficient period. These compounds are among the cheapest and most effective available for use against a wide range of insects and, in some instances, no alternatives are known.

There is need for more specificity in insecticides. Broad-spectrum insecticides may create problems through their effects on parasites and predators in the pastures. For example, DDT has been used extensively for controlling the red-legged earth mite, but in some areas this has led to a rapid build-up in numbers of the lucerne flea by killing one of its predators, the bdellid mite (*Bdellodes lapidaria*) (Wallace 1954, 1968).

Aircraft are now used extensively in the treatment of pastures, most commonly for controlling red-legged earth mite and lucerne flea, but also against caterpillars and grasshopper outbreaks.

Some pests can be controlled by cultural means. A good example is afforded by the web-worms (*Hednota* spp.) in Western Australia. The adult moths emerging in the autumn (April) prefer grassy areas for oviposition, and the newly hatched larvae depend on newly germinated grass for survival. A clean fallow at the time of oviposition and hatching may cause high mortality of larvae and result in satisfactory control (Button 1963a).

An interesting method especially for controlling lucerne flea and mites consists of treating the seed with a systemic insecticide prior to sowing (Wallace 1963; Goss and Shipton 1965). This has proved effective with many legume crops, such as peas, clovers, and lucerne, and has the advantages of high selectivity and action immediately the seed germinates. One disadvantage is the harmful effect of the insecticide on the nodulating bacteria applied to the seed at the same time. The importance of this is not yet clear and the depression in nodulation may be only temporary. Lime-pelleting seed to separate the bacterial inoculum from the insecticide may help to overcome this problem.

COPROPHAGOUS INSECTS

In recent years, pasture research workers have become increasingly aware of the beneficial effect that nutrient return to the soil in animal excreta has on sward production. In Australia, the dung from cattle and sheep remains on the surface of the pasture after deposition, and becomes hard and dry. Thus much of its nutrient value is lost. This is due mainly to the paucity of efficient coprophagous insects, which in many other countries, where the domesticated animals are indigenous, bury the dung and hasten its decomposition. Some species of Australian Scarabaeidae, such as Aphodius, are attracted to stock droppings but seldom dispose of them, probably because they find these large pats less acceptable than the smaller droppings of the native animals to which they are adapted.

Grass growth is prevented in the area covered by the dung pad, and a further loss results from the zone of rank growth around the pads, which cattle do not graze for up to a year. Weed growth is also encouraged. Bornemissza (1960) estimated the loss of production in dairy areas, where about 5 million cattle graze, at 300,000 acres annually. The beef cattle and sheep industries also suffer important losses.

Gillard (1967) concluded that incorporation of faeces into the soil and decomposition of macro-organic matter by coprophagous beetles would aid the decomposition of organic matter by soil microflora and fauna and increase its rate of mineralisation.

The process of introducing dung-feeding beetles into Australian pastures has now begun. Several species (drawn originally from Mexico, Africa, and Ceylon) have been imported to

Australia from Hawaii, where they have been established for the control of the horn fly (*Haematobia irritans*). These beetles have been liberated along the east coast of northern Queensland (Bornemissza, personal communication).

ACKNOWLEDGMENTS

Entomologists in the various State agricultural departments assisted in compiling this review. I am also grateful to my colleagues in the CSIRO Division of Entomology for many useful suggestions.

25

MINERAL STATUS OF GRAZING RUMINANTS IN AUSTRALIA

IAN W. MCDONALD

Many of the soils of Australia are deficient in nutrients for pasture plants and the ruminants grazing the pastures. Relatively small areas are so grossly deficient that conventional pasture plants cannot grow on them, and the natural vegetation is so poor that the grazing ruminants soon waste away and die. These are exceptional, but a very large part of the continent will support productive pasture only after the application of various plant nutrients, especially phosphorus, nitrogen, sulphur, and the trace elements zinc, copper, and molybdenum (see Chapter 21). It is, then, not surprising that much attention has been given to the study of inorganic nutrients for plants and animals. In this chapter, a brief account is given of the mineral deficiencies and excesses of sheep and beef cattle grazing pastures and grazing lands in Australia.

PHOSPHORUS

Most Australian soils are low in phosphorus, probably largely due to leaching of phosphate during the mid-Tertiary period (Wild 1958). Only a small fraction of pasture soils have an adequate phosphorus status; the consequence is that superphosphate is almost invariably used in the improvement of pastures where rainfall is adequate to make this an economic proposition. The indigenous flora tend to be tolerant of low phosphorus, so that the phosphorus content of grazed plants can be extremely low; in consequence, evidence of phosphorus deficiency in cattle has been noted for many years. Following the now classical researches in South Africa of Theiler and his colleagues in the 1920s and 1930s on phosphorus deficiency in cattle (see Theiler and Green 1932), the nature of the disease and methods for its control have become generally recognised in Australia. Two syndromes are evident. Depletion of phosphorus leads to reduced growth rate, impaired reproduction and lactation, and finally to osteomalacia with crippling deformities and fractures of bones; affected animals develop deranged appetites, in particular a tendency to chew bones. This tendency exposes animals to the risk of the second syndrome, botulism; in carcasses, the anaerobic bacterium *Clostridium botulinum* can grow and produce an extremely potent toxin, which is lethal to animals eating the carcass or its bones. Both these syndromes are well known in Australian cattle. The application of phosphatic fertilisers for pasture improvement reduces or eliminates these diseases. However, in the northern half of Australia, and in the lower rainfall areas of the southern half, many cattle pastures are not fertilised, so that control of the diseases requires the use of phosphatic supplements for the cattle and immunisation against botulism. Under the most extensive grazing conditions, even these protective procedures are not used, so that clinical forms of phosphorus deficiency are still readily observable. Cattle exposed to mild grades of deficiency are apparently healthy but may still have reduced growth rates, and can respond favourably to phosphorus supplements.

The apparent similarity of sheep and cattle in their digestion and metabolism led to general acceptance of the view that sheep would exhibit a phosphorus deficiency syndrome similar to that in cattle. Many experiments in Australia have failed to establish the existence of a primary phosphorus deficiency. The most critical test reported is that of Underwood *et al.* (1939, 1940), who studied sheep grazing an area of severely deficient soils in Western Australia; phosphorus supplements had no favourable effects on body growth, wool growth, reproduction, growth of lambs, or on the breeding performance of sheep born and reared during the experiment. Earlier, in South Africa, Du Toit, Malan, and Roussouw (1930) had recorded their observation that sheep remained apparently healthy in areas where cattle would suffer from severe phosphorus deficiency. A search of the literature has failed to disclose any unequivocal evidence of primary phosphorus deficiency in grazing sheep, though it is easy to produce a deficiency in pen-fed animals (Martin and Peirce 1934).

The responses of sheep and cattle are so different that most writers have difficulty in accepting the evidence, and it is still common practice in South Africa, Australia, and the U.S.A. for phosphatic supplements to be given to grazing sheep. No research work seems to have been undertaken to explain this difference between the species; McDonald (1968) has discussed the available information and made the following tentative explanation. It would seem that sheep have about the same ratio of phosphorus to bodyweight as do cattle, a similar efficiency in retaining phosphorus, and similar requirements of phosphorus for maintenance and growth when calculated per unit of bodyweight (Agricultural Research Council 1965). On the other hand, the species differ greatly in bodyweight, say in a ratio of about 8 : 1, but the relative energy requirements are related to $W^{0\cdot73}$ (where W is bodyweight); thus, the sheep will need to consume about 1·5 to 2 times as much feed per unit bodyweight and can therefore be expected to tolerate a lower concentration of phosphorus in the feed. It is probable, too, though not adequately proven, that the sheep can exercise greater selectivity in its grazing and thus collect forage with higher digestibility and higher concentrations of protein and phosphorus. These features indicate strong reasons why the sheep is less susceptible to phosphorus deficiency, but do not explain why deficiency does not, in fact, occur in pastoral conditions. In the vegetative parts of plants, there is a strong relation between phosphorus content and protein content. Even in an area with marked phosphorus deficiency in soils, there are great variations between seasons in the phosphorus and protein contents of plants, and these tend to vary together (Underwood, Shier, and Harvey 1937). Forage with a low protein content usually has also a low content of digestible energy, and the voluntary intake of such forage is low. It is clear that, in cattle, the beneficial response to phosphorus supplements is greatest when the animals are gaining in bodyweight; when the pasture matures and the nutritive value falls to such a level that cessation of growth or loss of bodyweight ensues, the supplements have little or no effect (Bisschop 1964); this is readily explicable as the phosphorus requirement would be reduced and phosphate can be mobilised from the tissues. It may therefore be concluded that, in sheep, protein deficiency precedes phosphorus deficiency in all the grazing situations studied; it has yet to be demonstrated that there are pastoral conditions in which the plants are so tolerant of a low phosphorus supply that sheep can obtain an adequate supply of protein and energy without consuming enough phosphorus.

CALCIUM

A survey of the literature by Russell and Duncan (1956) led them to conclude that there was no authentic record of a primary calcium deficiency in grazing cattle or sheep; examination of more recent publications serves only to confirm their conclusion. This is perhaps surprising, as the calcium content of some pasture plants is very low, but it seems to be generally true that when the calcium level is low, the content of phosphorus and protein is also low, and the forage has a low digestibility (see, for example, French 1957), these nutritional inadequacies would dominate the animal's response and prevent the exhibition of a calcium deficiency. The absence of a calcium deficiency in grazing animals must be contrasted with the ease of induction of a deficiency in hand-fed animals, especially those given diets based chiefly on cereal grains (Franklin, Reid, and Johnstone 1948).

The metabolic disorder of hypocalcaemia (so-called 'milk fever', or 'lambing sickness') is common in sheep in all States, though much less common in beef cattle. (By contrast, hypomagnesaemia has been more commonly observed in cattle than sheep.) The disease is chiefly related to grazing on young, rapidly growing pastures, especially when grass dominant, or on young cereal crops, especially oats; it is generally agreed that symptoms are frequently induced by various environmental stresses—driving, fasting, transport, and inclement weather. Very heavy losses have been recorded in sheep consuming plants with a high oxalate content (notably Oxalis, Rumex, Portulaca, Calandrinia, Salsola, Tetragonia, and Threlkeldia), though it should be noted that oxalate produces toxic effects other than hypocalcaemia.

It is not uncommon to find relatively high calcium contents in forages low in phosphorus; this is especially notable in mature plants and those growing on highly calcareous soils. The ruminants can tolerate high Ca/P ratios in their diets provided their supplies of vitamin D are adequate—grazing animals exposed to sunlight rarely lack this vitamin (Theiler, Green, and Du Toit 1927; Marston 1939). It is therefore unlikely that any untoward effects would accrue from excessive intake of calcium.

MAGNESIUM

Magnesium plays a vital role in the metabolism of cells, and when an animal is given a diet deficient in magnesium, but otherwise adequate, a slow depletion of body magnesium occurs, plasma magnesium concentration is lowered, and eventually a deficiency occurs with characteristic nervous disturbances. Magnesium deficiency in this sense has not been observed in grazing ruminants. However, a severe, and even fatal, metabolic disorder (variously called lactation tetany, grass tetany, or grass staggers), characterised by hypomagnesaemia, occurs in cattle and less commonly in sheep. The conditions that lead to hypomagnesaemia are imperfectly understood; it has been suspected that the concentrations of protein, calcium, potassium, phosphorus, and sulphate in forage, as well as the magnesium concentration and availability, may be involved. Wilson (1964) classifies the disease into two main forms. In the chronic form, a mild prolonged deficiency of magnesium causes a reduction in plasma magnesium concentrations, but the animal shows no clinical signs unless it is subjected to stress such as cold, wet, windy weather; response to magnesium therapy is poor, and prevention by provision of magnesium supplements is not very effective. By contrast, in the acute form, clinical signs appear shortly after animals are given access to lush pasture, magnesium therapy is effective, and the condition can be prevented by giving large dietary supplements of magnesium.

Hypomagnesaemia has long been recognised as a source of loss in cattle in all States (Johnstone 1933; McClymont 1943; Lavers 1951; Herd 1961–2), and has been particularly associated with grazing on rapidly growing sown pastures or fodder crops (especially oats). Some very heavy losses have been recorded but the incidence tends to be highly variable from year to year. Herd (1961–2) has observed a seasonal lowering of blood magnesium concentration and considers that metabolic stresses, especially inclement weather, lactation, oestrus or excitement, precipitate the onset of clinical signs; successful prevention has been obtained by the feeding of magnesium oxide with hay (Herd, Schuster, and Coltman 1965). As reported in other countries, there appears to be little or no correlation of the disease with magnesium content of the pasture.

In Australian sheep, the occurrence of hypomagnesaemia has been proven only recently (Herd and Peebles 1962); the characteristics of the disease resemble those in cattle, though a concurrent hypocalcaemia (Herd 1966) modifies the symptoms exhibited.

SODIUM AND CHLORINE

In Australia, as in other pastoral countries, the traditional practice of providing salt for grazing stock is firmly entrenched. It is therefore of great interest that there is no reliable evidence of any need for supplements of salt to maintain productivity. As there have been no suggestions of a specific lack of chlorine, this discussion is restricted to consideration of sodium status—both deficit and excess.

There is no question that pasture forage frequently has a low sodium content and that sheep and cattle develop a very strong desire for salt—a desire that is often exploited to enable small quantities of other substances, for example copper salts, to be taken therapeutically by the animals. Denton *et al.* (1961) recorded sodium concentrations as low as 0·005 per cent (dry weight) in forages of the arid areas of Queensland and the Northern Territory, and Bott *et al.* (1964) found values as low as 0·01 per cent in mountain pastures in Victoria, and less than 0·1 per cent in pastures irrigated with water from the Murray River. Cattle grazing the mountain pastures showed physiological signs of sodium deficit: a reduction in sodium concentration of the urine and a very marked fall in the Na/K ratio in saliva—to as low as 0·1 compared with values of 20–160 in cattle grazing foothill pastures with sodium concentration of about 0·65 per cent. However, McClymont (1954) could find no evidence in the literature of the need for a sodium supplement for grazing sheep, and recorded that his experiments at six centres failed to show a favourable response to salt. Similarly, there is no unequivocal evidence that grazing beef cattle suffer any untoward effect from a low sodium intake (see Horrocks 1964a and b). Presumably, the physiological compensations in grazing ruminants are always adequate to maintain health.

High concentrations of sodium chloride are common in both forage and water. Wilson (1966b) has recorded concentrations of sodium chloride as high as 21 per cent in the dry matter of saltbushes (Chenopodiaceae). As these shrubs often have a high protein content, they can be valuable fodders provided that the animals have ready access to an abundant supply of low-salt water. Wilson (1966b) found that pen-fed sheep given saltbush diets consumed up to 240 g NaCl/day and drank about 50 ml of water for each gram of salt; very high water intakes would severely limit the distance that sheep could travel between feed and water in arid regions.

Many of the pastoral water supplies in Australia are derived from bores, and the water often contains appreciable amounts of salts, principally the chlorides, sulphates, and carbonates of sodium, calcium, and magnesium. The waters from the Great Artesian Basin in Queensland have chiefly carbonates and the total salts are usually less than 0·2 per cent. In most of the other basins, chlorides predominate and concentrations are often high—commonly over 1 per cent total salts and sometimes over 2 per cent. Peirce (1966 and earlier papers) has conducted a series of long-term tests on the tolerance of sheep to saline waters. In brief, he found that the performance of sheep was unaffected by having drinking water containing 1·3 per cent NaCl, but that concentrations of 1·5 per cent were detrimental. In sheep given water with total salts of 1·3 per cent, 0·2 per cent $MgCl_2$ was harmful, but 0·1 per cent was harmless; in comparable tests, 0·5 per cent Na_2SO_4 or 0·3 per cent $CaCl_2$ was also harmless. Similarly, the combination of 0·4 per cent sodium carbonates with 0·9 per cent NaCl was harmless. In these experiments, Peirce was able to demonstrate that sheep needed time to adapt to highly saline waters if deleterious effects were to be avoided. Further, sheep on saline waters drank much larger volumes than those given rain water—sometimes 2·5 times as much. Such detailed and prolonged experiments have not been performed on beef cattle, but the general trend of evidence is that their tolerance is of the same order as that of sheep (see Payne 1966).

COPPER AND MOLYBDENUM

These two elements are essential in the nutrition of animals and are conveniently discussed together as their interactions are so critical. Copper provides the catalytically active centre of several mammalian enzymes, and the important enzyme cytochrome oxidase is a cupro-protein (see Gallagher 1964). Molybdenum is known to form an integral part of two tissue enzymes; however, the requirement for this element is apparently extremely minute—Higgins, Richert, and Westerfield (1956) found that rats and chicks could maintain normal health on a purified diet containing only 20 μg Mo/kg. No natural occurrence of a deficiency in animals has been recorded (Whitehead 1966). By contrast, a deficiency of molybdenum for pasture plants is common in Australia (see Chapter 21).

Copper deficiency of ruminants is widespread in Australia. In the early 1930s, copper deficiencies in cattle and sheep had been reported from Florida and Holland, and in 1937 Bennetts and Chapman in Western Australia showed that enzootic ataxia of lambs was also an expression of a copper deficiency. On Australian pastures, sheep are more commonly affected by copper deficiency than are cattle. In sheep, the principal manifestations are fleece abnormalities, enzootic ataxia of lambs, anaemia, and unthriftiness. Loss of colour in pigmented wool and hair is the first and most sensitive indication of copper deficiency (Lee and Moule 1947); it is curious that, when black sheep are given a constant diet for the experimental induction of hypocuprosis, the reduction in wool pigmentation is not uniform and pronounced banding of the staple occurs (Wynne and McClymont 1956). With more severe and prolonged deficiency, the wool fibres lose their crimp and become straight and lustrous (Bennetts 1932; Marston, Lee, and McDonald 1948). This condition is described in the wool trade as 'stringy' or 'steely' and is quite distinct from another fleece fault known as 'doggy', the cause of which has not been established (Chapman and Short 1964). Copper deficiency leads to delay in the keratinisation of the growing wool fibre (Marston 1955), but the biochemical mechanism involved has not been elucidated. The occurrence of steely wool is a useful indication, and often the only indication, of a copper deficiency in unpigmented sheep; the lesion is more easily detected in the highly crimped wool of Merinos than in the British breeds, but has been demonstrated amongst Romney Marsh, Border Leicester, Lincoln, and Dorset Horn sheep (Lee 1956b).

Enzootic ataxia is a nervous disorder of lambs characterised by muscular inco-ordination; calves are rarely affected. It may be congenital or develop during the first few months of life. In Australia, the disease is associated with a low copper content in the pasture grazed by ewes during pregnancy, while in some other countries the copper intake is apparently adequate; in the latter circumstances, excessive intake of molybdenum is sometimes, but not always, involved.

Copper deficiency in cattle has been noted in several States, but the deficiency is usually very mild, and expressed as loss of colour in pigmented hair, general unthriftiness, and sometimes diarrhoea; it is frequently complicated by other diseases: gastro-intestinal parasites, tick infestation, aphosphorosis, and undernutrition (Sutherland 1952; Harvey 1952a; Alexander and Harvey 1957). In Western Australia, a fatal disease in cattle, 'falling disease', characterised by fibrosis of the myocardium, has been described (Bennetts *et al.* 1939, 1942, 1948). The severe diarrhoea associated with copper deficiency in some other countries has been recorded in Australia only in Tasmania (Green 1956). In Queensland, a copper deficiency syndrome occurs in young cattle grazing pastures with apparently adequate copper content and with no excess of molybdenum; presumably some unknown factor in the pasture inhibits copper utilisation (Donaldson *et al.* 1964; Alexander *et al.* 1967).

It is still not certain whether any of the natural diseases are due solely to copper deficiency. Beck (1962) considered that sheep in Western Australia exhibited a simple copper deficiency when grazing pastures containing less than 3 mg Cu/kg; however, Dick (1954) and Suttle and Field (1967) failed to produce deficiency symptoms in sheep given diets containing only about 1 mg Cu/kg. It is quite definite that conditioned copper deficiencies can be produced by elevated intakes of molybdenum (see Allcroft 1963) and it seems certain that other conditioning factors remain to be discovered; for example, the falling disease of cattle, found in Western Australia and ascribed to simple copper deficiency, has been recorded elsewhere only in Tasmania (Dumaresq, quoted by Green 1956) and Florida (Davis 1950). Also, the identity is not yet known of the conditioning factors that lead to the occurrence in Britain of 'swayback' (enzootic ataxia) in lambs born to ewes grazing pastures containing a 'normal' copper content (Allcroft 1963).

Several procedures are available for preventing copper deficiency, but the most favoured one is the inclusion of copper sulphate in the fertiliser (usually superphosphate) that is used for top-dressing of pastures; indeed, in some areas, this practice has been taken to such a stage that copper poisoning in grazing stock has become a risk.

The interactions between molybdenum and copper are of critical importance in determining the induction of copper deficiency or toxicity. The reactions are complex and the mechanisms involved are incompletely understood—there is as yet no satisfactory hypothesis which adequately accounts for all the experimental and field findings. The Cu-Mo interactions are in turn subject to modifications by inorganic sulphate and by other, at present unknown, constituents of pasture plants. The principal features are as follows. Copper and molybdenum act antagonistically in animal metabolism; administration of copper can prevent the harmful effects of excess molybdenum intake, while excess molybdenum can induce copper deficiency in animals having an apparently adequate copper intake. The absorption, excretion, and utilisation of these elements all seem to be involved. The harmful effects of molybdenum on cattle depend on the Cu/Mo ratio of the diet as well as on the actual intake of molybdenum (Cunningham 1960); when copper intake is low, a small excess of molybdenum may be harmful. Molybdenum tends to reduce the liver copper storage of sheep and cattle (Dick and Bull 1945), and this effect requires the presence of sufficient inorganic sulphate in the diet (Dick 1952, 1953; Wynne and McClymont 1956; Mylrea 1958). At a given intake of sulphate, increasing intakes of molybdenum progressively reduce copper retention (Dick 1953), while at a moderate intake of molybdenum, increasing intakes of sulphate have a similar effect. Inorganic sulphate alone has no apparent effect on copper metabolism, but high sulphate intake increases the excretion and reduces the tissue retention of molybdenum (Dick 1956). The toxic effect of high molybdenum intakes on cattle is not dependent on the induction of a copper deficiency, although copper administration cures or prevents the disease (Allcroft 1963); sheep are much more tolerant of excess molybdenum than are cattle.

A high intake of molybdenum and sulphate can induce copper deficiency in sheep receiving an adequate, or even high, copper intake. When sheep are receiving relatively low copper intakes, small excesses of molybdenum could help to induce deficiency symptoms (Dick 1954; Beck 1962). Dick (1954) showed that sheep could maintain a normal copper status with a dietary concentration of about 1 ppm dm—yet copper deficiency is commonly observed in Australia and elsewhere on pastures providing considerably more than this amount; molybdenum is probably one of the factors precipitating copper deficiency in such circumstances. When the molybdenum content of pasture is very low, and this is accompanied by a low sulphate content, sheep can accumulate large amounts of copper in the liver and suffer the haemolytic crisis of cumulative copper poisoning (Dick 1953).

Molybdenum plus sulphate tend to increase the level of blood copper (Dick 1956); Smith, Field, and Suttle (1968) have shown that this rise is associated with the induction of an additional (unidentified) form of copper in the plasma. Smith *et al.* (1968) have also shown that molybdenum plus sulphate reduces the absorption of copper from the intestinal contents, reduces the rate of uptake of copper by tissues, and increases the rate of excretion of urinary copper and endogenous faecal copper.

In several of the temperate regions in Australia a disease (so-called toxaemic jaundice) is produced in grazing sheep by excessive accumulation of copper in the tissues. Two distinct forms of copper poisoning have been recorded in Australia. Large accumulations of liver copper occur when sheep consume pasture providing moderate amounts of copper (about 10–15 ppm dm), but having a very low content of molybdenum (often less than 1 ppm—Dick *et al.* 1953); a sudden release of copper into the bloodstream (particularly following loss of bodyweight) can precipitate a fatal haemolytic jaundice (phytogenous chronic copper poisoning: Bull *et al.* 1956). This form of chronic copper poisoning was first recorded from the Murray Valley in Australia and has not been observed in other continents. A similar fatal termination has been found as a consequence of liver damage from plant alkaloids (hepatogenous chronic copper poisoning—Bull *et al.* 1956); several species in Australian grazing lands (notably *Heliotropium* spp., *Echium* spp., and *Senecio* spp.) contain alkaloids that damage liver cells and this leads to excessive accumulation of copper when the sheep are grazing pastures that favour copper assimilation.

It is evident, then, that the grazing sheep has rather a narrow tolerance for copper—the herbage requires to have about 3 ppm dm to prevent deficiency symptoms, yet as little as 10 ppm can produce fatal intoxication. This must be coupled with the fact that the sheep requires extremely little molybdenum to meet its essential tissue needs, yet appreciable amounts are required to prevent copper intoxication at moderate levels of intake. The complex interactions between copper, molybdenum, and sulphate make it difficult to define the precise nutrient requirements of copper and to predict the reactions of animals to the nutritive conditions on any given pasture or grazing land.

In several countries, molybdenum toxicity in cattle has been observed. The main symptom is severe persistent diarrhoea, which causes animals to lose condition and which may be fatal. This syndrome has not been recorded in Australia, though it has been suspected in Tasmania (Green 1956) and South Australia (H. J. Lee, personal communication). In northern Queensland, some herbage species have been found to contain up to 34 ppm molybdenum (Moule, Sutherland, and Harvey 1959)—a level as high as that recorded for some 'teart' pastures in Britain and for pastures responsible for 'peat scours' in New Zealand (Ferguson, Lewis, and Watson 1943; Cunningham 1960).

COBALT

The discovery that cobalt is an essential nutrient for sheep and cattle came from research on naturally-occurring diseases in South Australia and Western Australia (Lines 1935; Marston 1935; Underwood and Filmer 1935). It was then soon established that comparable diseases, classified under the general term enzootic marasmus, occurred in many other countries. The function of cobalt in metabolism remained obscure until the discovery, in 1948, that the anti-pernicious anaemia factor, later named vitamin B_{12}, was a cobalt-containing compound. Smith, Koch, and Turk (1951) and Marston and Lee (1952) showed that parenteral administration of vitamin B_{12} restored the health of lambs given a cobalt-deficient diet.

The original studies in Australia were notably assisted by the occurrence of very severe deficiencies locally known as Coast Disease in South Australia and Denmark Disease in Western Australia. The distributions of deficiencies have been recorded for South Australia (Lee 1951), Western Australia (Bennetts 1955), Tasmania (Green 1956), and Queensland (Moule and Young 1950). Both in Australia and other countries, deficiency occurs in a wide variety of soil types. It is now known that relatively small areas are afflicted with the severe diseases, but very much more extensive areas have a mild cobalt deficiency. These milder forms tend to vary greatly in annual incidence and severity (McDonald 1942a; Lee 1963), and probably cause much more economic loss than the frank manifestations of the disease. In the severe form of the disease, there is gradual failure of appetite, loss of weight, muscular weakness, progressive anaemia, and eventually death; lambs born to affected ewes die at or soon after birth. In the mildest forms, no characteristic symptoms appear—the animals simply do not thrive as well as could be expected; in such circumstances, chemical or therapeutic tests are necessary to establish a diagnosis. Analysis of soil is helpful in determining areas where deficiency is likely to occur, and the cobalt status of the animal can be ascertained by estimations of cobalt in pasture or liver, and of vitamin B_{12} in liver or plasma. All these procedures are satisfactory for detecting frankly deficient or normal, healthy animals. When the deficiency is slight, the most critical test is therapeutic—that is testing the response to treatment with cobalt. Since the symptoms and post-mortem signs are principally those of gross undernutrition, the presence of other deleterious agents (e.g. intestinal parasites, infections) often makes differential diagnosis difficult.

So far as is presently known, the only function of cobalt in animal metabolism is expressed through vitamin B_{12}, which is synthesised in nature only by micro-organisms. In the ruminant, bacteria in the rumen produce vitamin B_{12} and several related compounds; this would appear to place the ruminant in a very favourable position for avoiding a vitamin deficiency, and it is therefore rather anomalous to find that a cobalt deficiency occurs only in ruminants—other herbivores (e.g. horse, rabbit) thrive on pastures that will not support sheep and cattle. It appears that the ruminants have an exceptionally poor capacity for absorbing vitamin B_{12} (Simnett and Spray 1965).

It has also been found in Australia that cobalt exerts a protective function against a toxin found in *Phalaris tuberosa.* This perennial grass is one of the major species used in sown pastures in south-eastern Australia, but sometimes causes deaths of sheep, and less commonly of cattle (McDonald 1942b, 1946; Moore *et al.* 1961); outbreaks have been recorded in South Australia, Western Australia, and New South Wales. The chronic syndrome of this disease can be prevented by administration of cobalt (Lee and Kuchel 1953; Lee, Kuchel, and Trowbridge 1956); the mechanism of this activity is unknown, but is not associated with the vitamin B_{12} status of the animal (Lee 1956a; Lee *et al.* 1957); presumably, cobalt influences the metabolism of ruminal microbes in such a way that the toxic principle (at present unknown) of the forage is destroyed. The acute forms of phalaris poisoning appear to be due to the presence of tryptamine alkaloids (Culvenor, Dal Bon, and Smith 1964; Gallagher *et. al.* 1966), but cobalt administration does not protect the sheep against these toxins (Moore and

Hutchings 1967) (see Chapter 26).

Effective methods have been developed for providing cobalt supplementation (for details see Lee 1963); these include use of cobalt in fertilisers, dosing per os, incorporation of cobalt in salt licks, and addition of cobalt to feedstuffs, feed supplements, or water supplies. However, these methods have now largely been superseded by the use of dense cobalt-containing pellets (Dewey, Lee, and Marston 1958) which can be easily administered to sheep or cattle, and which lodge permanently in the reticulo-rumen; slow release of cobalt from the pellet provides the animal with the minute daily dose required to maintain health and vigour.

SELENIUM

Excessive intake of selenium, consequent to the uptake of selenium by plants from seleniferous soils, produces severe abnormalities in grazing stock. The extensive literature on this subject has been thoroughly reviewed by Rosenfeld and Beath (1964). Two major chronic syndromes have been recognised in the U.S.A. and given the colloquial names of 'blind staggers' and 'alkali disease'; the former is associated with poisoning by the water-soluble organic Se-compounds in selenium 'indicator' plants, while the latter results from the ingestion of selenium bound in proteins as analogues of the sulphur-containing amino acids. These two naturally-occurring syndromes have clinical signs and pathological changes that differ appreciably from the chronic selenosis that can be induced experimentally by the administration of inorganic selenites and selenates.

In Australia, only one pastoral area has been recorded in which selenosis occurs in ruminants (McCray and Hurwood 1963). This is a large area in north-western Queensland where soils and plants contain notable quantities of selenium. The two main species known to accumulate selenium are *Neptunia amplexicaulis* and *Acacia cana;* concentrations in excess of 4000 ppm dm have been found in Neptunia. In spite of the large area involved, grazing sheep and cattle are usually little, if at all, affected. Only a few instances of severe toxicity have been noted and these have occurred where intensification of landuse and animal husbandry has been practised. Chronic selenosis in horses has been recorded in Cape York Peninsula (Knott and McCray 1959); the plant *Morinda reticulata* is able to accumulate large amounts of selenium even when growing on soils with an extremely low selenium content. The young growth of this plant at the beginning of the rainy season is readily eaten by horses.

By contrast, selenium in small concentrations has beneficial effects on grazing animals. It is now considered probable that selenium is an essential nutrient for animals, although no specific function for selenium in animal metabolism has been found and no specific selenium compound, other than analogues of sulphur compounds, has been found in animal tissues. Three distinct syndromes that respond to selenium administration have been recorded in grazing ruminants: a muscular dystrophy, so-called 'white muscle disease', in young lambs and calves; unthriftiness, with poor growth rates, occurring in the absence of any other recognised disease; and infertility in ewes. The last-named condition has been observed in a severe form only in New Zealand; lambing percentages may fall to very low levels in areas where other selenium-responsive conditions appear. The reproductive failure is principally associated with early embryonic mortality and excellent results from administration of selenium are obtained (Hartley 1963). As there are no characteristic symptoms or pathological changes, confirmation of diagnosis can be made only by therapeutic tests; it is clear that difficulty will be experienced in detecting moderate reductions of fertility associated with selenium-responsiveness.

The other two selenium-responsive conditions of unthriftiness and white muscle disease have been observed in Australia. The unthriftiness syndrome also has no characteristic clinical or pathological features and, again, diagnosis requires therapeutic testing. Differential diagnosis is important as comparable unthriftiness can derive from other causes, notably deficiencies of cobalt and/or copper, gastro-intestinal parasites and inadequate feed supplies. In several States, slight responses in bodyweight of lambs or weaners have followed selenium treatment, but it would appear that ill-thrift associated with selenium status is not a problem of major importance in Australia (Setchell *et al.* 1962; Skerman 1962; Pulsford, Rae, and Irving 1966).

The syndrome of white muscle disease has been reported from all States of Australia (Collins 1939; Walker *et al.* 1961; Roche 1961; Gardiner *et al.* 1962; Skerman 1962; Pulsford *et al.* 1966) and conforms with the condition as observed in other countries. It is noteworthy that the disease commonly occurs in lambs in good or even fat condition—indeed, several observations of the pathological condition of the musculature had been made at abattoirs prior to the recognition of the clinical entity (Walker *et al.* 1961). The muscular dystrophy has been induced experimentally by feeding lambs on diets with excess of unsaturated fats (see Blaxter and Brown 1952), or with large amounts of torula yeast (Hopkins, Pope, and Baumann 1964; Godwin and Fraser 1966), or by feeding pregnant ewes with a natural dystrophogenic diet (Oldfield, Muth, and Schubert 1960), but to date there has been no report of the induction of a simple selenium deficiency by a purified diet with conventional constituents. Australian findings (e.g. Gardiner and Gorman 1963; Peirce and Jones 1968) are in accord with American experience (Allaway and Hodgson 1964) that the selenium-responsive diseases do not always appear in areas where forages have as low a selenium content as occurs in the so-called deficient areas. Peirce and Jones (1968) obtained no response to selenium in growth rate or wool growth in young sheep grazing pastures containing low concentrations of selenium (0·015–0·03 ppm); these values are as low as those considered deficient in New Zealand (A.B. Grant, quoted by Davies and Watkinson 1966), Western Australia (Gardiner *et al.* 1962) or the U.S.A. (Allaway *et al.* 1966; Allaway and Hodgson 1964).

These findings, together with the facts that selenium is a potent inhibitor of enzyme systems, is toxic in very small amounts, and can be incorporated into compounds forming analogues to sulphur compounds (e.g. the S-amino acids, cysteine and methionine), make it probable that the naturally-occurring selenium-responsive diseases are not primary deficiencies, but are induced by harmful agents whose effects are antagonised by selenium compounds. In similar vein, it may be noted that the toxic effects of selenium tend to be counteracted by administration of arsenic compounds (Moxon *et al.* 1944). Recently, Kondos and McClymont (1967) have suggested that the selenium status of grazing sheep may influence susceptibility to poisoning by carbon tetrachloride, used for the treatment of liver fluke infection; a low selenium status appears to render the sheep more susceptible, and protection can be achieved by administering small doses of selenium, while high doses of selenium increase susceptibility to CCl_4. Tocopherol had no such protective action.

OTHER INORGANIC NUTRIENTS

Fluorine

Fluorine is not an essential element in the usual nutritional sense (Jenkins 1967); its only known function is the prevention of dental caries under conditions permitting that disease to develop; such conditions are not found with grazing ruminants. Disease due to excessive intake of fluorine has been recorded in many countries. In the Australian pastoral industry, the main source of excess fluorine is in drinking water; a minor source is the use of phosphatic supplements containing fluorine. Waters from the Great Artesian Basin are used for sheep and cattle over much of the eastern half of the continent; fluorine contents greater than 5 ppm are common in artesian bore waters, and the concentration may be greatly increased due to evaporation as the water flows along the open bore drains. Further, the pasture plants that grow along the bore drains may contain abnormally high amounts of fluorine during dry seasons, these plants can provide an important source of feed for stock, and thus may form an additional source of fluorine (Harvey 1952b, 1953). The principal effect of excess fluorine is interference with the formation of tooth enamel in young animals; affected teeth tend to wear excessively and unevenly, leading to impaired chewing and grazing efficiency. Adult sheep are little, if at all, affected by quite high intakes of fluorine (e.g. 20 ppm in water), though dental impairment of the foetal lamb may occur when ewes consume water with 15 ppm fluorine (Peirce 1952, 1954, 1959; Harvey 1952b). Contamination of pastures by industrial effluents has not been a problem in Australia.

Zinc

It is well established that zinc is an essential element and a deficiency can be produced in ruminants (Miller and Miller 1962; Ott *et al.*

1965). Zinc is an integral component of several mammalian enzymes. In British Guiana, Legg and Sears (1960) observed in grazing cattle a clinical condition of parakeratosis that responded to administration of zinc. Zinc-deficiency of pasture plants is common in Australia, but no deficiency in grazing sheep or cattle has been recorded; however, M. Somers (personal communication) found, in pen-fed sheep, that testicular development was impaired at levels of zinc intake equivalent to that for sheep grazing pastures on zinc-deficient soils in Western Australia.

Iodine

Although endemic goitre in man is common in Australia, grazing ruminants are not often affected; this anomaly may in part be explained by the passage of goitrogens into cow's milk used for human consumption (Clements 1960). An extensive survey of sheep in pastoral areas (Dawbarn and Farr 1932) failed to reveal any indications of iodine deficiency. Since that time, congenital goitre in lambs, and less in calves, has been reported in New South Wales and Tasmania (Southcott 1945; Green 1956; Setchell *et al.* 1960; George, Farleigh, and Harris 1966). The syndromes observed conform to findings in other countries, and responses to iodine therapy have been satisfactory (George 1966; Setchell and Dickinson 1966). The histories of the recorded outbreaks suggest that plant goitrogens are involved in causing the goitrous changes, but the nature of the goitrogens received by ewes grazing permanent pastures has not been determined. Although serious losses of newborn lambs have occurred on individual farms, goitre is not an important problem for the pastoral industry.

Iron and Manganese

No deficiencies of iron or manganese have been observed in grazing animals. In Australia, there has been no suggestion of manganese-responsive conditions comparable with those reported in the Netherlands and Great Britain (see Highett 1956).

26

DISORDERS OF GRAZING ANIMALS DUE TO PLANT CONSTITUENTS

A. W. H. BRADEN AND IAN W. MCDONALD

Apart from the presence in pasture, or associated with it, of plants that contain substances that are toxic or harmful to animals that graze them, some of the valuable and widely used pasture species under certain circumstances may cause disorders in the grazing animals. In this chapter, some of the animal disorders of this type that occur in Australia, and that have been subjected to a considerable amount of study in this continent, are reviewed. The first to be dealt with (phyto-oestrogens) only rarely causes a significant effect on the health of the animal or on wool production in sheep, but the important effect is a depression of fertility of the females. The effects occur over a wide enough area to be quite important economically. The second disorder reviewed (phalaris staggers) on the other hand is often fatal, but, though the plant is grown quite widely as a pasture constituent, only a very small proportion of sheep are lost. The other plants dealt with mostly fall into the category of toxic plants that are not normal pasture constituents.

PHYTO-OESTROGENS IN PASTURE LEGUMES

Of the pasture legumes of temperate regions, some of the most important have been found to cause oestrogenic effects in the animals that graze them. The main species involved are subterranean clover (*Trifolium subterraneum*), red clover (*T. pratense*), and several medics, including lucerne (*Medicago sativa*) and barrel medic (*M. truncatula*).

The oestrogenicity of the subterranean clovers was discovered through the appearance in Western Australian about 1944 of a serious depression in the fertility of sheep grazing pastures dominated by this species (Bennetts, Underwood, and Shier 1946). This led to intensive investigation of (1) the substances in the plant responsible for the oestrogenicity and their metabolism in sheep, (2) the variation in activity among strains of clover, (3) the selection and breeding of strains with low activity, (4) the effect of soil nutrients on activity in the plant, and (5) the mechanism involved in loss of fertility in ewes.

No major infertility or other problems have been reported in animals grazing the medics, but problems similar to those occurring on subterranean clover can occur on red clover. While much attention has been devoted to the deleterious effects of pasture oestrogens, it must not be forgotten that at lower levels of intake they might, in fact, be advantageous, for oestrogens are known to have an anabolic effect (Oldfield *et al.* 1966).

Effects in Grazing Animals

The effects in sheep of grazing highly oestrogenic pasture became evident by a rather dramatic fall in the number of lambs marked per 100 ewes mated (from about 80 per cent to less than 30 per cent) on many properties in Western Australia about 1944. The syndrome was characterised by maternal dystokia, post-natal mortality of lambs, infertility amongst ewes, and uterine prolapse and lactation in virgin and non-pregnant ewes (Bennetts *et al.* 1946). In wethers, enlargement of the teats and lactation, and enlargement of the accessory sex glands, were common (Bennetts 1946). The incidence of dystokia in some flocks was as high as 40 per cent of the ewes that carried lambs to full term, and accounted for the death of up to 20 per cent of all ewes mated. Young ewes mated for the first time seemed most susceptible to dystokia, and, in consequence, death rates amongst them sometimes reached 70 per cent. Severe neo-natal mortality accounted for the loss of 40–50 per cent of the lambs that survived birth. There was also considerable wastage of

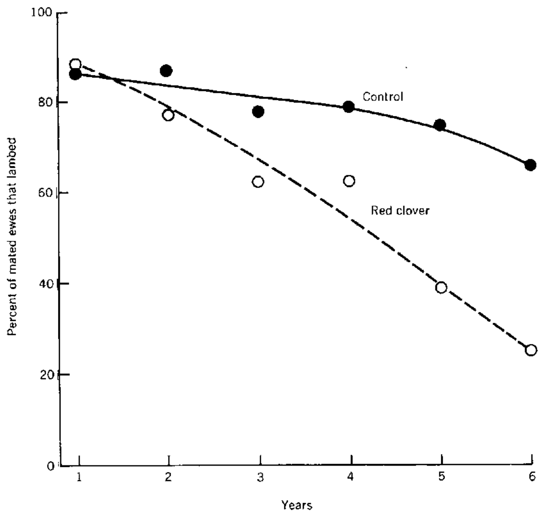


Fig. 26 : 1 Decline in fertility in Merino ewes associated with grazing oestrogenically active red clover pastures for 8 months in each year

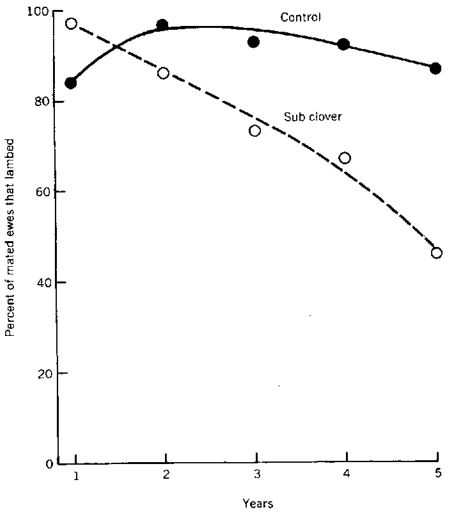


Fig. 26 : 2 Development of 'permanent infertility' in a flock of crossbred ewes that grazed *Trifolium subterraneum* var. Dwalganup (subterranean clover) for 5 months each year

ewes due to retained and mummified foetuses, or from metritis, with consequent sterility. Uterine prolapse rarely affected a high proportion of ewes, although in some flocks its incidence reached 10 per cent and constituted the only manifestation of the problem for one or two years; more commonly, the yearly incidence was less than 2 per cent.

Pathologically, the syndrome was characterised in ewes by cystic glandular hyperplasia of the endometrium.

The fertility of the flocks usually declined progressively. Reports from the field indicated that infertility, once established, was permanent, and this was confirmed experimentally by Schinckel (1948) and Underwood and Shier (1951). Furthermore, the infertility has been produced experimentally in ewes grazing red clover in New South Wales (Barrett, George, and Lamond 1965), and in ewes grazing subterranean clover (cv. Dwalganup) in Western Australia (Davenport 1967). Figures 26 : 1 and 26 : 2 show the decline in fertility. More recently Lloyd Davies, Rossiter, and Maller (personal communication) studied the fertility of ewes that grazed either Dwalganup, Yarloop, Geraldton, Woogenellup or Mt Barker cultivars of subterranean clover for four years. The conception rates observed were significantly related to the concentration of formononetin in the cultivars. The groups on the high formononetin cultivars (Dwalganup, Yarloop, Geraldton) showed a significant decline over the four years in the proportion of ewes conceiving; the groups on the other two cultivars did not.

As graziers have become aware of the cause of the trouble and have taken steps to minimise it (by reducing intake of active clover by sheep), the more extreme manifestations of the syndrome are disappearing; the prime trouble is now subnormal fertility. This permanent type of infertility due to phyto-oestrogens also occurs and is of economic importance, in some parts of South Australia, Victoria, Tasmania, and New South Wales.

Flocks affected by 'permanent infertility' exhibit lowered fertility even when mated 1–2 years after removal from clover pastures. There is, however, another infertility syndrome which has been called 'temporary infertility'. This is exhibited when sheep graze highly oestrogenic pastures at the time of mating (Morley, Axelsen, and Bennett 1964; Clark 1965). Within five weeks after removal from clover their fertility is normal again (Morley, Axelsen, and Bennett 1966). The severity of the infertility is not great enough to be readily detected under normal farming conditions (nor is it simple to detect experimentally, because large numbers of sheep are needed), but nevertheless could be important economically. The infertility demonstrated experimentally in sheep grazing red clover or Dwalganup subterranean clover at the time of mating involved a decrease of 15–20 per cent in the number of ewes lambing, and sometimes also a decrease of 20–30 per cent in the proportion of twins born (Morley, Axelsen, and Bennett 1966; Clark 1965).

The 'permanent' type of infertility is apparently caused by failure of fertilisation. This, in turn, is caused by poor transport and survival of sperm in the ewe genital tract, and is associated with a cystic condition of the cervix. Loss of fertilised eggs or early embryos also contributes to the low fertility (Turnbull, Braden, and George 1966; Lightfoot, Croker, and Neil 1967; Fels and Neil 1968). The mechanisms involved in the 'temporary' type of infertility have not been elucidated. They do not, however, appear to involve failure of fertilisation (A. W. H. Braden and P. E. Mattner, unpublished observations).

While infertility of sheep grazing oestrogenic pastures has been, and to a lesser extent still is, a serious economic problem in some areas in Western Australia and South Australia, cattle were generally unaffected. However, in the northern part of Tasmania infertility apparently attributable to subterranean clover has been reported in dairy cattle (Thain 1966 and 1968). A similar uterine lesion to that seen in sheep (cystic endometrial hyperplasia) was found in cattle from affected areas. It is surprising that the variety of subterranean clover mainly incriminated (Mt Barker) has generally been found to have very low oestrogenicity in sheep (Davies and Bennett 1962; Bennett, Morley, and Axelsen 1967), and does not appear to be responsible for sheep infertility in other parts of Australia. The phyto-oestrogen (isoflavone) content of the Mt Barker clover growing in Tasmania is similar to that grown elsewhere, though on farms where the infertility occurs a red coloration of the clover leaves has been noted. Such leaves have a higher content of formononetin (0·22 cf. 0·08 per cent) and genistein (2·0 cf. 0·4 per cent) than apparently normal leaves from other parts of the farm (Thain and Robinson 1968). This increase, however, does not seem a sufficient explanation for the observed infertility. Comparison of blood levels of the phyto-oestrogens (Lindner 1967) in sheep and cattle fed several varieties of clover in Tasmania is being undertaken in an attempt to explain the anomaly.

The Metabolism and Relative Oestrogenicity of the Phyto-oestrogens

Phyto-oestrogens that have been identified in the pasture plants under consideration fall into two main groups—the isoflavones and the coumestans. The former are the major phyto-oestrogens in clovers and the latter in the medics. The main isoflavones found in the clovers are the 5-hydroxy-isoflavones, genistein and biochanin A, and the 5-deoxy-isoflavones, daidzein and formononetin (see Fig. 26 : 3 for structures). Another isoflavone present in small amounts in red clover is pratensin. The major coumestans in medics are coumestrol and 4′0-methyl-coumestrol (Bickoff *et al.* 1957 and 1965; Millington, Francis, and McKeown 1964; Francis, personal communication). Very little is known about the metabolism of the coumestans in sheep except that 4′0-methyl-coumestrol is evidently demethylated to coumestrol in the rumen (Shutt, Braden, and Lindner 1969). The isoflavones genistein, biochanin A, and formononetin, are often present in clovers in high concentration—combined levels in the leaves up to 5 per cent on a dry matter basis (Beck 1964). Typical levels are given in Table 26:1.

Using synthetic compounds (including some ^{14}C-labelled), the metabolism in sheep of biochanin A, genistein, and formononetin has been studied. The O-methyl compounds biochanin A and formononetin are demethylated to genistein and daidzein respectively both in the rumen and after absorption into the general circulation (Nilsson 1961 and 1962; Lindner 1967; Batterham *et al.* 1969), but thereafter the pathways apparently differ. In the metabolism of genistein the molecule splits at the C ring, the B ring being excreted as p-ethyl-phenol (Batterham *et al.* 1965, pers. comm.), and the A ring possibly as a phenolic acid. It was estimated that 60–80 per cent of the genistein and biochanin A ingested could be accounted for as p-ethyl-phenol in the

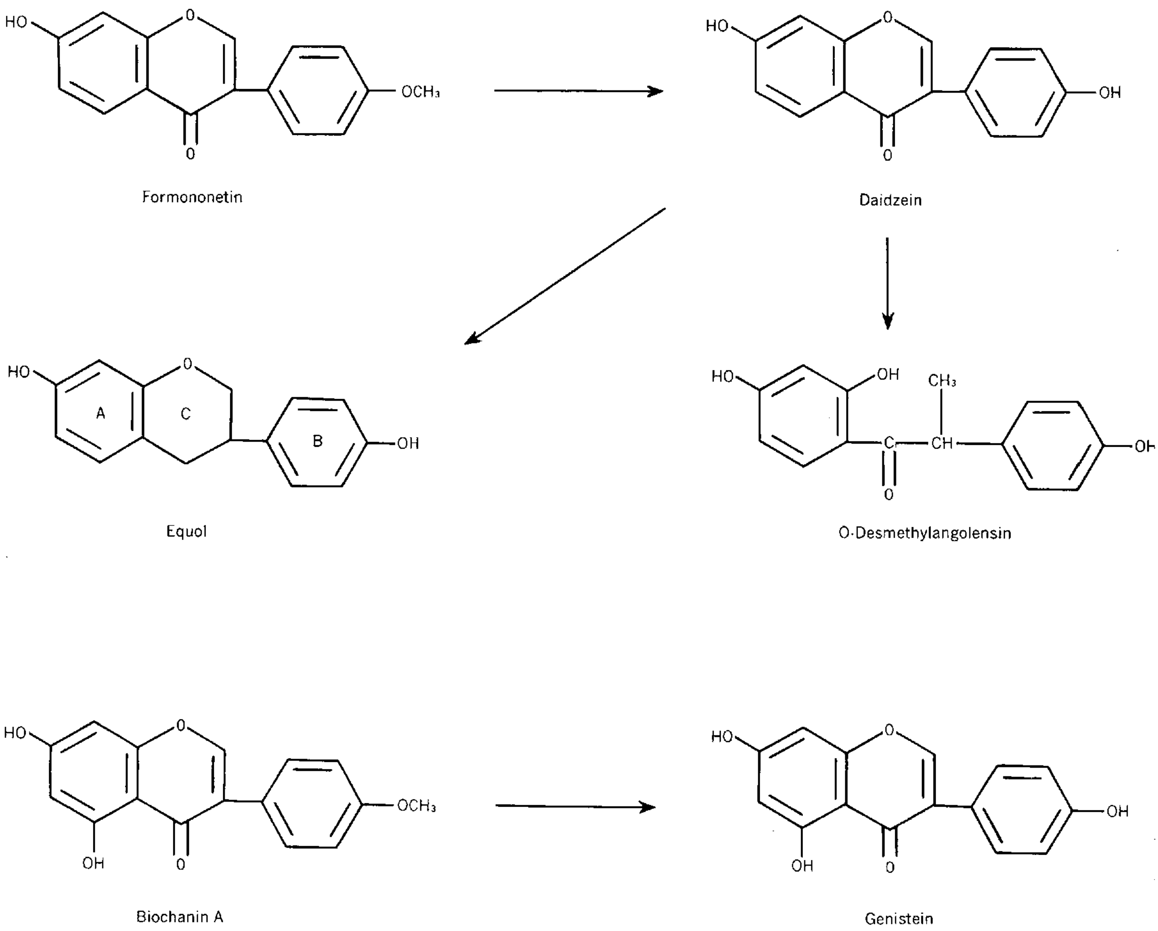


Fig. 26 : 3 The chemical structures of some of the isoflavone phyto-oestrogens and their metabolites

urine (Batterham *et al.* 1965). Daidzein, on the other hand, can apparently be metabolised by either of several pathways, the importance of which can vary with the length of feeding, etc. (Shutt and Braden, unpublished observations). Metabolites of daidzein that have been identified in the sheep are equol (Batterham *et al.* 1965, pers. comm. Nilsson, Hill, and Davies 1967) and O-desmethyl-angolsin (Shutt and Braden 1968; Batterham *et al.* pers. comm.). These two compounds must be produced by different pathways (Fig. 26 : 3). In a controlled feeding experiment the amount of equol recovered in the urine accounted for about 70 per cent of the formononetin ingested in the clover (D. A. Shutt, R. H. Weston, and J. P. Hogan, personal communication 1968). O-desmethyl-angolensin is usually found in much lower concentrations in the blood and urine than equol. It does not appear that p-ethyl-phenol is one of the end-products of the metabolism of formononetin. Most of the metabolism can take place in the rumen and, in fact, with the isoflavones ingested in their natural condition contained in the plant, only a very small proportion of the isoflavone is absorbed into the bloodstream; most is completely metabolised in the rumen.

Bioassay of pasture has been attempted using a variety of test animals (mice, rats, guinea pigs, and sheep—see Moule, Braden, and Lamond 1963 for summary), but because of the differences in metabolism of the isoflavones between monogastric animals and ruminants, it has become clear that assays are best conducted using sheep.

TABLE 26 : 1 Phyto-oestrogen content of the leaves of various pasture legumes (green)

Species	Cultivar	Isoflavones as % of dry matter			Coumestrol ppm
		Formononetin	Genistein	Biochanin A	
T. subterraneum (subterranean clover)	Dwalganup	0·7 –1·9	1·1–2·1	0·4–0·9	0–5
	Yarloop	0·7 –1·6	1·0–3·5	0·1–0·9	—
	Geraldton	0·7 –1·5	0·3–0·6	0·5–1·3	
	Clare	0·1 –0·3	0·7–4·3	0·1–2·3	
	Mt Barker	0·06–0·3	0·2–1·0	1·1–2·3	
	Uniwager	0·05–0·2	0·1	—	
T. pratense (red clover)	Grasslands Hamua Broad	0·6 –1·15	0–0·13	0·4–1·3	—
	N.Z. Cow Grass	1·2	Trace	1·0	
	Ulva (4x)	1·15	Trace	1·0	
T. israeliticum	Various	0·5 –1·4	0·4–1·5	0·05–1·5	
T. globosum		1·5	3·5	Trace	
T. repens (white clover)	Ladino	0·01–0·02	0–0·02	0–0·05	5–10
	Vic. irrigation	0–0·08	—	—	0–20
T. fragiferum (strawberry clover)		0·01–0·02	—	—	2–25

Sources: Beck (1964); Francis and Millington (1965a and b); Millington, Francis, and Davies (1966); Bennett, Morley, and Axelsen (1967); Francis, Millington, and Bailey (1967).

Several assay methods are available—uterine weight increase in ovariectomised ewes (Davies and Bennett 1962; Bennett and Dudzinski 1967), increase of teat length in wethers (Braden, Southcott, and Moule 1964), and changes in the cervical mucus of ovariectomised ewes (Turnbull, Shutt, and Braden 1967; Lindsay and Francis 1968). The oestrogenic response in sheep has been found to be correlated with the formononetin content of the plant fed (Millington, Francis, and McKeown 1964), though in more extensive tests this was not always found to hold true (Davies and Dudzinski 1965; Bennett, Morley, and Axelsen 1967); sometimes pastures low in formononetin but high in biochanin A or genistein showed considerable activity.

Investigation of the oestrogenicity of synthetic phyto-oestrogens given intramuscularly (i/m) or intrarumenally (i/r) to ewes indicated that genistein, biochanin A, and formononetin have similar activities when given i/r (1×10^{-5} times that of stilboestrol given i/m); coumestrol i/r was some 15 times more active than the isoflavones (Braden, Hart, and Lamberton 1967). Genistein and biochanin A are about 20 times more active when given i/m than when given i/r. Formononetin is not active i/m, apparently because of its low solubility. The reason for the discrepancy between these findings and those of Millington *et al.* (1964), Davies and Dudzinski (1965), and Bennett *et al.* (1967) on clovers containing the isoflavones, probably lies in a difference between the two methods of administration in the rate of metabolism of the isoflavones in the rumen and in the rapidity of absorption into the bloodstream. Studies of the blood levels of the isoflavones and their metabolites after ingestion of clovers containing high concentrations of isoflavones suggest that the clovers high in formononetin owe their activity in large measure to the metabolite equol, which is oestrogenic (Shutt and Braden 1968), and possibly also to daidzein and O-desmethylangolensin which are present in lower levels in the blood and in the uterus. O-desmethylangolensin has been shown to be oestrogenic by Micheli *et al.* (1962).

Earlier it was thought that the phyto-oestrogens were 'pro-oestrogens', that is that they were not themselves oestrogenic, but were metabolised to active oestrogens. It now seems unlikely that this is the case. Shutt (1967) has produced evidence that genistein is not a 'pro-oestrogen' but a weak oestrogen that can act (as is characteristic of weak oestrogens) as an anti-oestrogen when in competition with a highly active oestrogen such as oestradiol. Because of its poor solubility when injected i/m it is uncertain whether formononetin is itself oestrogenic or whether it depends for its oestrogenicity when given orally on daidzein, equol, or O-desmethylangolensin.

Factors Affecting the Phyto-oestrogen Content of Plants

Environmental factors do have some influence on the phyto-oestrogen content of the clovers and medics, but it is small compared to the genetic effects. As indicated in Table 26:1 varieties of subterranean clover vary markedly in the type of isoflavone present and in the total amount of isoflavone per gram of leaf. Because of the fertility problems in sheep grazing the clover pastures in Western Australia, the University of Western Australia undertook the selection of low-isoflavone mutants produced by a chemical mutagen. One mutant produced has been developed into a strain (Uniwager) that shows some promise of being suitable in areas where the highly oestrogenic cultivars Dwalganup and Geraldton are well adapted. The formononetin content of Uniwager is about 0·08 per cent compared to 1·5 and 1·0 for Dwalganup and Geraldton (Quinlivan, Francis, and Poole 1968). Uniwager is also being used in a cross-breeding program to develop other low isoflavone strains with a variety of agronomic characteristics (Francis 1968).

Study of four of the mutants produced by the mutagen treatment of Geraldton subterranean clover indicated that they were simple recessives (Francis and Millington 1965a). One mutant lacked the enzyme needed for release of the isoflavones from the bound (glycosidic) form in which they occur in the plant; the oestrogenicity when fed to sheep was nevertheless high, indicating that hydrolysis of the glycosidic linkage occurs readily in the sheep (probably in the rumen) (Millington, Francis, and Davies 1966). Another mutant contained high concentrations of daidzein (which usually occurs only in low concentrations) and genistein, suggesting that the enzyme needed for the methylation of these compounds to formononetin and biochanin A, respectively, was missing. This mutant also had high oestrogenicity when fed to sheep. The other two mutations studied caused a great reduction in the amount of isoflavone synthesised, the total isoflavone content being less than 0·25 per cent; both had negligible oestrogenicity when fed to sheep. One of these has been registered as Uniwager, the cultivar referred to above.

In addition to the mutant Uniwager, two naturally occurring cultivars—Daliak and Seaton Park—both low in formononetin, have been selected for further study of the infertility problem (R. C. Rossiter, personal communication). Both cultivars have been registered and seed supplies have been built up for commercial use. The earlier maturing cultivar Daliak, which has been shown to have low oestrogenicity when grazed by sheep (Davies and Dudzinski 1965), is adapted to much of the area presently sown to Dwalganup, while Seaton Park is comparable to Yarloop in flowering time, and is a possible replacement for it.

Although oestrogenic effects in sheep grazing the medics have not been recognised as a problem in Australia, it is possible that unrecognised 'temporary' infertility has occurred, for the activity, particularly in dry pastures, would seem to be high enough to produce such an effect (Francis and Millington 1965c). Consequently, a study of species and varietal differences in coumestrol content and oestrogenic activity was undertaken. Results from crossing plants with high and low coumestrol contents indicate that selection of strains with low activity could be readily achieved (Millington and Francis 1966).

The effects of a variety of environmental factors (temperature, light, phosphate, zinc and nitrogen deficiencies, and defoliation) have been investigated for subterranean clover (Rossiter and Beck 1966a and b, 1967; Rossiter 1967 and 1969; Rossiter, personal communication). A nutrition study has been made with red clover in New Zealand (N, P, and K levels were studied) by Butler, Steemers, and Wong (1967). All factors had some effect on the isoflavone levels in the leaves, but the only one likely to be of much significance in relation to sheep infertility in the field is phosphate deficiency. The isoflavone levels in the clovers are not greatly affected when the plant is cut and dried artificially, but they decrease markedly when the plant wilts and dries in the field (Davies and Dudzinski 1965). On the contrary, with medics the coumestrol content increases with the ontogeny of the plant through to maturity and a further increase often takes place on drying in the field (Francis and Millington 1965c).

In U.S.A. the coumestrol content of lucerne (alfalfa) has been found to increase sharply when the plants are infected with foliar pathogens, but was not much affected by phosphate levels, temperature, or stage of growth (Loper and Hanson 1964). In Australia no effect of fungal infection on coumestrol content of medics has been noted, though a 3-to-4-fold increase due to infection with the rust *Uromyces striata* in the medic *M. polymorpha* was found (Millington and Francis 1966).

PHALARIS TUBEROSA

Phalaris tuberosa is a widely used perennial grass in sown pastures, but sheep grazing such pastures sometimes show neurological disturbances or may die suddenly. Cattle are less frequently affected. Three distinct syndromes have been described: peracute, acute, and chronic (Gallagher, Koch, and Hoffman 1966). The chronic form was described as early as 1942 by McDonald and has generally been known as 'phalaris staggers'. The peracute syndrome has become known as 'sudden death'; affected sheep collapse suddenly without premonitory signs, particularly when disturbed or excited. Death appears to be due to ventricular fibrillation and cardiac arrest. The acute syndrome, on the other hand, is primarily neurological, but there is considerable variation in the type and degree of disorder exhibited. In the most severe form the sheep are found lying on the ground with the legs displaying violent spasms, the head dorsiflexed and the jaws clamped or grinding. Less affected animals are very excitable, with incoordinated walk and muscular spasms and twitches. Sheep may recover completely from both peracute and acute symptoms if removed from the pasture.

The chronic syndrome, on the other hand, is characterised by persistence of symptoms long after removal from the pasture. The symptoms are neurological and stem from demyelination lesions in the central nervous system (McDonald 1942b). The symptoms include ataxia, weakness of the front legs, head-nodding, etc.

The major alkaloids found in phalaris are N, N-dimethyltryptamine, 5-methoxy-N, N-dimethyltryptamine and 5-hydroxy-N, N dimethyltryptamine (Culvenor, Dal Bon, and Smith 1964). The total concentration of tryptamine alkaloids in toxic pastures is sometimes over 0·04 per cent dm (Moore, Williams, and Chia 1967). These alkaloids are structurally related to serotonin (5-hydroxytryptamine) which is found in mammalian tissues and has a powerful action on smooth muscle and on the central and autonomic nervous systems. The alkaloids probably act by inhibiting the breakdown of serotonin by the enzyme monoamineoxidase.

Parenteral administration to sheep of the alkaloids found in phalaris produces symptoms resembling the peracute and acute syndromes; there is now strong evidence that these syndromes are, in fact, caused by the plant alkaloids. However, the cause of the chronic syndrome is still obscure; repeated administration of sublethal doses of the alkaloids have failed to induce the disease (Lee and Kuchel, personal communication). The chronic syndrome, but not the acute and peracute ones, can be prevented by regular administration of cobalt (Lee and Kuchel 1953; Lee, Kuchel, and Trowbridge 1956; Moore and Hutchings 1967), but the mechanism involved is unknown; it is not related to the vitamin B_{12} status of the sheep (Lee 1956a).

Pastures that cause the acute and peracute syndromes have been found to have higher alkaloid levels than pastures that do not. Nitrate nitrogen levels are also higher in both soil and plants in toxic pastures than in non-toxic. There is a diurnal rhythm in the alkaloid content of the pasture with a peak in the morning. Pastures appear to be most toxic when the phalaris is freshly shooting and the nitrogen content of the soil is high and the weather is foggy or cloudy. The alkaloids break down quickly in mown pastures.

Phalaris toxicity is nevertheless not very commonly reported. In South Australia an average of one or two outbreaks of the peracute form per year were noted from 1953 to 1966 and generally the losses in these were relatively low (a total loss of less than 700 out of 1·5–2 million sheep; Fearn 1966). Losses due to the chronic disease are prevented by cobalt administration to the sheep per os or via the pasture, and this prophylaxis is widely used so that losses are small now. The chronic syndrome is rare in New South Wales, possibly due to an adequate level of cobalt in the soils.

Tryptamine alkaloids occur in a wide variety of plants: Culvenor *et al.* (1964) cites references involving thirty-five species in seven families.

LUPINS

In Western Australia, the naturalised blue lupin (*Lupinus cosentini* syn. *L. digatatus*) has been used extensively to improve the fertility of poor, sandy soils and has proved to be a valuable stock feed. The New Zealand blue lupin (*L. angustifolius*) has more recently been cultivated for forage. After many years of successful use of the plant, disease in sheep and cattle appeared in forms comparable with those previously known overseas. Intensive research since 1950 has established the main features of the toxic conditions observed (see review by Gardiner 1967). Two distinct diseases are produced. The alkaloids of 'bitter' lupins occur in high concentrations, especially in the seeds, and can induce a fatal paralysis of the respiratory and vasomotor centres; the alkaloids are not cumulative in their effects, and, unlike the pyrrolizidine alkaloids, do not produce liver damage—this disease is called 'lupin poisoning'. A totally different disease is 'lupinosis', which is primarily caused by hepatotoxic substances (as yet not identified) produced by fungi (also not yet classified) that grow specifically on the dry mature vegetative parts of lupins following humid, rainy weather in summer; the green, living plant is not toxic. Great complexity is introduced into this disease problem due to interactions between the effects of the toxin and the copper content of the liver, infestation by gastro-intestinal parasites, toxic reactions to some anthelmintics, nutritional status of the sheep, and impairment of the liver's capacity to remove ammonia derived from the metabolism of protein.

RYEGRASS

Perennial ryegrass (*Lolium perenne*) occasionally causes a neurological disease known as 'ryegrass staggers' in sheep, cattle, and horses (Hopkirk 1935; Cunningham and Hartley 1959). Death rarely occurs. Recent work by Aasen *et al.* (1969) indicates that ryegrass from pastures consisting solely of seedlings or new shoots, and on which 'staggers' was observed in sheep and cattle, had a much higher alkaloid content than more mature ryegrass. In mature ryegrass the major alkaloid was found to be perloline, but in seedlings halostachine was also present in appreciable concentrations. Symptoms resembling the staggers syndrome were produced by parenteral administration of perloline, but not by oral administration of either alkaloid, so that the question of the agent responsible is still unsettled.

LEUCAENA

Leucaena leucocephala, a tropical leguminous shrub (Pl. 63) that has been introduced into Australia for grazing, contains the toxic amino acid mimosine. Mimosine is more toxic to monograstric animals than to ruminants, and this appears to be due to detoxication in the rumen (Hegarty, Schinckel, and Court 1964). Detoxication in the rumen is more complete in sheep adapted to *L. leucocephala* feeding. The most common symptom of mimosine poisoning is shedding of wool or hair.

OTHER TOXIC PLANTS

Most of the pastures in Australia can be described as natural plant communities; even where clovers and grasses have been sown, it is usual to find a wide range of native and introduced plants present—only a minor proportion of pastures would contain only cultivated species. It is now well known that many plants occurring in pastures contain toxic substances; in Australia, several hundred species have been found poisonous. Compilations of data from the various regions have been published by Hurst (1942) for New South Wales; Webb (1948) and Everist (1964) for Queensland; Gardner and Bennetts (1956) for Western Australia; St George-Grambauer (1957) for South Australia; extensive information is also available for the Northern Territory (Anon. 1956, 1957, 1959a).

Three main factors tend to limit the occurrence of toxic manifestations: (a) poisonous plants are often distasteful to animals; (b) stock seem to acquire a capacity to avoid dangerous plants in their environment; (c) toxic species will often form only a minor fraction of the diet: (d) the intake of toxic substances may be within the animal's tolerance (this is well reflected in one of the trivial names, 'Salvation Jane', given to *Echium lycopsis* syn. *E. plantagineum*), a species containing pyrrolizidine alkaloids that may induce a fatal liver damage; Bull 1961). Exceptions to these generalisations can readily be found: the Darling pea (*Swainsona* spp.) induces an addiction so that affected animals wander about seeking the plant; some of the cyanogenetic plants are useful forages and are dangerous only at certain seasons; during a drought, scarcity of the normal forages may force animals to consume plants that are usually avoided.

Experimental work has been mainly directed toward the frank manifestations of toxicity; little is known of the influence of subclinical intoxications on animal productivity.

A considerable range of chemical compounds has been incriminated; a brief outline of the main groups is given in the following sections.

Oxalates

Oxalate occurs in very high concentration (up to 15 per cent of dry weight) in soursob (*Oxalis pes-caprae*) and induces tetany and a nephritis due to accumulation of calcium oxalate crystals in the kidney (Bull 1929). Dodson (1959) found that oxalate is readily degraded by rumen micro-organisms, which thus provide a first line of defence against the poison. Many plants species contain appreciable quantities of oxalate (notably in the genera Rumex, Salsola, Threlkeldia and Portulaca), but in Australia serious disease from this source has been described only with Oxalis.

Photosensitising Agents

Several species of plants induce photosensitisation of unpigmented areas of skin. This may be due to plant substances having a direct effect on the skin (as, for example, hypericin of St John's wort (*Hypericum perforatum*): see Hurst 1942), but more commonly is induced as a secondary effect to impairment of liver function caused by hepatotoxins; impaired liver function allows phylloerythrin (a metabolite of chlorophyll) to accumulate in peripheral blood and sensitise the skin to sunlight (Rimington and Quin 1934). Photosensitisation has also been described in animals grazing medics (*Medicago polymorpha* and *M. minima*) but the active principle has not been identified.

In New Zealand, it has been shown that the disease 'facial eczema' is a photosensitisation secondary to liver damage caused by sporidesmin (Thornton and Percival 1959; Synge and White 1959); this toxic substance is produced by a fungus, *Pithomyces chartarum*, which grows, under favourable weather conditions, on plant detritus in the pasture. This disease has been recorded in Australia but is not common.

Hepatotoxins

Hepatotoxic substances have been recorded in several genera (Tribulus, Heliotropium, Echium, Senecio, Crotolaria, Panicum, Lantana, Erechtites, and Amsinckia), and are responsible for very serious and even fatal jaundice. Particular study has been given in Australia to the effects of *Heliotropium europaeum*. The pyrrolizidine alkaloids in this species are responsible for a slowly progressive liver damage; losses of sheep after one summer's grazing are usually low, but after a second summer on the weed, deaths may amount to 90 per cent of the flock (Bull *et al.* 1961). There are important differences between animals in their response to the plant; British breeds and crossbred sheep readily eat the weed, but Merino sheep and cattle avoid it if other feed is available; the plant is much more toxic to cattle than to sheep. Affected sheep may die of jaundice or become severely emaciated; photosensitisation occurs when the sheep consume lush chlorophyll-rich vegetation following autumn rains. The jaundice closely resembles that due to phytogenous chronic copper poisoning, a disease recorded only in Australia (see Chapter 25). Still further complexity is introduced by the finding of a third disease which is a combination of heliotrope poisoning and a resultant chronic copper poisoning due to injury of the liver cells (hepatogenous chronic copper poisoning); this is the most common form of 'toxaemic jaundice' in New South Wales. Heliotrope consumption increases the retention of copper in liver cells, and the liver copper level may rise to a point at which a fatal chronic copper poisoning can be precipitated (Bull *et al.* 1956 and 1961).

'Walkabout' disease of horses is caused by the pyrrolizidine alkaloids of *Crotolaria retusa*, which produces a slowly progressive liver damage strictly analogous to that caused by the better known pyrrolizidine alkaloids of Senecio and Heliotropium (Rose *et al.* 1957). The curious behaviour that gives this disease its name is a terminal feature considered to be due to failure of the liver to prevent accumulation of ammonia in peripheral blood, with consequent intoxication of the central nervous system.

Nitrate

Nitrate is a normal constituent of plant leaves and has a very low toxicity. In some species, nitrate may accumulate to high levels and, if sufficient of the plant is consumed, may cause toxicity due to the formation of nitrite by bacterial reduction in the rumen. In Australia, the main species incriminated are the variegated thistle (*Silybum marianum*) (see Hurst 1942) and mint weed (*Salvia reflexa*) (Williams and Hines 1940). Deaths occur only when hungry animals are given access to these plants.

Fluoroacetate

Fluoroacetate is a highly poisonous substance, first recorded in pasture plants in South Africa. Its toxic action is due to the formation within the animal's body of fluorocitrate, a powerful inhibitor of an enzyme (aconitase) in the tricarboxylic acid cycle. Fluoroacetate is found in gidgee (*Acacia georginae*) (Oelrichs and McEwan 1962), which occurs in the Georgina River basin of Queensland and Northern Territory, in heartleaf (*Gastrolobium grandiflorum*) (McEwan 1964), which grows on the poorer sandstone country in western Queensland and the Gulf country of the Northern Territory, and in York Road poison (*G. calycinum*) which is common in Western Australia. Death of sheep and cattle following ingestion of either of these plants has been described by Bell *et al.* (1955) and Gardner and Bennetts (1956). The animals exhibit cardiac, respiratory, and nervous symptoms. Losses from *G. grandiflorum* poisoning are sometimes very large; on one property in Queensland carrying 6000 cattle, an annual loss of 150–300 head has been ascribed to this species, and in another area a whole flock of 2000 sheep was poisoned by it (Hall 1964).

Cyanide

Plants of many genera contain cyanogenetic compounds (especially glycosides); examples are Andrachne, Brachyachne, Chenopodium, Chloris, Cynodon, Dactyloctenium, Eleusine, Eremophilia, Eucalyptus, Euphorbia, Goodia, Heterodendron, Indigophera, Juncus, Lotus, and Sorghum. Most outbreaks of poisoning have been recorded in hungry travelling stock given access to toxic feed. Enzymes liberating cyanide from glycosides are found in some plants, but high glycosidase activity is also shown by the ruminal microbes (Coop and Blakley 1949).

Neurotoxins

Several syndromes, popularly described as 'staggers', have been recorded, but only in the case of *Phalaris tuberosa* has extensive investigation been undertaken (see p. 387). The causative substances (presumably neurotoxic) have not been identified, and it seems unlikely that the various genera have a common toxic principle. Severe staggers, in which an abnormal gait is continuously present, is produced by *Swainsona* spp., *Echinopogon ovatus*, *Macrozamia* sp. and *Cycas* sp., *Xanthorrhea australis*, and *Atalaya hemiglauca*. Less severe abnormalities, appearing only when the animals are driven, are induced by feeding on *Malva parviflora*, *Malvastrum spicatum*, *Stachys arvensis*, *Lamium amplexicaule* and the ferns, *Cheilanthes tenuifolia* and *Notholaena distans* (see McDonald 1942b).

Selenium

Diseases due to excessive intake of selenium have been described in many countries. In Australia, highly seleniferous soils have been noted only in Queensland where the main species of accumulator plants are *Neptunia amplexicaulis* and *Acacia cana* (McCray and Hurwood 1963). In Cape York Peninsula, *Morinda reticulata* accumulates selenium even though the soil content is low; the plant has caused selenium poisoning in horses (Knott and McCray 1959).

Goitrogens

Goitrogens of several types are known, particularly in the brassicas which, in addition to the crop species, often occur as minor components of pastures. Although there are indications of goitre in lambs in Tasmania, there appears to be no record of any major economic problem in Australia (see Clements 1960).

Miscellaneous

In addition to the examples given above, there is a large number of species known, or suspected, to be toxic to grazing animals. Some produce highly toxic alkaloids—e.g. erythrophleine in *Erythrophloeum chlorostachys;* nicotine in *Duboisia hopwoodii* and *Nicotiana* spp., solanine in

Solanum spp. Other known toxic principles are glycosides (non-cyanogenetic), saponins, toxalbumins, essential oils, and lysergic acid derivatives. In many cases the toxic principles have not been identified—future research on this topic is likely to be very fruitful, not only to aid in the prevention of losses, but to add to knowledge of pathology and pharmacology. Differences between animal species in their response to poisons, and the ecological factors modifying the responses, are likely to prove of great interest.

27

GRASSLAND MANAGEMENT

W. M. WILLOUGHBY

Grasslands are the major medium for utilising Australia's land resources. They occupy 96 per cent (1132 million acres or 466 million ha) of all land used for agricultural and pastoral purposes, and they are practically the sole and year-round source of food for the nation's 167 million sheep and 21 million cattle.

The grasslands are divided into approximately 200,000 holdings, or properties as they are commonly called, some of which include crop lands in addition to grazing lands. Within each property there may be during the year some changes in livestock numbers due to birth, seasonal sales, and interchange of animals between properties, and some changes in grassland area due to cropping, but generally each has a fairly fixed area of pasture or grazing land supporting a fairly constant livestock population. The upper limit to the size of this population is set by the need to ensure satisfactory production per head and to avoid hand-feeding when seasonal or unseasonal feed shortages occur on the grassland.

GRASSLAND AS A FEED SUPPLY

The total plant material in the grasslands within a property can be regarded as a feed supply from which each day the livestock obtain their food. The supply is subject to continuous change, it is increased in quantity and quality whenever plant growth occurs, and decreased in quantity or quality because of ageing and breakdown of plant material and intake by the livestock population. Throughout the year, and from year to year, growth, ageing and breakdown vary considerably in response to climate and in relation to the current quantity and status of the grassland. Intake also varies because of changes in the number of animals by birth and sale, their changing demands for maintenance, growth, pregnancy, lactation, etc., and with the capacity of the grassland to supply those demands.

Grassland in a pastoral situation is thus a dynamic component of a continuing climate-soil-plant-animal system, the combined effect of climate and grazing leading to considerable changes with time in the quality and quantity of feed available to the livestock. In some environments these changes follow a fairly regular seasonal pattern. In others, particularly the drier environments, the pattern is irregular. But in all situations there are alternate periods in which the feed is surplus or deficient in quality and/or quantity relative to the current demands of the livestock population.

The alternation between surplus and deficit severely reduces the efficiency with which the grasslands can be used. The greater the amount and the duration of the surplus the greater is the opportunity for feed to be lost by ageing and breakdown (or possibly fire) rather than used for livestock production. The greater the severity and the duration of the deficiency, the less the basic number of animals that can be supported year-round on grassland and the less their production per head.

Many procedures have been proposed for overcoming the inefficiencies caused by alternate surpluses and deficiencies of the grassland or feed supply. In the main, they are based on adjusting feed supply to animal demand, or vice versa. However, most are impracticable or uneconomic in the pastoral situation.

Firstly, the same extremes occur simultaneously over vast areas, so limiting large-scale movements of livestock, and sometimes of supplementary feed. Secondly, the period of feed surplus is insufficiently long or reliable to allow part of the grassland to be replaced with a cash crop and returned to grass before the next deficiency period. Thirdly, a large proportion of livestock owners follow a program of genetic improvement of their flocks or herds, which would not be possible if livestock were purchased and sold to match variations in feed supply. Finally, facilities for harvesting and storing feed in periods of surplus rate a lower investment priority in year-round grazing situations than in situations where there is no winter grazing and hand-feeding is imperative.

AUSTRALIAN EXPERIMENTATION IN GRASSLAND MANAGEMENT

It seems to be fairly commonly believed that the disadvantages of not being able to make adjustments from time to time between grassland production and animal demand can be reduced or overcome by adjusting the grazing periods on different parts of a holding, that is by grazing management. It is claimed that by subdividing the grazing area and confining the animals to one part at a time, there will be more growth and better use of feed, and thereby more stock can be carried at a greater production per head. Other advantages claimed are less need to hand-feed, greater control of pasture composition, less internal parasite infestation in the livestock, etc. Considering the holding as a unit, it is presumably assumed that the benefit to be derived from decreasing the grazing pressure on one part will outweigh disadvantages due to simultaneously increasing the grazing pressure on the remaining part.

Because animal production from grasslands is affected by the continuous interplay of climatic and grazing influences, there is no way of estimating the extent to which production is affected by various grassland management procedures other than by grazing experiments. The following is a brief summary of published grazing experiments in Australia which have compared year-round systems identical in all respects except for the management procedures under study. Only a few have repeated each management treatment at a range of stocking rates, an essential requirement for determining the effect of the treatment on production per acre. Experiments that confound management and stocking rate, for example comparisons between continuous grazing at a low stocking rate and other systems at higher stocking rates, have not been included.

Effects of Subdivision

For any form of grassland management the area must be subdivided into two or more paddocks. The provision of fencing and of drinking water facilities in each paddock has been estimated by Clinton (1968) to cost an average $10 per acre ($25 per ha) plus maintenance costs.

Southcott, Roe, and Turner (1962) obtained similar levels of production over a 3–year period from sheep stocked at a constant rate of 1 per acre (2·5 per ha) on native grazing land in paddocks of 4, 8, 16, and 32 acres (1·6, 3·2, 6·4, and 12·8 ha). Elliott (1966) similarly reported no difference in animal production from winter growing pastures of 5, 40, or 107 acres (2, 16, or 43 ha). Southcott *et al.* (1968) found that weight gains of Hereford heifers grazing sown pastures did not differ between paddocks of 20, 40, and 90 acres (8, 16, and 36 ha), stocked at 0·5 or 1 heifer per acre (1·25 or 2·50 per ha).

These experiments suggest that subdivision in itself does not increase animal production. They also suggest that animal production from experimental treatments which faithfully reproduce on a smaller scale the conditions within a grazing holding, is a reliable indication of levels of production likely to be obtained in practice.

Management of Grazing Lands

Roe and Allen (1945) reported the results of a 3–year grazing experiment on Mitchell grass (*Astrebla* spp.) dominant grassland at Cunnamulla in south-western Queensland where the mean rainfall is 14 in. (350 mm), mainly of summer incidence. Continuous year-round grazing was compared with a 6-month rotation, the stock being confined to one-half of the grazing area during winter, and the other half during the summer. Each management treatment was compared at three stocking rates, 0·13, 0·20 (district average), and 0·40 Merino wethers per acre (0·33, 0·50, and 1·00 per ha). In his summary Roe states, ‘the total forage available was slightly greater under continuous grazing throughout, and the advantage tended to be greater the heavier the rate of stocking . . . No significant differences in liveweight or wool production were recorded for sheep on continuous and rotational grazing at comparable rates.’

At Trangie, N.S.W., in a region of slightly higher rainfall averaging approximately 17 in. (432 mm) per annum and erratic seasonal incidence, Biddiscombe *et al.* (1956) conducted a 5-year experiment on Stipa-Chloris grazing land.

Continuous year-round grazing was compared with a 6-week deferment of grazing following autumn rains and with a 6-week deferment of grazing following spring rains. Each of these three treatments was repeated at three stocking rates: 0·5, 0·66 (district average), and 1·0 Merino wether per acre (1·25, 1·66, and 2·50 per ha). The experiment demonstrated the marked influence of autumn and winter rainfall on the composition and production of the grazing land. However, deferment gave no advantage at any stocking rate over continuous grazing either in terms of bodyweight and wool production of the sheep, the amount of pasture available, or the density and basal area of the perennial grasses.

Roe, Southcott, and Turner (1959) conducted a 4-year grazing experiment on grazing land dominated by *Bothriochloa macera* syn. *B. ambigua* in a 30 in. (762 mm) rainfall environment at Armidale, N.S.W. The poor quality of this pasture in winter results in liveweight losses at that time, and inhibits breeding, whilst heavy infestations of internal parasites are common. Continuous grazing at 1 sheep per acre (2·5 per ha) was compared with a 4–paddock rotation system at the same stocking rate, 150 sheep being involved in each treatment. No significant differences in grassland production, in botanical composition, in stock liveweight, in wool quantity or quality, or in parasite infection, were recorded between the continuous and the rotational grazing systems.

O. B. Williams (1968) considered that in the early days of European settlement in Australia the grazing lands were degraded by being stocked to utilise fully their maximum growth. He concluded that the communities which resisted high grazing pressure from sheep, cattle, rabbits, and drought now dominate the degraded grazing lands and can show no pronounced benefit from long protection from grazing.

Conversion to Sown Pastures

The replacement of native grazing lands in the higher rainfall areas with clover-based pastures, top-dressed with superphosphate, has been the dominant factor in raising levels of livestock production. Because of the increase in soil fertility resulting from the applications of fertilisers and the fixation of nitrogen by clovers, sown pastures are more responsive to the seasonal changes in weather. Greater increases in growth occur in the periods when feed is already in excess than in periods when it is less than the animals' requirements. Although small, it is the increased production in the latter period that permits greater animal numbers year-round and contributes markedly to greater production per head. Increased pasture growth in periods of feed surplus is of doubtful value (Fig. 12:2) (Willoughby 1959).

Because of the need to withhold stock for considerable periods from areas in process of conversion from native grazing lands to sown pastures, generally only part of a holding is sown in any one year, and this is separately fenced. While a holding is partly sown to pasture, it is possible to adjust the stocking rate on the sown areas so as to make optimum use of seasonal surplus feed. However, this is achieved only by making less efficient use of the grazing lands. When all the land is sown to pasture the capacity to make seasonal adjustments is zero, and despite the greater animal numbers that are now possible the amount of feed surplus to the requirements of the animal is much greater than before. Such a situation stimulates interest in pasture management practices which are believed to make better use of this excess.

Continuous versus Rotational Grazing

Moore, Barrie, and Kipps (1946) at Canberra, A.C.T., in a 23 in. (584 mm) mainly winter rainfall environment, made a comparison over four years between continuous grazing, 4-weeks rotational, and 8-weeks rotational grazing. They used identical numbers of Merino wethers on a *Phalaris tuberosa*-subterranean clover (*T. subterraneum*), lucerne (*Medicago sativa*) pasture community. The total yields of the main constituents of the pasture, namely phalaris and subterranean clover, were not affected by the method of grazing at any time. Lucerne, however, was practically eliminated from the continuously grazed system, considerably reduced in the 4-week rotational system, but remained as a productive stand in the 8-week rotation. However, the lucerne was most productive during the period of pasture surplus. No advantages from lucerne or from rotational grazing were obtained in normal years, but in a drought year lucerne slightly reduced the losses in liveweight and the depressions in wool production experienced on all treatments. Apart from the effect on lucerne and its relatively small effect on animal production in a drought year, there were no advantages in pasture or animal production from rotationally grazing pastures. The conclusions were drawn that effects of management on the grazing animal were minimal when the rate of pasture production was either above or below the rate of pasture consumption, and that one or other of these conditions nearly always exists in year-round grazing systems. The authors further stated that unless stocking rates can be adjusted so that the rate of consumption is of the same order as the rate of growth of a pasture, no increase in yield can be expected from rotational as compared with continuous grazing of a botanically stable pasture mixture.

On the other side of the continent at Perth, W.A. where the rainfall averages 35 in. (889 mm) per annum and is predominantly of winter incidence, Rossiter (1952b) made a 4-year comparison between continuous and rotational grazing on a perennial veldt grass (*Ehrharta calycina*)-subterranean clover pasture grazed by 4 wethers per acre (10 per ha) for 10 months of the year. The veldt grass declined rapidly in both treatments but at a faster rate in the continuously grazed paddocks. However, the clover replaced the grass so that the total pasture production was almost identical for the two treatments. There were no consistent differences in sheep bodyweights or wool production.

Later at Canberra in the same environment as Moore *et al.* (1946), and with similar sheep and similar pasture but without lucerne, Willoughby (1959) reported that by adjusting sheep numbers from time to time, 300 lb of sheep liveweight gain per acre (335 kg per ha) could be achieved. However, this adjustment could be done on only part of the area required for year-round grazing of the sheep and when the other part was taken into account the average annual production from the system as a whole was only about 90 lb liveweight gain per acre (100 kg per ha). Restricting sheep to part of the area when pasture growth was slow reduced their current intake and current rate of animal production. Feed available on the whole area became greater, but this increased only the potential level of future animal production. However, conditions for rapid pasture growth on all treatments came about before this potential was achieved, so that the system with unrestricted grazing maintained its advantage for animal production. The management system most closely approximating continuous grazing over the whole of the pasture for the whole of the year gave the highest meat and wool production. It was concluded that there was no reason why management systems other than this could be expected to give higher animal production, at least with non-breeding livestock which have relatively constant intake demands.

There may be as yet unproven advantages from systems of grazing management. For example, Hilder (1966) has shown a substantial transfer of essential plant nutrients from grazing areas to resting or camp sites where the livestock deposit a large proportion of their dung and urine. He believes that the impoverishment of the greater portion of the grazing area can lead to less grassland production, which is not compensated for by enrichment of the camp site where little grows and from which nutrient losses can occur. Hilder's experiments show a hastening of the impoverishment as stocking rates are increased, and he suggests that some form of livestock management such as confinement for very short periods to very small paddocks may result in better distribution of plant nutrients by the grazing animal.

Rotational Grazing of Lucerne

As an addendum to the paper by Moore, Barrie, and Kipps, J. G. Davies (1946) suggested that lucerne was eliminated from the continuously grazed pasture because it was preferred and selectively grazed by sheep. However, the other sown species were adequate in quality and quantity for animal production to be unaffected by the elimination of lucerne.

Peart (1968) has shown that in semi-arid areas such as at Trangie, N.S.W., where lucerne is the only species available for sowing, a system of rotational grazing was again essential for maintenance of the lucerne. In a year of only 14 in. (356 mm) rainfall, lucerne was rapidly eliminated from a continuously grazed system, partially eliminated in a 4-week rotation, and as Moore *et al.* (1946) found, satisfactorily maintained in an 8-week rotation. Since it was the only species of value in the community, animal production was greatest in the 8-week rotation. After 7 months, 5 Merino sheep per acre (12·5 per ha) weighed only 55 lb (25 kg) per head on the continuous system and had to be taken off the plots, while those on the rotational system weighed 104 lb (47 kg) per head and remained on lucerne for the full year.

Autumn Saving for Breeding Ewes

Wheeler (1965) in a 30 in. (762 mm) rainfall environment at Armidale, N.S.W., compared continuous grazing with a system which withheld 25 per cent of the pasture from grazing in autumn for use by the ewes in late winter before they lambed in early spring. He used a perennial ryegrass (*Lolium perenne*)-white clover (*Trifolium repens*) pasture grazed by Merino ewes at three stocking rates: 3, 5, and 7 per acre (7·4, 12·4, and 17·3 per ha). H.L. Davies (1968), in a 23 in. (584 mm) rainfall environment at Canberra, compared continuous grazing with systems which withheld 30 per cent of the holding from autumn grazing for use by the ewes either 6 weeks before, or immediately after, lambing in spring. He used pastures of phalaris and subterranean clover and of annual grasses and subterranean clover at two stocking rates of Merino ewes, 5·25 and 10·50 per acre (13 and 26 per ha).

Normally in both environments the amount of feed on pastures progressively declines as the ewe's demands increase with advancing pregnancy. In both experiments the objective of deferred grazing was to provide better winter nutrition for spring lambing ewes in late pregnancy.

In Wheeler's experiment 'the saving of a part of the total grazing area during autumn generally reduced the rate of gain of the sheep compared with the gain when allowed access to the whole area. The reductions are the result of the higher stocking rate that necessarily occurs on the remainder of a plot or farm when grazing is withheld from a portion of it.' When the reserved portion was later grazed, the losses were recouped, but only to the extent that lambing percentages, lamb birth weights and ewe wool weights again became equivalent to those on treatments without autumn saving.

In Davies's experiments effects on animals were no different on continuously grazed and autumn deferred grazing treatments at the low stocking rates. At high stocking rates deferment of grazing of the pasture until late pregnancy reduced the liveweight gain in early pregnancy and led to a greater liveweight gain in late pregnancy. However, the total effect was not great, and Davies's overall conclusion was 'the results suggest that only at high stocking rates, possibly above those likely to be used in practice, can beneficial effects on sheep production be expected from systems of management for the breeding ewe other than continuous grazing'.

Strip Grazing

On irrigated pastures Freer (1959) obtained no significant differences in milk production from dairy cows strip and rotationally grazed at the same stocking rates. He concluded, as have many other investigators, that the advantages claimed for the more complicated, and often the more expensive, management systems have been based on experiments which allotted a higher stocking rate to the system believed to be the best. Any advantage shown was most probably due to the higher stocking rate and not to the system.

Creep Grazing

Arnold and Bush (1962) at Canberra, and Fletcher and Geytenbeek (1968) at Kybybolite, S.A., using perennial grass-subterranean clover pastures, compared continuous grazing of ewes and lambs together with various types of lamb raising systems. In both experiments, parts of the grazing areas were withheld at times from the ewes but allowed to be grazed by the lambs. In both environments it was concluded that neither the production of the ewes nor the growth rate of the lambs was appreciably affected by the managerial treatments.

Conservation

It appears to be almost universally accepted that the disadvantages of seasonal feed deficits and surfeits can be considerably reduced if not overcome by conservation and storage of the surplus for feeding in periods of deficiency. Despite the very considerable capital and running costs involved, few inquiries of an experimental nature have been made as to the returns likely from such practices.

Hutchinson (1966), at Armidale, compared year-round grazing systems differing only in whether they did or did not conserve pasture in the period of surplus and feed it back in the period of deficiency. Each system was operated at a range of stocking rates so as to examine the proposition that conservation permits higher animal numbers to be supported year-round. Increasing the stocking rate from 4 to 8 to 12 sheep per acre (10 to 20 to 30 per ha) on the non-conservation treatment increased total animal production. Conservation had practically no effect at 4 sheep per acre (10 per ha), markedly increased animal production at 8 sheep per acre (20 per ha), but considerably decreased it at 12 sheep per acre (30 per ha). At the highest stocking rate depression in animal production in the spring due to the withdrawal from grazing of areas for conservation was not later compensated for by feeding the conserved material. The reversal in trend from increased to decreased production from conservation as stocking rate was increased fails to support the commonly held belief that conservation is universally beneficial.

ASPECTS OF PASTURE MANAGEMENT INDICATED BY GRAZING EXPERIMENTS

The experiments reviewed above indicate several aspects of pasture management. Firstly, continuous grazing is a practicable system of grassland utilisation and is capable of high animal production. Secondly, any other system of pasture management requires that the stock be restricted for a time to less than the whole food supply available and thus introduces the risk of current animal production being depressed. For a management system to be superior to continuous grazing, subsequent access to the previously protected area or material must more than compensate for this prior depression.

Favourable years and low stocking rates increase the amount and duration of feed surplus, so that there is minimal depression of animal production during the period of restricted grazing. But these conditions also lead to minimal increase of animal production during the subsequent period of use of the protected area, so that the total effect of the management treatment on annual animal production is small. The less favourable the year or the higher the stocking rate, the greater and more prolonged are the feed deficiencies; the depression in animal production during the period of restriction is aggravated and pasture growth on the protected area may not be sufficient to make up for this loss.

These conclusions are in keeping with the concept that all the grasslands within a property are a feed supply which is augmented by plant growth and depleted by breakdown and intake. To increase the supply, either growth must be increased or breakdown or intake must be decreased. For a given grassland community, the only one of these aspects that can be directly manipulated by management is to decrease intake, and this can be achieved by restricting grazing to only a part of the grassland. Thus a reduced intake with its associated risk of lower current animal production is a necessary preliminary to increasing feed supply by management. A high level of available feed in turn may mean a high level of breakdown (Willoughby 1959). The levels of all these factors determine whether final animal production is reduced, unchanged, or increased by the management procedure.

PASTURE MANAGEMENT IN PRACTICE

Some Australian advisory services actively recommend intensive subdivision and frequent movement of stock between the subdivisions, claiming that this improves the quality of the feed and gives a more even supply throughout the year. On the other hand, some extension services recommend continuous grazing or set stocking, particularly for ewes with lambs.

In practice most holdings are subdivided into several paddocks for a number of reasons not related to management practices. For convenience the livestock are confined to one or several of these at a time. The experimental evidence would suggest the likelihood that such confinement may have little effect on animal production, slight increases or decreases being possible.

Where sown pastures have been established, more intensive subdivision, and in particular, conservation, are increasing. Many livestock owners have been led to believe that these are necessary preliminaries to high stocking rates, even though experiments on sown pastures have not confirmed these beliefs. Rather, the experiments suggest that sown pastures in any grazing system have higher carrying capacities than those currently practised. On present evidence, lucerne excepted, the only surety attached to the adoption of most grazing management practices is the extra cost they incur. The possibility of greater returns from the management of conventional grassland communities remains in doubt.

D

GRASSLAND PRODUCTION

THE MAJOR LIVESTOCK INDUSTRIES

28

THE MAJOR LIVESTOCK INDUSTRIES

FRED H. G. GRUEN

Sheep and beef and dairy cattle are the basis for the major livestock industries of Australia. These three industries account for almost three-fifths of the value of Australian total rural production and about two-fifths of Australia's total exports. Of the three, sheep are by far the most important, accounting for about 30 per cent of the total value of Australia's rural output in recent years (i.e. the three years ended June 1968) and almost 30 per cent of total exports. Beef production accounted for 17 per cent of rural output and 7 per cent of total exports. Dairy production accounted for about 12 per cent of total rural production and for some 4 per cent of export income. In addition, about 10–15 per cent of total beef production has come from the slaughter of dairy cattle and from calves originating from dairy herds in recent years.

Table 28:1 provides a cross-classification of Australian rural holdings according to the main activity of each holding and the proportion of the nation's sheep, cattle, and pig populations on the different types of farms. There are about a quarter of a million rural holdings in Australia, including some 14,000 'unused' holdings. Of the remaining 238,000 'used' holdings, almost half carry some sheep, the number of sheep flocks in 1966 being 112,600. Wool and the sale of sheep and lambs are the major economic activities on 43,600 holdings; these farms account for some 63 per cent of all sheep pastured in Australia. A further 28 per cent of the national sheep flock are run on the 31,800 sheep/cereal-grain farms predominantly devoted to wheat and sheep. In other words, over 90 per cent of all sheep are run on those farms specialising in sheep or wheat and sheep. But such farms account for only two-thirds of all sheep flocks.

Almost half the used rural holdings in Australia carry some beef cattle. In fact, with 118,900 holdings carrying some beef cattle in 1966, beef cattle are now carried on more rural holdings than sheep. This represents a considerable change from the position in 1960 when 85,900 holdings carried beef cattle and there were 118,600 sheep flocks. However, since 1965 there has been a slight change in the Statistician's definition. Cattle are now classified according to two main purposes: (1) milk production, and (2) meat production, irrespective of breed, whereas previously they were classified into dairy and beef breeds respectively. The differences of definition probably had only a small effect on the numbers in each classification. Although there are over 100,000 beef cattle herds, only 16,000 farms specialise in beef production. These specialist holdings account for about three-fifths of total beef cattle numbers.

Dairy cattle were carried on 77,000 holdings in 1965–6, a considerable reduction from 1959–60 (118,000 dairy herds). Almost 50,000 holdings specialise in dairying and these carry all but 5 per cent of the total dairy cattle population.

SHEEP

Geographical Distribution

The wide geographical distribution of sheep on the Australian continent is shown in Fig. 6:1. The major climatic factors influencing the geographical distribution of sheep are rainfall and temperature. A comparison of Fig. 6 : 1 with Fig. 1 : 4, an average rainfall map, shows that sheep densities are greatest in the southern 20 to 30 in. (508–762 mm) rainfall belt, that is in the temperate woodlands. As rainfall falls below an average of 20 in. (508 mm)—and particularly below 15 in. (381 mm)—the amount of feed produced severely limits the number of sheep carried per area. In the less than 15 in. (381 mm) areas, soil types and their associated native grazing lands are important factors in determining stocking rates. Lastly, the available water supply often provides an important additional obstacle to carrying larger numbers of stock in arid areas.

TABLE 28 : 1 Australian rural holdings classified by type of activity and other characteristics: comparison of 1965–6 with 1959–60 (in brackets)

Type of activity	No. of holdings '000	Total area		Percentage of total[a]						
		'00,000 acres	'00,000 ha	Area under crop	Area under wheat	Area under sown grass	No. of sheep	No. of beef cattle	No. of dairy cattle	No. of pigs
Sheep-cereal grain	32	766	310	54	63	30	28	4	[b]	12
	(33)	(709)	(287)	(61)	(75)	(27)	(23)	(3)	(1)	(11)
Sheep	44	4694	1901	8	1	40	63	20	1	3
	(52)	(4873)	(1974)	(11)	(4)	(46)	(71)	(21)	(3)	(3)
Cereal grain	12	211	85	23	30	3	2	2	[b]	6
	(8)	(90)	(36)	(13)	(16)	(1)	(1)	(1)	(1)	(3)
Beef cattle	16	5712	2313	2	[b]	9	1	62	[b]	1
	(11)	(5195)	(2104)	(1)	(2)	(3)	(1)	(66)	(1)	(1)
Dairying	49	157	64	4	1	11	1	4	95	52
	(55)	(181)	(73)	(6)	(1)	(14)	(1)	(3)	(85)	(57)
Vineyards	5	3	1·2	[b]	[b]	[b]	[b]	[b]	[b]	[b]
	(4)	(2)	(0·8)							
Fruit (other than vine)	12	13	5·3	[b]	[b]	[b]	[b]	[b]	[b]	[b]
	(13)	(14)	(5·7)						(1)	
Vegetables:										
Potatoes	2	5	2·0	[b]	[b]	[b]	[b]	[b]	[b]	[b]
	(2)	(5)	(2·0)							
Other and mixed	6	7	2·8	1	[b]	[b]	[b]	[b]	[b]	[b]
	(7)	(7)	(2·8)	(1)					(1)	
Poultry	4	3	1·2	[b]	[b]	[b]	[b]	[b]	[b]	1
	(5)	(4)	(1·6)							(1)
Pigs	2	5	2·0	[b]	[b]	[b]	[b]	[b]	[b]	11
	(1)	(16)	(6·5)							(10)
Sugar	8	18	7·3	2	[b]	[b]	[b]	[b]	[b]	[b]
	(7)	(17)	(6·9)	(2)					(1)	
Tobacco	1	3	1·2	[b]	[b]	[b]	[b]	[b]	[b]	[b]
	(1)	(4)	(1·3)							
Other	2	9	3·6	1	[b]	[b]	[b]	[b]	[b]	[b]
	(2)	(8)	(3·2)	(1)						
Multi-purpose	9	97	39	5	3	4	3	5	3	11
	(8)	(78)	(32)	(4)	([b])	(3)	(2)	(2)	(3)	(9)
Unclassified sub-commercial	34	182	74	[b]	[b]	1	1	2	1	1
	(30)	(119)	(48)			(2)	([b])	(1)	(2)	(1)
Unused, special, etc.	14	130	53	[b]	[b]	1	[b]	[b]	[b]	[b]
	(12)	(159)	(64)			([b])		(1)	(1)	(1)
Total all holdings (rounded figures)	252	12,015	4866							
	(253)	(11,481)	(4650)							

[a] Private estimate from the source given below.

[b] Less than 1 per cent.

Source: Commonwealth Bureau of Census and Statistics, *Classification of Rural Holdings by Size and Type of Activity, 1959–60, Bulletin No. 7 Australia*, Tables 23 to 28; *Classification of Rural Holdings by Size and Type of Activity, 1965–66, Bulletin No. 7 Australia.*

In southern areas of the continent where the average annual rainfall exceeds 30 in. (762 mm) the factors limiting sheep numbers are largely economic. Other forms of landuse may be more profitable (e.g. dairying), clearing costs are higher, and control of diseases (e.g. worm infestation and foot rot) are more costly. In northern areas the physical environment is unfavourable to sheep. They do not thrive on the tall grasses of tropical and sub-tropical woodlands. Temperatures are an important deterrent in the drier tropics. Reproduction rates are lower in the hotter parts of Australia and this reduces the economic attractiveness of running sheep.

TABLE 28 : 2 Distribution of sheep by States and zones
(3-year averages)

	N.S.W.	Vic.	Q'ld	S.A.	W.A.	Tas.	A.C.T.	Total	Total nos.
	%	%	%	%	%	%	%	%	million
1932–4									
High-rainfall zone	8·90	9·06	—	1·80	2·07	1·69	0·20	23·72	27·59
Wheat-sheep zone	24·92	6·16	—	2·96	2·54	—	—	36·58	42·53
Pastoral zone	14·15	—	18·86	2·07	4·62	—	—	39·70	46·17
Total	47·97	15·22	18·86	6·83	9·23	1·69	0·20	100·00	116·29
1937–9									
High-rainfall zone	9·43	10·56	—	2·35	2·33	2·09	0·22	26·98	31·87
Wheat-sheep zone	23·09	6·27	—	3·66	3·06	—	—	36·08	42·63
Pastoral zone	12·86	—	19·53	2·09	2·46	—	—	36·94	43·65
Total	45·38	16·83	19·53	8·10	7·85	2·09	0·22	100·00	118·15
1947–9									
High-rainfall zone	9·33	12·04	—	2·61	2·67	1·94	0·21	28·80	32·37
Wheat-sheep zone	23·16	7·29	0·19	4·59	4·39	—	—	39·62	44·52
Pastoral zone	11·96	—	14·99	1·61	3·02	—	—	31·58	35·49
Total	44·45	19·33	15·18	8·81	10·08	1·94	0·21	100·00	112·38
1957–9									
High-rainfall zone	8·40	12·15	—	3·64	3·61	2·20	0·18	30·18	49·55
Wheat-sheep zone	23·36	7·25	0·56	5·01	4·82	—	—	41·00	67·36
Pastoral zone	11·34	—	13·76	1·65	2·07	—	—	28·83	47·36
Total	43·10	19·40	14·32	10·30	10·50	2·20	0·18	100·00	164·28
1964–6									
High-rainfall zone	8·72	13·72	—	4·51	5·42	2·40	0·17	34·94	62·05
Wheat-sheep zone	20·96	6·95	0·34	5·01	6·41	—	—	39·67	70·50
Pastoral zone	9·05	—	12·26	1·46	2·62	—	—	25·39	45·11
Total	38·73	20·67	12·60	10·98	14·45	2·40	0·17	100·00	177·67

Source: Figures for sheep and lambs shorn from B.A.E., *Tables of Sheep Numbers and Wool Production by States and Zones, 1931–32 to 1966–67*, Canberra, July 1968.

The Bureau of Agricultural Economics distinguishes between three major Australian sheep zones. These are the Pastoral, Wheat-Sheep and High-Rainfall zones. While the precise boundaries between these zones are—to some extent—arbitrary, there are important climatic and agricultural differences involved in delimiting the different zones. The Pastoral Zone (arid shrublands and grasslands, and semi-arid woodlands) is the area where rainfall is lowest, and sheep are raised entirely on the existing vegetation (see Chapters 16 and 17). Rainfall is too low and unreliable for crops. Stocking rates range from one sheep to 5 acres (1 to 2 ha) in the climatically most favoured parts of the zone to one sheep to 100 acres (1 to 40 ha) in the areas which are at the edge of the unused desert. The average is around one sheep to 10 acres (1 to 20 ha).

The Wheat-Sheep Zone (the drier temperate woodlands and wetter mallee), on the other hand, comprises the major cereal-growing areas and the sheep enterprise is normally carried on in conjunction with the cultivation of crops—primarily wheat. In the Wheat-Sheep Zone sheep graze predominantly on sown or volunteer pastures though grazing of cereal stubble also provides an important source of feed (see Chapters 14 and 15). Feeding of grain or grazing of crops provide a comparatively minor proportion of the total feed supply. Average stocking rates are about 3 sheep to 4 acres (1 to 0·5 ha), though here again there is a wide range.

The High-Rainfall area (sclerophyll forests and woodlands) has, as its name implies, a higher rainfall than either of the other two zones and is suitable for the sowing of pastures and in particular for pastures of perennial species. Stocking rates average almost 2 sheep per acre (5 per ha).

During the last thirty-five years there has been a major shift in the proportion of the sheep population in these different areas in Australia. In the early 1930s almost two-fifths of all sheep were carried in the Pastoral Zone, with the High-

TABLE 28 : 3 Distribution of sheep holdings and of national flock, by flock size 1919–20, 1948, 1956, 1960, and 1966

Flock size (Number of sheep)	1919–20[a]		1948		1956		1960		1966	
	Percentage of holdings	Percentage of sheep population	Percentage of holdings	Percentage of sheep population	Percentage of holdings	Percentage of sheep population	Percentage of holdings	Percentage of sheep population	Percentage of holdings	Percentage of sheep population
Less than 500	67·7	11·3	50·8	10·3	40·4	7·2	38·5	n.a.	33·9	4·9
500–1000	14·7	10·6	23·1	15·3	25·9	15·6	23·5	n.a.	22·5	11·7
1000–2000	8·9	12·6	14·4	18·9	20·0	23·0	21·5	n.a.	23·8	23·9
2000–5000	5·3	16·5	8·3	24·0	10·0	25·6	12·1	n.a.	15·9	33·5
5000 or more	3·4	48·8	3·4	31·5	3·7	28·6	4·3	n.a.	4·1	25·9
	'000	'000	'000	'000	'000	'000	'000	'000	'000	'000
Total number	79·2	76,896	92·6	102,470	111·0	139,059	118·6	155,174	112·6	157,563

[a] Victoria, 1 Mar. 1919; Queensland, Western Australia, 31 Dec. 1919; Tasmania, 1 Mar. 1920; New South Wales, South Australia, and Australian Capital Territory, 30 June 1920. Excludes Northern Territory.

Source: Commonwealth Bureau of Census and Statistics.

Rainfall Zone accounting for less than a quarter of the total and the Wheat-Sheep Zone for somewhat more than one-third. Since then, total sheep numbers have increased, but the number in the Pastoral Zone has not. As a result, the proportion of sheep in the Pastoral Zone has declined substantially (to less than 25 per cent in the most recent years). Both the Wheat-Sheep and the High-Rainfall zones have gained proportionately, with the greatest relative increase occurring in the High-Rainfall Zone where the technical possibilities of improving pastures are greatest.

Table 28:2 shows the distribution of sheep by States and zones at selected periods in the last thirty-five years. In terms of normal State boundaries, there has been a relative increase of the Australian sheep population in Western Australia and to a lesser extent in Victoria and South Australia. On the other hand, New South Wales and Queensland still account for half the sheep run in Australia (compared to 65 per cent in the early thirties).

Flock Size Distribution

Table 28:3 provides the available information on the changes in the Australian flock size distribution in the post-war period (the only Australia-wide pre-war classification—for the years 1919 to 1920—is also included for purposes of comparison). The changes portrayed in Table 28:3 are twofold—a decline in both the very small and the very large sheep flocks. The smallest size group (i.e. below 500 sheep) has been declining steadily since 1920 and the next smallest group of 500 to 1000 sheep has been declining since 1956. The basic reasons for this trend are, first, the increasing specialisation of farming, and second, and probably more importantly, economic pressure. With 1000 sheep or fewer it is becoming increasingly difficult to earn a real income comparable with that attainable in the rest of the economy.

The decline of the largest sheep flocks is partly due to government policies—on the one hand the compulsory acquisition and subdivision of large holdings by State governments has directly reduced the number of large holdings, on the other the progressive nature of both death duties and land taxes has contributed indirectly to this trend. In addition, the Pastoral Zone contains many of the very large sheep flocks (average flock size is about four times as large in the Pastoral Zone as in the other two zones). Hence the decline in the proportion of sheep carried in the Pastoral Zone can be expected to show up in the total Australian statistics as a decline in the proportion of sheep in the largest size group.

Changes in Total Sheep Numbers

This section relies heavily on papers by Cum-

TABLE 28 : 4 Changes in sheep numbers, Australia, 1944–5 to 1967–8

Year 1 April–31 Mar.	Sheep numbers ('000) (1)	Gain or loss on previous year (%) (2)	Ewes mated as proportion of total flock (%) (3)	Lambs marked as proportion of ewes mated (%) (4)	Natural increase as proportion of opening sheep numbers (%) (5)	Deaths as proportion of total[a] (%) (6)	Number exported or slaughtered as proportion of total (%) (7)	Lambs slaughtered as proportion of total[b] (%) (8)	Adult sheep slaughtered as proportion of total[c] (%) (9)
1944–45	123,174	—	35·4	58·9	20·9	14·5	20·8	8·2	12·6
1945–46	105,371	−14·5	36·6	53·7	19·7	11·3	16·8	5·9	10·9
1946–47	96,396	−8·5	42·2	61·9	26·1	7·7	19·1	8·2	10·8
1947–48	95,723	−0·7	44·2	71·3	31·5	6·5	17·9	8·8	9·0
1948–49	102,559	7·1	42·6	70·2	29·9	6·5	17·4	8·2	8·8
1949–50	108,735	6·0	40·5	69·0	27·9	4·8	19·4	9·4	9·8
1950–51	112,891	3·8	39·2	67·3	26·4	9·7	14·3	6·6	7·8
1951–52	115,596	2·4	38·1	61·7	23·5	8·3	13·4	5·8	7·5
1952–53	117,646	1·8	38·7	70·0	27·1	4·4	18·0	7·8	10·1
1953–54	123,072	4·6	38·7	67·7	26·2	6·0	17·1	6·9	10·1
1954–55	126,945	3·1	37·0	69·9	25·9	5·0	17·8	7·8	9·9
1955–56	130,849	3·1	39·2	72·0	28·2	5·6	16·3	7·3	8·9
1956–57	139,124	6·3	39·8	72·0	28·7	6·9	14·1	6·2	7·8
1957–58	149,802	7·7	37·9	64·9	24·6	8·5	16·4	6·9	9·4
1958–59	149,315	−0·3	37·2	69·8	26·0	5·5	18·1	7·8	10·3
1959–60	152,685	2·3	40·1	72·2	29·0	6·1	21·2	8·6	13·1
1960–61	155,174	1·6	36·9	69·5	25·6	6·2	21·1	8·7	12·3
1961–62	152,679	−1·6	40·3	74·1	29·9	4·6	22·0	9·1	12·7
1962–63	157,712	3·3	39·2	73·1	28·7	6·4	21·7	9·4	12·1
1963–64	158,626	0·6	40·2	74·9	30·1	5·0	21·2	9·2	11·8
1964–65	164,981	4·0	38·7	74·5	28·8	5·0	20·4	8·9	11·4
1965–66	170,622	3·4	35·7	66·1	23·6	7·5	19·7	7·6	12·1
1966–67[d]	157,563	−7·7	41·6	72·9	30·3	4·9	21·0	9·3	11·7
1967–68[d]	164,237	4·2	[e]	[e]	[e]	[e]	[e]	9·4	10·8[b]
10 year averages									
1947 to 1957		4·6	39·8	69·1	27·5	6·4	16·6	7·5	9·0
1958 to 1967		1·0	38·9	71·2	27·7	6·0	20·3	8·6	11·7

I Column 2 in year t = Columns 5 − (7 + 6) in year t − 1

II $\text{Column 5} = \frac{\text{Column 3 . Column 4}}{100}$

III Column 7 = Column 8 + Column 9

[a] Deaths are calculated as a residual.

[b] Slaughtered for human consumption only.

[c] Slaughtered for human consumption, including those boiled down during the year.

[d] Subject to revision.

[e] Not yet available.

Sources: I Commonwealth Bureau of Census and Statistics,

1. Statistical Bulletin, *Livestock Numbers, Australia* (various issues).
2. Statistical Bulletin, *Rural Industries* (various issues).
3. Statistical Bulletin, *Meat Industries* (various issues).

II. Bureau of Agricultural Economics, *Quarterly Review of Agricultural Economics*, Vol. XIX, No. 4 (Oct. 1966).

ming (1966), Watson (1967), and an unpublished paper by R. M. Parish.

Changes in Australian sheep numbers in the post-war period are given in Table 28:4. This period begins and ends with drought—often an important determinant of sheep numbers in Australia. Between the two droughts of 1944–6 and 1965–7 there was a remarkable growth in the Australian sheep population—a numerical increase which had not been equalled since those years in the last century when sheep first spread over the continent.

If one ignores the relatively insignificant exports and imports of live sheep, changes in sheep numbers in any one year are equal, as a matter of arithmetic, to the number of new lambs dropped minus the number of sheep which are slaughtered or die during the year. Table 28:4 is arranged to show changes in some of the important ratios which affect the rate of growth of the total sheep population. As Cumming has pointed out, the percentage change in sheep numbers can be expressed as follows:

$$N = \frac{M \times L}{100} - (R + D)$$

where

N = the percentage increase in the flock in any one year;

M = ewes mated as a percentage of total flock;

L = lambs marked as a percentage of ewes mated;

R = total slaughterings and exports expressed as a percentage of the total flock;

D = deaths as a percentage of the total flock.

The first point about Table 28:4 is that it shows little evidence of any long-term trends operating in any of the ratios given. There are variations, from year to year and, in some cases, over periods of years. But there is little evidence of long-term secular trends: for instance of any long-term decline in the proportion of sheep which die, of any pronounced rise in lambing percentages, or of any increase in the proportion of mated ewes in the national flock.

During drought periods death rates rise (though even in normal years they average almost 6 per cent). In addition there is a decline in the lambing percentage (column 4). Lower lambings during droughts result both from a postponement of mating and from lower lambing percentages.

In a drought it is more profitable to feed ewes than other sheep; as a result a higher proportion of ewes survives. Hence the proportion of ewes in the remaining national flock rises at the end of a drought. Consequently, recovery of sheep numbers after drought is somewhat more rapid than suggested by pre-drought growth rates. However, in spite of this, the periodic decimation of stock numbers by drought remains a serious and an important economic loss both to individual stock owners and to the nation as a whole.

As shown in Table 28:4 the proportion of lambs and adult sheep slaughtered has shown a substantial increase since 1957. In the last ten years (1958–9 to 1967–8) slaughterings averaged over 20 per cent of sheep numbers compared with some 16 per cent in the ten years before that. This increase can be largely attributed to the decline in wool prices after 1956–7 and to the build-up of sheep numbers in the preceding decade closer to the natural carrying capacity of the land. Parish has shown that the changes in age structure (inferred from the aggregate statistics) are not an adequate explanation of the increased rate of slaughtering. 'Graziers are sending more sheep to slaughter, not because they have to, but because they choose to.' Within the last ten years, graziers have chosen to slaughter a higher proportion because of the greater financial attractions of other forms of landuse—in particular wheat growing and the raising of beef cattle. As a result, the rate of growth of the sheep population has slowed down markedly since 1957. Between 1948–9 and 1957–8 sheep numbers increased at an average annual rate of 4·5 per cent; between 1958–9 and 1967–8 this slowed down to an average annual increase of 1 per cent.

On the other hand, even if wool growing had remained as profitable as it was between 1947 and 1957, it is extremely unlikely that sheep numbers would have continued to grow at the rate achieved in that decade. By 1957 sheep numbers in the Pastoral Zone had regained their pre-1945 drought levels. Since there is comparatively little scope for expansion in stock numbers there, a cessation in the rate of growth of sheep numbers in the Pastoral Zone was to be expected after 1957.

The 1965–6 drought reduced the national flock from a record 171 million in March 1965 to 158 million 12 months later. Since then there has been a renewed increase. At the recently ruling wool prices (i.e. 1966–7 and 1967–8), past experience would lead one to expect a continuation of the low long-term growth rate of sheep numbers. On the other hand, the current interest in higher stocking rates on improved pastures could possibly counteract this.

Mutton and Lamb Production

The growth of mutton and lamb production in the last ten years has been mentioned above.

Slaughterings of adult sheep have risen more rapidly than the slaughter of lambs. Mutton appears to be essentially a by-product of the major product of the Australian sheep industry—namely wool. Mutton is produced mainly from the slaughter of cast-for-age sheep; generally these are 'retired' wool producers. There is little evidence that changes in mutton prices affect the volume of mutton production. There is evidence that mutton production responds to changes in wool prices and also to the relative attractiveness of running sheep for wool or devoting the land to other rival uses.

On the other hand, prime lamb is derived from lambs which are raised specifically for meat production. Merino lambs are generally unsatisfactory for this purpose; Australian prime lambs may be produced from a wide variety of breed combinations. From these three main types of lamb enterprises can be distinguished:

(a) Breeding from Merino ewes using Border Leicester, to a lesser extent Romney Marsh or Downs breed rams to produce a first cross lamb. (The Downs breed include Southdown, Ryeland, Dorset Horn, Suffolk, and Sussex.) This type of enterprise is common in the drier areas in the Wheat-Sheep Zone which specialise in lamb production. The wethers are usually sold as prime lambs while ewe lambs are often bought by producers of second cross lambs in the higher rainfall zones and irrigation areas.

(b) Breeding from first cross ewes and a Downs breed ram. This type of lamb enterprise is more typical of the High-Rainfall Zone and irrigation areas, though with the recent relative decline in price of crossbred wool it is becoming somewhat less popular.

(c) Breeding from a commercial Corriedale and, to a lesser extent, Polwarth flock. Both these are dual-purpose sheep suitable for meat and wool production.

Lamb production appears to respond both to the relative prices for lamb and wool and also to the lamb/dairy price ratio. In irrigation areas and many other high rainfall regions, breeding lambs and dairying are important alternative forms of landuse.

Seasonal peaks of lamb output, during the spring flush growing period, were a characteristic feature of the industry some twenty years ago. With the growth of lamb production on irrigation farms and on highly improved pastures under natural rainfall this seasonability has been greatly reduced. Table 28:5 provides some figures to document this development.

TABLE 28 : 5 Seasonality of Australian lamb production
Average monthly production = 100

Month	1943–48	1955–60	1962–67
January	91	88	97
February	68	80	92
March	68	84	97
April	68	75	92
May	72	79	91
June	71	77	90
July	75	78	87
August	77	82	88
September	110	108	101
October	175	156	126
November	174	158	125
December	149	137	114
Average monthly production (in '000 tons)	10·5	13·8	18·5

Source: Commonwealth Bureau of Census and Statistics, *Statistical Bulletin: The Meat Industry* (various years).

Changes in the Breed Composition of the National Sheep Flock

Table 28:6 gives some information on the changes in the breed composition of the Australian sheep flock in recent years. Merinos are by far the most popular breed, accounting for three-quarters of all sheep. During both World War I and World War II the proportion of Merinos in the national flock declined; in wars there has been a shift in the relative price in favour of meat (as opposed to wool) and in favour of stronger rather than finer wools; both these trends encourage the relative expansion of the non-Merino breeds.

In addition there has been a relative growth of other pure breeds, in particular Border Leicester, Dorset Horn, Corriedale, and Romney Marsh. This increase has been at the expense of crossbred and Merino comeback—in particular the latter. Little is known about the reasons for this trend. It may be related to the difficulties associated with managing comeback flocks which involves keeping two breeds of rams and the production of a large variety of lines of wool

TABLE 28 : 6 Main breeds of sheep, Australia, various years

	Merino		Other pure breeds		Merino comeback		Crossbred		Total
	'000	%	'000	%	'000	%	'000	%	'000
1 Jan.									
1959	87,500	78·8	1,654	1·5	8,955	8·1	12,949	11·6	111,058
31 Mar.									
1947	66,961	70·0	4,867	5·1	5,712	6·0	18,183	18·9	95,723
1950	82,134	72·8	9,978	8·8	6,218	5·5	14,561	12·9	112,891
1953	90,714	73·7	11,204	9·1	7,178	5·8	13,976	11.4	123,072
1956	106,744	76·7	11,583	8·3	7,107	5·1	13,690	9·9	139,172
1959	114,223	74·8	15,683	10·3	7,826	5·1	14,953	9·8	152,686
1962	119,234	75·6	17,946	11·4	5,467	3·5	15,065	9·5	157,712
1965	129,754	76·0	19,587	11·5	4,361	2·6	16,920	9·9	170,622

Sources: Bureau of Agricultural Economics, *Statistical Handbook of the Sheep and Wool Industry*, 1961 and *Supplement*, 1964. 1965 Data: Bureau of Census and Statistics, Adelaide.

with a consequent increase in the proportion of star lots. The growth of off-peak lamb production referred to previously may be related to this change in the breed structure.

BEEF CATTLE

The distribution of beef cattle in Australia is shown in Fig. 6:2. The beef industry can be divided into two fairly distinct geographical sections:

1. the beef industry in the northern half of the continent including the Kimberleys of Western Australia, the Northern Territory, and most of Queensland;
2. the southern industry in the remaining parts of the continent.

In the remoter northern beef areas, cattle were traditionally run on an extensive range system. Under this system there was comparatively little handling of stock between annual musters. At these musters calves were branded and cattle were drafted off—for transport to the best market outlet.

Since the establishment of the northern cattle industry, this extensive and static system of operation has been carried on with relatively few changes. During most years of the first half of the twentieth century export prices for beef were low and cattle production in the remoter areas of Australia was generally unprofitable. Investment in watering facilities and fencing proceeded very slowly. In addition the technology of raising beef cattle under extensive tropical and sub-tropical conditions had made little headway.

However, in recent years a series of developments has taken place which promises to transform the northern cattle industry. The most important of these is the improvement of beef prices which, at least since the growth of the American market in the late 1950s, has offered great incentives to producers to develop their holdings and thus increase beef production. As a result expenditure on fencing, watering facilities, new pastures, and better livestock is growing rapidly.

New beef roads in northern areas and lower haulage charges are encouraging the rapid growth of road transport of beef cattle to meatworks or railheads, with resulting improvements in turn-off rates and higher prices for younger, better quality animals. The establishment of meatworks in the Northern Territory has also reduced the need for walking aged store cattle over long and tortuous stock routes to the nearest railhead. As a result, production of beef and veal from Northern Australia has increased by more than 50 per cent in the last twenty-five years, whilst the cattle population increased by only 22 per cent.

The development of new tropical cattle breeds based on some admixture of Brahman cattle with the traditional British breeds has led to 30 per cent greater weight gains and earlier maturity under northern conditions where seasonal feed variability and tick infestation are serious handicaps.

Last, but perhaps most important of all, a pasture legume, Townsville lucerne (*Stylosanthes humilis*) has been introduced which promises to lead to a 5– or 10–fold increase in the carrying capacity of those northern regions with 30 in. (762 mm) of rainfall or more. Within the last two or three years, there has been a spectacular increase in commercial plantings of Townsville lucerne (see Chapter 8). At present there are still some technical problems associated with managing Townsville lucerne pastures under extensive, commercial conditions. However, the prospects for a substantial growth of cattle numbers and beef production in these areas appear very promising.

As shown in Table 28:7 most of the beef cattle in Queensland and the Northern Territory are run on properties where the raising of beef is the major enterprise. In contrast, the beef industry in the southern parts of Australia is less concentrated. Sixty per cent of the beef cattle herd in the southern States are carried on farms where sheep, wheat-sheep, dairying or some other enterprise is the major economic activity.

TABLE 28 : 7 Distribution of beef cattle among rural holdings, 1965–6

Main activity of holding	Number '000s	Percentage total beef cattle[a]		
		Qld and N.T.	Southern States	Total Australia
Sheep-cereal grain	32	—	7	4
Sheep	44	7	32	20
Cereal grain	12	2	1	2
Beef cattle	16	83	40	62
Dairying	49	2	6	4
Multi-purpose	9	2	7	5
All other	90	4	7	3
		Total beef cattle (millions)		
Total holdings	252	6·7	6·5	13·2

[a] Estimated from Commonwealth Bureau of Census and Statistics, *Classification of Rural Holdings by Size and Type of Activity 1965-66*, Bulletin Nos. 1, 2, 4, 5, 6, 7.

In the post-war period, beef cattle numbers have increased more rapidly in the southern parts of the continent. In March 1967 Queensland accounted for 44 per cent of the national beef herd and the Northern Territory for 8 per cent. In 1948 these percentages were 51 and 11 respectively.

Beef cattle have always been important as a sideline on sheep properties; but, as a result of recent economic trends, they have become a much more important income earner. It used to be broadly true that Australian beef cattle raising developed primarily in areas which were for some reason unsuitable for the more profitable activities of wool growing (in inland areas) and dairying (on the coast). Specialised beef cattle properties in southern States still tend to be restricted to mountainous country where the land is too steep for dairying and the rainfall and pasture growth relatively unsuitable for sheep.

But raising beef cattle has become a more financially attractive sideline in recent years. With the growth of the U.S. market for Australian beef after 1958–9, beef production has become more attractive economically. Thus during the three years ended June 1968 the beef/wool price ratio has been twice as high as it was during the early 1950s (e.g. during 1952–4). It is not surprising therefore that beef cattle numbers in southern States have grown more rapidly than the sheep population in recent years and that the sale of beef is accounting for an increasing proportion of the southern woolgrowers' gross receipts. For instance, in Victoria beef numbers rose by 51 per cent in the decade prior to 1967 whilst the number of sheep increased by only 22 per cent.

In the two post-war decades Australian production of beef and veal has increased by almost 100 per cent—from less than half a million tons in the post-drought year 1946-7 to just over one million tons in the pre-drought year of 1964–5. Since then there has been a slight decline. Cattle now tend to be turned off at a younger age than in earlier years; as a result average dressed weights are now lower than they used to be. Beef and veal production has increased somewhat more rapidly than cow numbers; the proportion of breeding animals in the national beef herd has also risen slowly. Cows and heifers amounted to 50 per cent of the total national beef herd in the three years ended June 1966 compared with 43·5 per cent in the three years ended June 1959. In the last decade, beef production has grown particularly rapidly in Victoria which now accounts for over 20 per cent of Australia's beef exports (compared with less than 5 per cent before 1958).

No accurate statistics are available for the amount of beef that comes from the Australian dairy herd, but estimates based on the assumptions in B.A.E. Beef Research Report No. 2, February 1966, plus the additional assumption that changes in dairy cattle numbers also affect beef production, suggest that it is a declining proportion. Approximately 10 per cent of total beef production came from the slaughter of dairy cows and bulls in the three years ended June 1966 compared with 14 per cent in the three years ended June 1949.

DAIRY CATTLE

The Australian dairying industry has been the subject of more economic studies and surveys than perhaps any other major rural industry. Jensen's (1967) survey of the literature on the industry gives no fewer than eighty-five references for the post-war period. The major reasons for this high degree of concern are twofold. On the one hand the amount of protection received by butter and cheese producers is high—in absolute terms it accounts for almost half the total amount of protection granted to all rural export industries. Protection is obtained through two-price schemes, through prohibitive duties on imports of butter, and through the limitation on the quantity of table margarine that can be produced.

On the other hand, the dairying industry accounts for the largest single group of low income farm operators in the economy. Whilst dairy farming employs about a fifth of the rural labour force (and accounts for a fifth of all rural holdings), about half the low income farms classified by McKay (1967a) were in the dairying industry. (Low income farms were defined as those with net incomes below $2,000 or $1,000 respectively. On both definitions, dairy farms comprised about half the total.)

Most dairy farms in Australia are located in the coastal high rainfall districts of the continent and along the irrigated regions of the Murray River (see Fig. 6:3). Victoria is the most important dairying State, producing nearly half the total milk (for all purposes). New South Wales accounts for about one-fifth of total milk output, followed by Queensland (about 15 per cent).

From an economic point of view two different types of milk producers should be distinguished:

1. The manufacturing sector which consists of those farmers selling milk or cream solely for manufacturing purposes (i.e. for conversion into butter, cheese, and condensory products)
2. The whole milk or 'milk zone' sector comprising those farms which deliver all or part of their milk for sale to the local liquid milk markets of the major cities. In most States they are located near the major consuming centres.

About 22·5 per cent of Australian milk production is consumed as milk; about 60–65 per cent is made into butter; 8–10 per cent is used in the manufacture of cheese, and 5–6 per cent for condensory products.

For that portion of their milk which is used for the city milk trade, city milk suppliers receive approximately twice as much per gallon as producers of manufacturing milk. This is not all profit—in return they have to undertake to produce certain minimum quantities throughout the whole year. But it is broadly true that city milk supply is much more profitable than the sale of manufacturing milk. As a result, it pays city milk suppliers to use more fertiliser and to feed more grain and concentrates. However, even for city milk suppliers, pasture normally constitutes the dominant proportion of their cows' nutrient intake.

Since milk zone farms are primarily concerned with production of milk rather than with its butterfat content, the dairy breeds used in the milk zone (mainly Friesian and Illawarra Shorthorn—a locally evolved breed) are those which produce a high volume of milk with a relatively low butterfat percentage. Farmers in manufacturing areas are paid primarily on a butterfat basis. The most common breeds in manufacturing areas are Jersey and, to a lesser extent, Guernsey—both breeds producing milk with a relatively high butterfat percentage.

Occasionally farmers in manufacturing areas deliver whole milk rather than butterfat to the local dairy factory. Then they receive an extra payment for the skim milk they supply, but the bulk of their income still comes from the sale of butterfat. This skim milk allowance varies from factory to factory. It has tended to rise in the post-war years. As a result, an increasing proportion of skim milk has been processed. According to McClelland (1965) the proportion of the total estimated skim milk production which has been used for manufacture (of casein and skim milk powder) rose from 15 per cent in 1949–50 to 42 per cent by 1963–4. Since mid-1968 the sale of skim milk to processing factories has become much less profitable.

In regions supplying milk for manufacturing purposes, pig raising is often an important sideline. For Australia as a whole, 41 per cent of specialist dairy enterprises carried some pigs in 1965–6 (48 per cent in 1959–60). On dairy farms pigs are raised on skim milk and purchased grains or concentrate supplements. Pig raising is therefore largely an alternative to the supply of skim milk to processing factories.

There has been some tendency towards larger sized dairy herds. Between 1948 and 1966 the proportion of dairy cattle herds with 20 cattle or less declined from 54 to 30 per cent, whilst those with 50 cattle or more increased from 25·5 per cent to almost 50 per cent over the same period. Since 1959–60 only herds with 100 or more dairy cattle have increased absolutely. In the 11-year period 1952–63 average butter production per survey farm included in the Bureau of Agricultural Economics Australia-wide *Dairy Survey* increased by 36 per cent.

Australian dairy cow numbers have tended to be static over the last 10–15 years, with increases in cow numbers in Victoria and Tasmania being offset by declines in Queensland and New South Wales. Between 1946 and 1950 Australian dairy cow numbers increased from 3 to 3·2 million; in the next two years numbers again declined to the 1946 levels. After 1952 they increased gradually to a peak of 3·45 million in 1957. Since then cow numbers have gradually declined to 3·06 million in 1967. It has been shown by Gruen, Ward, and Powell (1966) that these fluctuations in dairy cow numbers are largely the result of adjustments to the changing profitability of dairying compared to the major alternative forms of landuse—namely beef production and the raising of prime lambs.

In the two decades since World War II, Australia's total milk production (including milk used for butter manufacture) has risen by about 50 per cent. Since total dairy cow numbers have remained virtually static, this increase can be assigned to the rise in milk yields per cow. Since the early 1950s yields per cow have increased at an average annual rate of 1·7 per cent. The main factor responsible for this increase in yields was probably the better feeding of dairy cattle on improved pastures. It is significant that milk yields per cow have remained virtually static in Queensland during the last thirty years whilst Victorian average yields have risen by some 25 per cent over this period. Until recently there has been no pasture improvement in Queensland.

The gradual concentration of cow numbers in those areas where high milk yields have been obtained has also played a part in lifting the national milk yield per cow. The relative movement of the industry from Queensland and northern New South Wales to Victoria and Tasmania has accounted for about a quarter of the rise in average Australian milk yields over the last ten years. In addition cow numbers have probably increased more in those areas (or on those farms) which obtain the higher prices payable for supplying the city milk trade. Thus in New South Wales milk yields from Milk Board supplying areas have been estimated to be 15 to 20 per cent higher than those ruling in other areas. This difference results from the use of high yielding and relatively lower butterfat-producing cows which was mentioned earlier and from the more intensive feeding of cows on farms supplying the liquid milk trade. Better breeding and better management generally have probably also made some contribution to the increase in the national average yields per cow.

CONCLUSION

In conclusion one should again stress the overwhelming dependence of all three of these livestock industries on pastures and grazing lands. Overseas visitors from the more densely settled countries in the northern hemisphere are often surprised by the levels of production, both per farmer and per animal, that are achieved through almost total reliance on pastures in Australia.

This is largely a question of climate and economics. Our climate is such that housing of animals in the winter is unnecessary. Again, the price of livestock products in Australia is normally too low to permit the use of more expensive feeds than grass.

ACKNOWLEDGMENTS

The author is indebted to Professor A. G. Lloyd and Mr N. M. Tulloh of the University of Melbourne and Mr R. M. Carraill of the Victorian Department of Agriculture for helpful comments on an earlier draft of this paper.

REFERENCES

Aasen, A. J., Culvenor, C. C. J., Finnie, E. P., Kellock, A. W., and Smith, L. W. (1969). Alkaloids as a possible cause of ryegrass staggers in grazing livestock. *Aust. J. agric. Res.* **20**: 71–86.

Agricultural Research Council (1965). *The nutrient requirements of farm livestock. No.* 2. *Ruminants.* Agricultural Research Council, London.

Aitken, Yvonne (1955). Flower initiation in pasture legumes. I. Factors affecting flower initiation in *Trifolium subterraneum* L. *Aust. J. agric. Res.* **6**: 212–44.

——— and Drake, F. R. (1941). Studies of the varieties of subterranean clover. *Proc. R. Soc. Vict.* **53**: 342–93.

Albiston, H. E., Bull, L. B., Dick, A. T., and Keast, J. C. (1940). A preliminary note on the aetiology of enzootic jaundice, toxaemic jaundice or 'yellows' of sheep in Australia. *Aust. vet. J.* **16**: 233–43.

Alexander, G. I. and Chester, R. D. (1956). Growth studies of beef cattle in Queensland. *Qd J. agric. Sci.* **13**: 69–95.

——— and Harvey, J. M. (1957). A survey of the incidence of copper deficiency in dairy cattle in coastal Queensland south of Brisbane. *Qd J. agric. Sci.* **14**: 23–7.

———, Harvey, J. M., Lee, H. J., and Stubbs, W. C. (1967). Studies on copper and cobalt therapy of cattle in central coastal Queensland. *Aust. J. agric. Res.* **18**: 169–81.

Alexander, M. (1961). *Introduction to soil microbiology.* New York, Wiley.

Allaway, W. H. and Hodgson, J. F. (1964). Symposium on nutrition, forage and pastures: selenium in forages as related to the geographic distribution of muscular dystrophy in livestock. *J. Anim. Sci.* **23**: 271–7.

———, Moore, D. P., Oldfield, J. E., and Muth, O. H. (1966). Movement of physiological levels of selenium from soils through plants to animals. *J. Nutr.* **88**: 411–18.

Allcroft, R. (1963). Copper deficiency and molybdenum excess. In *Animal health, production and pasture* ed. A. N. Worden, K. C. Sellers, and D. E. Tribe. London, Longmans. pp. 632–61.

Allen, G. H. (1960). A pasture legume for Queensland. *Qd agric. J.* **86**: 273–5.

——— and Cowdry, W. A. R. (1961). Beef gains from irrigated pastures in the Burdekin Delta. *Qd agric. J.* **87**: 175–9.

Anderson, A. J. (1942). Molybdenum deficiency on a South Australian ironstone soil. *J. Aust. Inst. agric. Sci.* **8**: 73–5.

——— (1946). Fertilisers in pasture development on peat soils in the lower south-east of South Australia. *J. Coun. scient. ind. Res. Aust.* **19**: 394–403.

——— (1952). Responses of subterranean clover and lucerne to boron. *J. Aust. Inst. agric. Sci.* **18**: 159–63.

——— (1956a). Molybdenum deficiencies in legumes in Australia. *Soil Sci.* **81**: 173–258.

——— (1956b). Molybdenum as a fertiliser. *Adv. Agron.* **8**: 163–202.

——— and McLachlan, K. D. (1951). The residual effect of phosphorus on soil fertility and pasture development on acid soils. *Aust. J. agric. Res.* **2**: 377–400.

——— and Moye, D. V. (1952). Lime and molybdenum in clover development on acid soils. *Aust. J. agric. Res.* **3**: 95–110.

——— and Neal-Smith, C. A. (1951). Pasture development on a deep sand of the heath country in the Upper South East of South Australia. *CSIRO Aust., Bull.* **263.**

——— and Oertel, A. C. (1946). Plant responses to molybdenum as a fertiliser. II. Factors affecting the response of plant to molybdenum. *Coun. scient. ind. Res. Aust. Bull.* **198**: 25–44.

——— and Thomas, M. P. (1946). Plant responses to molybdenum as a fertiliser. I. Molybdenum and symbiotic nitrogen fixation. *Coun. scient. ind. Res. Aust. Bull.* **198.**

Andrew, C. S. (1960). The effect of phosphorus, potassium and calcium on the growth, chemical composition, and symptoms of deficiency of white clover in a subtropical environment. *Aust. J. agric. Res.* **11**: 149–61.

——— (1963a). Copper deficiency symptoms of some tropical and temperate pasture legumes. *Aust. J. agric. Res.* **14**: 654–59.

——— (1963b). Manganese excess. *CSIRO Aust., Div. Trop. Past. Annual Report 1962–3.* pp. 35–6.

——— (1966a). Aluminium excess. *CSIRO Aust., Div. Trop. Past., Annual Report 1965–6.* p. 63.

——— (1966b). A kinetic study of phosphate absorption by excised roots of *Stylosanthes humilis*, *Phaseolus lathyroides*, *Desmodium uncinatum*, *Medicago sativa* and *Hordeum vulgare*. *Aust. J. agric. Res.* **17**: 611–24.

——— and Bryan, W. W. (1955). Pasture studies on the coastal lowlands of sub-tropical Queensland. I. Introduction and initial plant nutrient studies. *Aust. J. agric. Res.* **6**: 265–90.

——— and ——— (1958). Pasture studies on the coastal lowlands of sub-tropical Queensland. III. The nutrient requirements and potentialities of *Desmodium uncinatum* and white clover on a lateritic podzolic soil. *Aust. J. agric. Res.* **9**: 267–85.

——— and Henzell, E. F. (1964). Mineral nutrition of plants *in* Some concepts and methods in sub-tropical pasture research. *Comm. Bur. Past. Fld Crops, Bull.* **47**: 93–101.

———, Kipps, E. H., and Barford, H. (1952). Plant responses to nitrogen and sulphur on a heavy clay soil from the Darling Downs, south-east Queensland. *Aust. J. agric. Res.* **3**: 111–24.

——— and Norris, D. O. (1961). Comparative responses to calcium of five tropical and four temperate pasture legume species. *Aust. J. agric. Res.* **12**: 40–55.

——— and Thorne, Peggy M. (1962). Comparative responses to copper of some tropical and temperate pasture legumes. *Aust. J. agric. Res.* **13**: 821–35.

Andrew, W. D. and Hudson, W. J. (1954). A superior strain of medic—barrel medic 173 (*Medicago tribuloides* Desr.). *Agric. Gaz. N.S.W.* **65**: 76–80.

——— and Milligan, R. T. (1954). Different molybdenum requirements of medics and subterranean clover on a red brown soil at Wagga, New South Wales. *J. Aust. Inst. agric. Sci.* **20**: 123–4.

Angove, P. C. (1952). Lucerne in South Australia. *J. Dep. Agric. S. Aust.* **55**: 490–9, 551–60.

Anon. (1933). Pasture improvement. A summary of a progress report on the investigations initiated in 1932 by the Department of Agriculture in co-operation with the Victorian Pasture Improvement League. *J. Agric. Vict. Dep. Agric.* **31**: 235–7.

——— (1948). Leucaena glauca as a substitute for oil cake meals. *University of Hawaii agric. Expt. Stn Report for biennium ending June 30*, pp. 38–9.

——— (1953). Better pastures for the New South Wales Tablelands. *CSIRO Aust. Pamph.*

——— (1956, 1957, 1959a). Poisonous plants of the Northern Territory. Parts I, II, and III. Extension article No. 2, Northern Territory Administration Animal Industry Branch.

——— (1959b). *The economic importance of cattle tick in Australia.* Bureau of Agricultural Economics, Canberra. p. 84.

——— (1960). Climatological Survey Region 10—Capricornia, Queensland. Commonwealth Bureau of Meteorology, Melbourne.

——— (1961a). Climatological Survey Region 6—Western Downs, Queensland. Commonwealth Burreau of Meteorology, Melbourne.

——— (1961b). Residual value of trace elements. How frequently should trace elements be applied to soils? *J. Agric. West Aust.* **2**: 222–3.

——— (1963). Annual Report, Queensland Department of Agriculture and Stock.

——— (1965a). Report of Queensland Dairy Industry Advisory Committee. Mimeo.

——— (1965b). *Annual Report, Queensland Department of Primary Industries, 1964–5.* Brisbane.

——— (1966a). Beef cattle in the north. *Current Affairs Bulletin.*

——— (1966b). More sheep per acre. *J. Agric. West Aust.* **7**: 430–1.

——— (1966c). *CSIRO Aust., Div. Trop. Past., Annual Report 1965–6*: 97–9.

——— (1967a). *Statistical Register of South Australia for 1967.* Part Va, Agricultural Production. Canberra, Commonwealth Bureau of Census and Statistics.

——— (1967b). *Chemical Fertilizers.* Canberra, Commonwealth Department of Primary Industry.

——— (1967c). *CSIRO Aust., Div. Trop. Past., Annual Report.* pp. 58–60.

——— (1967d). Queensland Government Statistician, *Report* SR27/68.

Aplin, T. E. H. (1967). Poison plants of Western Australia—the toxic species of the genera *Gastrolobium* and *Oxylobium*. *J. Agric. West Aust.* **8** (4th series): 42–52, 200–6, 408–14.

——— (1968). Cyanogenetic plants of Western Australia. *J. Agric. West. Aust.* **9** (4th series): 328–31.

Armstrong, J., Henderson, A. G., Lang, D. R., Robinson, D. W., and Suijdendorp, H. (1968). Preliminary observations on the productivity of female cattle in the Kimberley region of north-western Australia. *Aust. vet. J.* **44**: 357–63.

Arndt, W. and Norman, M. J. T. (1959). Characteristics of native pasture on Tippera clay loam at Katherine, N.T. *CSIRO Aust., Div. Land Res. Reg. Surv., Tech. Pap.* **3**.

Arnold, G. W. and Bush, I. G. (1962). Effects of stocking rate and grazing management on fat lamb production. *Proc. Aust. Soc. Anim. Prod.* **4**: 121–9.

——— and McManus, W. R. (1960). The effects of level of stocking on two pasture types upon wool production and quality. *Proc. Aust. Soc. Anim. Prod.* **3**: 63–8.

Arnold, Jennifer M. (1963). Climate of the Wiluna-Meekatharra area. *CSIRO Aust., Div. Land Res. Ser.* **7**: 73–92.

Atkinson, W. T., Walker, M. H., and Reis, P. J. (1958). Seasonal comparisons of dry matter and protein yield from sown and natural pastures on granitic soils at Shannon Vale Nutrition Station. *Proc. 2nd Aust. Agrostology Conference* **1** (1): 59–1, 59–17.

Australian Water Resources Council (1965). *Review of Australia's water resources 1963.* Canberra, Department of National Development.

Bailey, E. T. (1966). Rose clover. *J. Agric. West. Aust.* **7** (4): 170–5.

——— (1967). Consumption and digestion of dry cupped clover. *J. Agric. West. Aust.* **8**: 199.

Bailey, F. M. and Tenison-Woods, J. E. (1879). A census of the flora of Brisbane. *Proc. Linn. Soc. N.S.W.* **4**: 137–204.

Barley, K. P. and Kleinig, C. R. (1964). Occupation of newly irrigated lands by earthworms. *Aust. J. Sci.* **26** (9): 290–1.

Barnard, A. (ed.) (1962). The simple fleece. Melbourne, Melbourne University Press.

Barnard, C. (1967). *Australian herbage plant register.* CSIRO Aust., Div. Pl. Ind.

Barrett, J. F., George, J. M., and Lamond, D. R. (1965). Reproductive performance of Merino ewes grazing red clover (*Trifolium pratense* L.), improved pasture, or native pasture. *Aust. J. agric. Res.* **16**: 189–200.

Barrow, N. J. (1966). The residual value of the phosphorus and sulphur components of superphosphate on some Western Australian soils. *Aust. J. exp. Agric. Anim. Husb.* **6**: 9–16.

——— (1967a). Studies on the adsorption of sulphate by soils. *Soil Sci.* **104** (5): 342–9.

——— (1967b). Sulphur and developing agriculture in Western Australia. *The Sulphur Institute Journal* **3**(1): 2–5.

———, Spencer, K., and McArthur, W. M. (1969). Effects of rainfall, parent material, on the ability of soils to adsorb sulphate. *Soil Sci.* **108**: 120–6.

Bashaw, E. C. (1962). Apomixis and sexuality in buffel grass. *Crop Sci.* **2**: 412–15.

——— and Holt, E. C. (1958). Megasporagenesis, embryo sac development and embryogenesis in Dallis grass, *Paspalum dilatatum*, Poir. *Agron. J.* **50**: 753–6.

Batterham, T. J., Hart, N. K., Lamberton, J. A., and Braden, A. W. H. (1965). Metabolism of oestrogenic isoflavones in sheep. *Nature, Lond.* **206**: 509.

Bauer, F. H. (1959). Historical geographic survey of part of northern Australia. *CSIRO Div. Land Res. Reg. Surv., Divisional Report* 59/2.

——— (1964). Historical geographic survey of part of northern Australia. *CSIRO Aust., Div. Land Res. Reg. Surv., Divisional Report* **64/1**.

Beadle, N. C. W. (1948). *The vegetation and pastures of western New South Wales with special reference to soil erosion.* Sydney, Government Printer.

——— (1962). An alternative hypothesis to account for the generally low phosphate content of Australian soils. *Aust. J. agric. Res.* **13**: 434–42.

——— (1966). Soil phosphate and its role in moulding segments of the Australian flora and vegetation with special reference to xeromorphy and sclerophylly. *Ecology.* **47**: 992–1007.

——— and Costin, A. B. (1952). Ecological classification and nomenclature. *Proc. Linn. Soc. N.S.W.* **77**: 1–2, 61–82.

Beattie, W. A. (1956). A survey of the beef cattle industry of Australia. *CSIRO Aust., Bull.* **278**: 135.

Beck, A. B. (1962). The levels of copper, molybdenum and inorganic sulphate in some Western Australian pastures. *Aust. J. exp. Agric. Anim. Husb.* **2**: 40–5.

——— (1964). The oestrogenic isoflavones of subterranean clover. *Aust. J. agric. Res.* **15**: 223–30.

Begg, J. E. (1959). Annual pattern of soil moisture stress under sown and native pastures. *Aust. J. agric. Res.* **10**: 518–29.

——— (1963). Comparative responses of indigenous, naturalised and commercial legumes to phosphorus and sulphur. *Aust. J. exp. Agric. Anim. Husb.* **3**: 17–19.

——— (1965). High photosynthetic efficiency in a low latitude environment. *Nature, Lond.* **205**: 1025–6.

Beggs, J. P. (1961). Soil sterilant aid to clover establishment indicates anti-nodulation factors in soils. *N.Z. Jl Agric.* **103**: 325, 334.

——— (1964). . Spectacular clover establishment with formalin treatment suggests growth inhibitor in soil. *N.Z. Jl Agric.* **108**: 529–35.

Bell, A. T., Newton, L. G., Everist, S. L., and Legg, J. (1955). *Acacia georginae* poisoning of sheep and cattle. *Aust. vet. J.* **31**: 249–57.

Bennett, D. and Dudzinski, M. L. (1967). Bioassay responses of ewes to legume swards. I. Uterine weight response: variability, calibration, and prediction. *Aust. J. agric. Res.* **18**: 485–94.

———, Morley, F. H. W., and Axelsen, A. (1967). Bioassay responses of ewes to legume swards. II. Uterine weight results from swards. *Aust. J. agric. Res.* **18**: 495–504.

Bennetts, H. W. (1932). Enzootic ataxia of lambs in Western Australia. *Aust. vet. J.* **8**: 137–42.

——— (1937). Copper deficiency—the cause of enzootic ataxia ('rickets') of lambs. *J. Dept Agric. West. Aust.* **14**: 247–50.

——— (1946). Metaplasia in the sex organs of castrated male sheep maintained on early subterranean clover pastures. *Aust. vet. J.* **22**: 70–8.

——— (1955). Copper and cobalt deficiency of livestock in Western Australia. *J. Agric. West. Aust.* **4** (3rd series): 43–63.

——— (1959). Copper and cobalt deficiency of livestock in Western Australia. Part 1—Distribution and effects. Part 2—The control of copper and cobalt deficiencies in animals. *J. Agric. West. Aust.* **8**: 631–48.

———, Beck, A. B., and Harley, R. (1948). The pathogenesis of 'falling disease'. Studies on copper deficiency in cattle. *Aust. vet. J.* **24**: 237–44.

——— and Chapman, F. E. (1937). Copper deficiency in sheep in Western Australia: a preliminary account of the aetiology of enzootic ataxia of lambs and an anaemia of ewes. *Aust. vet. J.* **13**: 138–49.

——— and Hall, H. T. B. (1939). 'Falling disease' of cattle in the south-west of Western Australia. *Aust. vet. J.* **15**: 152–9.

———, Harley, R., and Evans, S. T. (1942). Studies on copper deficiency of cattle: the fatal termination ('falling disease'). *Aust. vet. J.* **18**: 50–63.

———, Underwood, E. J., and Shier, F. L. (1946). A specific breeding problem of sheep on subterranean clover pastures in Western Australia. *Aust. vet. J.* **22**: 2–12.

Bergersen, F. J. (1961). The growth of Rhizobium in synthetic media. *Aust. J. biol. Sci.* **14**: 349–60.

———, Brockwell, J., and Thompson, J. A. (1958). Clover seed pelleted with bentonite and organic material as an aid to inoculation with nodule bacteria. *J. Aust. Inst. agric. Sci.* **24**: 158–60.

Bettenay, E. (1962). The salt lake systems and their associated aeolian features in the semi-arid regions of Western Australia. *J. Soil Sci.* **13**: 10–17.

Bickoff, E. M., Booth, A. N., Lyman, R. L., Livingston, A. L., Thompson, C. R., and Deeds, F. (1957). Coumestrol, a new estrogen isolated from forage crops. *Science, N.Y.* **126**: 969–70.

———, Livingston, A. L., Witt, S. C., Lundin, R. E., and Spencer, R. R. (1965). Isolation of 4′-0-methylcoumestrol from alfalfa. *J. agric. Fd Chem.* **13**: 597–9.

Biddiscombe, E. F. (1953). A survey of the natural pastures of the Trangie district, New South Wales, with particular reference to the grazing factor. *Aust. J. agric. Res.* **4**: (1) 1–28.

——— (1963). A vegetation survey in the Macquarie region, New South Wales. *CSIRO Aust., Div. Pl. Ind. Tech. Pap.* **18**.

——— (1964). The response of *Phalaris tuberosa* and other grasses to seasonal heavy stocking on the southern tablelands of N.S.W. *Aust. J. exp. Agric. Anim. Husb.* **4**: 141–51.

———, Cuthbertson, E. G., and Hutchings, R. J. (1954). Autecology of some natural pasture species at Trangie, N.S.W. *Aust. J. Bot.* **2** (1): 69–98.

———, Hutchings, R. J., Edgar, G., and Cuthbertson, E. G. (1956). Grazing management of natural pastures at Trangie, New South Wales. *Aust. J. agric. Res.* **7**: 233–47.

Bisschop, J. H. R. (1964). Feeding phosphates to cattle. *Scient. Bull. Dep. Agric. S. Afr.* **365**.

Bisset, W. J. (1960). Overcoming white spear grass and yabilu grass problems. *Qd agric. J.* **86**: 401–6.

——— (1963). There's a place for sown pastures in the Central West. *Qd agric. J.* **89**: 282–8.

Black, J. M. (1943–57). *Flora of South Australia.* 2nd ed.

Adelaide, Government Printer.

Black, J. N. (1964). An analysis of the potential production of swards of subterranean clover (*Trifolium subterraneum* L.) at Adelaide, South Australia. *Jnl appl. Ecol.* **1**: 3–18.

Blackwood, H. K. (1967). The influence of weeds on the seed industry. *Proc. Weed Soc. N.S.W.* **1**: 5–1, 5–3.

Blair, I. D. (1967). Studies on Rhizobium strains. II. *Rhizobium trifolii. N.Z. Jl agric. Res.* **10**: 237–52.

Blake, S. T. (1938). The plant communities of western Queensland and their relationships with special reference to the grazing industry. *Proc. R. Soc. Qd* **49**: 156–204.

Blaxter, K. L. and Brown, F. (1952). Vitamin E in the nutrition of farm animals. *Nutr. Abstr. Rev.* **22**: 1–21.

Bogdan, A. V. (1959). The selection of tropical ley grasses in Kenya: general considerations and methods. *E. Afr. agric. J.* **24**: 206–17.

——— (1961). Intra-variety variation in Rhodes (*Chloris gayana* Kunth.) in Kenya. *J. Brit. Grassld Soc.* **16**: 238–9.

——— (1966). *Glycine javanica* under experimental cultivation in Kenya. *Trop. Agric., Trin.* **43**: 99–105.

Bond, R. D. and Harris, J. R. (1964). The influence of the microflora on physical properties of soils. I. Effects associated with filamentous algae and fungi. *Aust. J. Soil Res.* **2**: 111–22.

Bornemissza, G. F. (1960). Could dung-eating insects improve our pastures? *J. Aust. Inst. agric. Sci.* **26**: 54–6.

Bott, E., Denton, D. A., Goding, J. R., and Sabine, J. R. (1964). Sodium deficiency and corticosteroid secretion in cattle. *Nature, Lond.* **202**: 461–3.

Bouma, D. and Dowling, E. J. (1962). The physiological assessment of the nutrient status of plants. I. Preliminary experiments with phosphorus. *Aust. J. agric. Res.* **13**: 791–800.

——— and ——— (1966a). The physiological assessment of the nutrient status of plants. II. The effect of the nutrient status of the plant with respect to phosphorus, sulphur, potassium, calcium, or boron on the pattern of leaf area response following the transfer to different nutrient solutions. *Aust. J. agric. Res.* **17**: 633–46.

——— and ——— (1966b). The physiological assessment of the nutrient status of plants. III. Experiments with plants raised at different nitrogen levels. *Aust. J. agric. Res.* **17**: 647–55.

———, Spencer, K., and Dowling, E. J. (1969). The assessment of the phosphorus and sulphur status of subterranean clover pastures. III. Plant tests. *Aust. J. exp. Agric. Anim. Husb.* **9**: 329–40.

Bourke, M. E. (1964). A comparison of grazing systems for prime lamb production. *Proc. Aust. Soc. Anim. Prod.* **5**: 129–34.

Bowen, G. D. (1956). Nodulation of legumes indigenous to Queensland. *Qd J. agric. Sci.* **13**: 47–60.

——— and Kennedy, Margaret, M. (1959). Effect of high soil temperatures on Rhizobium spp. *Qd J. agric. Sci.* **16**: 177–97.

——— and ——— (1961). Heritable variation in nodulation of *Centrosema pubescens* Benth. *Qd J. agric. Sci.* **18**: 161–70.

Bowyer, J. W., Atherton, J. G., Teakle, D. S., and Ahern, Gabrielle A. (1969). Mycoplasma-like bodies in plants affected by legume little leaf, tomato big bud, and lucerne witches' broom diseases. *Aust. J. biol. Sci.* **22**: 271–4.

Boyle, A. J. (1961). *Sorghum almum*, popular in North West. *Agric. Gaz. N.S.W.* **72**: 338–44, 379.

Braden, A. W. H., Hart, N. K., and Lamberton, J. A. (1967). The oestrogenic activity and metabolism of certain isoflavones in sheep. *Aust. J. agric. Res.* **18**: 335–48.

———, Southcott, W. H., and Moule, G. R. (1964). Assessment of oestrogenic activity of pasture by means of increase of teat length in sheep. *Aust. J. agric. Res.* **15**: 142–52.

Braithwaite, B. M. (1959). Insect pests of pastures on the north coast of New South Wales. *Agric. Gaz. N.S.W.* **70**: 586–97.

——— (1967). Tropical legume pest survey and clover root weevil studies. *Wollongbar agric. Res. Stn, N.S.W., Annual Report 1966–7*, pp. 31–3.

———, Jane, A., and Swain, F. G. (1958). *Amnemus quadrituberculatus* (Boh) a weevil pest of clover pastures on the north coast of New South Wales. *J. Aust. Inst. agric. Sci.* **24**: 146–54.

Bray, R. A. (1967). The effect of creeping-rootedness on survival in lucerne. *J. Aust. Inst. agric. Sci.* **33**: 46–7.

——— (1969). Variation in and correlations between yield and creeping-rootedness in lucerne. *Aust. J. agric. Res.* **20**: 47–55.

Breakwell, E. (1923). The grasses and fodder plants of New South Wales. Sydney, Government Printer, p. 370.

Brimblecombe, A. R. (1968). Felted grass couid on Rhodes grass in Queensland. *Qd agric. J.* **94**: 258–61.

Brockwell, J. (1962). Studies on seed pelleting as an aid to legume seed inoculation. *Aust. J. agric. Res.* **13**: 638–49.

———, Asuo, S. K., and Rea, Geraldine (1966). Acid production by rhizobia from the genera Trifolium and Lotus. *J. Aust. Inst. agric. Sci.* **32**: 295–7.

Brockwell, J. and Dudman, W. F. (1968). Ecological studies of root nodule bacteria introduced into field environments. II. Initial competition between seed inocula in the nodulation of *Trifolium subterraneum* L. seedlings. *Aust. J. agric. Res.* **19**: 749–58.

——— and Hely, F. (1966). Symbiotic characteristics of *Rhizobium meliloti*: an appraisal of the systematic treatment of nodulation and nitrogen fixation interactions between hosts and rhizobia of diverse origins. *Aust. J. agric. Res.* **17**: 855–99.

——— and Phillips, L. J. (1965). Survival at high temperatures of *Rhizobium meliloti* in peat inoculant on lucerne seed. *Aust. J. Sci.* **27**: 332–3.

——— and Whalley, R. D. B. (1962). Incorporation of peat inoculant in seed pellets for inoculation of *Medicago tribuloides* Desr. sown into dry soil. *Aust. J. Sci.* **24**: 458–9.

Brookfield, M. Dune trends in wind regimes. *Am. J. Sci.* (in press).

Browning, T. O. (1954). Observations on the ecology of the Australian field cricket, *Gryllulus commodus* Walker, in the field. *Aust. J. Zool.* **2**: 205–22.

Bruce, R. C. (1965). Effect of *Centrosema pubescens* Benth. on soil fertility in the humid tropics. *Qd J. Agric. anim. Sci.* **22**: 221–6.

Bryan, W. W. (1961). *Lotononis bainesii* Baker, a legume for sub-tropical pastures. *Aust. J. exp. Agric. Anim. Husb.* **1**: 4–10.

——— (1966). The pasture value of species of Desmodium. *Proc. 10th Int. Grassld Congr., Sect.* 1, *Pap.* **54**.

——— (1968a). Grazing trials on the Wallum of south-eastern Queensland. 1. A comparison of four pastures. *Aust. J. exp. Agric. Anim. Husb.* **8**: 512–20.

——— (1968b). Grazing trials on the Wallum of south-eastern Queensland. 2. Complex mixtures under common grazing. *Aust. J. exp. Agric. Anim. Husb.* **8**: 683–90.

——— and Andrew, C. S. (1955). Pasture studies on the coastal lowlands of subtropical Queensland. II. The interrelation of legumes, rhizobium, and calcium. *Aust. J. agric. Res.* **6**: 291–8.

——— and Evans, T. R. (1967). Coastal lowlands. Beef production from nitrogen-fertilised Pangola grass. *CSIRO Aust., Div. Trop. Past., Annual Report 1966–7*, pp. 20–1.

——— and ——— (1968). *CSIRO Div. Trop. Past., Annual Report 1967–8*, p. 21.

——— and Sharpe, J. P. (1965). The effect of urea and cutting treatment on the production of Pangola grass in south-eastern Queensland. *Aust. J. exp. Agric. Anim. Husb.* **5**: 433–41.

——— and Shaw, N. H. (1964). *Paspalum plicatulum* Michx. two useful varieties for pastures in regions of summer rainfall. *Aust. J. exp. Agric. Anim. Husb.* **4**: 17–21.

Bull, L. B. (1929). Poisoning of sheep by soursobs (*Oxalis cornua*): chronic oxalic acid poisoning. *Aust. vet. J.* **5**: 60–9.

——— (1961). Liver diseases in livestock from intake of hepatotoxic substances. *Aust. vet. J.* **37**: 126–30.

———, Albiston, H. E., Edgar, G., and Dick, A. T. (1956). Toxaemic jaundice of sheep: phytogenous chronic copper poisoning, heliotrope poisoning, and hepatogenous chronic copper poisoning. Final report of the Investigation Committee. *Aust. vet. J.* **32**: 229–36.

———, Dick, A. T., Keast, J. C., and Edgar, G. (1956). An experimental investigation of the hepatotoxic and other effects on sheep of consumption of *Heliotropium europaeum* L.: Heliotrope poisoning of sheep. *Aust. J. agric. Res.* **7**: 281–332.

———, Rogers, E. S., Keast, J. C., and Dick, A. T. (1961). Heliotropium poisoning in cattle. *Aust. vet. J.* **37**: 37–43.

Burbidge, N. T. (1946). Morphology and anatomy of the Western Australian species of *Triodia* R. Br. II. Internal anatomy of leaves. *Trans. R. Soc. S. Aust.* **70**: 221–34.

——— (1960). The phytogeography of the Australian region. *Aust. J. Bot.* **8**: 75–212.

Bureau of Agricultural Economics (Australia) (1964). *Supplement to the statistical handbook of the sheep and wool industry.*

——— (1965). *Road transport of beef cattle in Queensland.* Beef Research Report **1**.

——— (1966). *Increased beef production on dairy farms in Western Australia.* Beef Research Report **2**.

——— (1967). *The Australian sheep industry survey 1963–4.*

——— (1968a). *The beef situation.*

——— (1968b). *The Northern Territory beef cattle industry—an economic survey.*

——— (1968c). *The Australian dairy industry—an economic survey 1961–2 to 1963–4.*

Bureau of Meteorology (1956). *Climatic averages, Australia.* Melbourne, Government Printer.

——— (1963). *Australian radiation records 1958–61 and monthly means 1953–61.* Melbourne, Government Printer.

——— (1964). *Average monthly total radiation maps.* Melbourne, Government Printer.

——— (1965). *Climate and meteorology of Australia, Bulletin* **1**. Melbourne, Government Printer.

——— (1966). *Australian radiation records 1962–4.* Melbourne, Government Printer.

Burton, G. W. and Forbes, I. (1960). The genetics and manipulation of obligate apomixis in common bahia grass (*Paspalum notatum* Flugge). *Proc. 8th Int. Grassld Congr.*: 66–71.

Burton, J. C. (1965). The rhizobium-legume association. In *Microbiology and soil fertility* ed. M. Gilmour and O. N. Allen. Oregon State University Press. pp. 107–34.

Burvill, G. H. (1965). Plant nutrition in Western Australia. *J. Agric. West. Aust.* **6**: 353–71.

——— and Marshall, A. J. (1951). *Paspalum vaginatum* or seashore paspalum. *J. Dept Agric. West. Aust.* **28**: 191.

Butler, B. E. (1950). A theory of prior streams as a causal factor of soil occurrence in the Riverine Plain of south-eastern Australia. *Aust. J. agric. Res.* **1**: 231–52.

——— (1956). Parna, an aeolian clay. *Aust. J. Sci.* **18**: 145–51.

——— (1958). Depositional systems of the Riverine Plain of south-eastern Australia in relation to soils. *CSIRO Aust., Soil Publication* **10**.

——— (1967). Soil periodicity in relation to landform development in south-eastern Australia. In *Landform Studies from Australia and New Guinea* ed. J. N. Jennings and J. A. Mabbutt. Canberra, A.N.U. Press. pp. 231–55.

Butler, G. W., Steemers, M. A. Th., and Wong, E. (1967). The effect of nitrogen, phosphorus, and potassium supply on the isoflavone content of leaves of red clover (*Trifolium pratense* L.). *N.Z. Jl agric. Res.* **10**: 312–15.

Button, J. A. (1963a). Control of the webworm. *Dep. Agric. West. Aust. Bull.* **3174**.

——— (1963b). The webworm. *Dep. Agric. West. Aust. Bull.* **3175**.

Byrne, P. F. (1968). An evaluation of different stocking rates of merino sheep. *Comm. Aust. Bur. Agric. Econ. Wool Economic Research Report* **13**: 1–75.

Byth, D. E. (1964). Breeding system and chromosome number in *Lotononis bainesii* Baker. *Nature, Lond.* **202**: 830–1.

Calaby, J. H. (1963). Australia's threatened mammals. *Wildlife* **1**: 15–18.

Callaghan, A. R. (1939). Cropping results for the 1937 season at Roseworthy Agricultural College. *J. Dep. Agric. S. Aust.* **42**: 558–73.

Cameron, D. F. (1965). Variation in flowering time and in some growth characteristics of Townsville lucerne

(*Stylosanthes humilis*). *Aust. J. exp. Agric. Anim. Husb.* **5**: 49–51.

——— (1967a). Flowering in Townsville lucerne (*Stylosanthes humilis*). II. The effect of latitude and time of sowing on the flowering time of single plants. *Aust. J. exp. Agric. Anim. Husb.* **7**: 495–500.

——— (1967b). Flowering time and the natural distribution and dry matter production of Townsville lucerne (*Stylosanthes humilis*) populations. *Aust. J. exp. Agric. Anim. Husb.* **7**: 501–8.

——— (1967c). *Stylosanthes* species. *CSIRO Aust., Div. Trop. Past., Annual Report 1966–7.* pp. 98–101.

——— (1967d). Chromosome number and morphology of some introduced *Stylosanthes* species. *Aust. J. agric. Res.* **18**: 375–9.

——— (1968). *Stylosanthes* species. *CSIRO Aust., Div. Trop. Past., Annual Report 1967–8.* pp. 101–3.

Cameron, D. G. (1959). Grasses tested for soil conservation. Results to April 1958. *J. Soil Conserv. Serv. N.S.W.* **15**: 189–202.

Campbell, K. O. (1964). An assessment of the case for irrigation development in Australia. In *Water resources, use and management.* Melbourne, Melbourne University Press. pp. 450–7.

Campbell, M. H. (1960a). Identification of serrated tussock. *Agric. Gaz. N.S.W.* **71**: 561–73.

——— (1960b). Only well managed sown pastures provide permanent tussock control. *Agric. Gaz. N.S.W.* **71**: 9–19.

——— (1963). The use of the chisel plough and improved pastures for controlling serrated tussock. *Aust. J. exp. Agric. Anim. Husb.* **3**: 329–32.

——— (1968). Establishment, growth and survival of six pasture species surface sown on unploughed land infested with serrated tussock (*Nassella trichotoma*). *Aust. J. exp. Agric. Anim. Husb.* **8**: 470–7.

——— and Annand, A. M. (1962). The effect of herbicides and burning treatments in killing serrated tussock (*Nassella trichotoma* (Nees) Hack.). *Aust. J. exp. Agric. Anim. Husb.* **2**: 35–9.

Cariss, H. G. and Quinlivan, B. J. (1967). Serradella. *J. Agric. West. Aust.* **8**: 226–34.

Carn, K. G. (1938). Non-edible scrubs. *Agric. Gaz. N.S.W.* **49**: 124–7.

Carne, P. B. (1956). An ecological study of the pasture scarab *Aphodius howitti* Hope. *Aust. J. Zool.* **4**: 259–314.

Carraill, R. M. (1967). The beef cattle industry of southern Australia. *World Rev. Anim. Prod.* **111**: 39–44.

Carrington, D. L. (1963). Prospects of the fat lamb industry. *Q. Rev. agric. Econ.* **16**: 155.

Carter, E. D. (1958). Fertiliser investigations with special reference to phosphate use on the lateritic soils of Kangaroo Island. *Proc. Aust. Agrostology Conference* **1**: 33 (1–15).

Carter, E. P. and Wegg, P. M. (1963). Pasture establishment on problem soils of Kangaroo Island. *J. Dep. Agric. S. Aust.* **66**: 464–75.

Cashmore, A. B. (1938). Cape tulip, *Homeria collina* Vent. var. *aurantiaca* Sweet. Life History Studies. *J. Coun. scient. ind. Res. Aust.* **11**: 233–8.

Cass Smith, W. P. and Goss, Olga M. (1958). A method of inoculating and lime-pelleting leguminous seeds. *J. Agric. West. Aust.* **7** (3rd Ser.): 119–21.

——— and Holland, A. A. (1958). The effect of soil fungicides and fumigants on the growth of subterranean clover on new light land. *J. Agric. West. Aust.* **7** (3rd Ser.): 225–31.

Cassidy, G. J. (1968). Dairy pastures in Queensland. Advisory Leaflet **950**. Division of Plant Industry, Department of Primary Industries, Queensland.

Cassidy, P. A. and Burns, E. O. (1965). Economic investigation of dairying practices, Wide Bay area. Interim Report 3. *Dryland tropical pastures.* Department of Primary Industries, Queensland. Mimeo.

Chapman, R. E. and Short, B. F. (1964). Crimp in wool: growth characteristics of well-crimped and abnormally crimped fibres. *Aust. J. biol. Sci.* **17**: 771–91.

Chatel, D. L., Greenwood, R. M., and Parker, C. A. (1968). Saphrophytic competence as an important character in the selection of Rhizobium for inoculation. *Ninth International Congress of Soil Science*, Adelaide. **11**: 65–73.

Chester, R. D. (1952). Some problems of beef cattle production. *Aust. vet. J.* **28**: 273–87.

Chippindall, Lucy K. A. (1955). The grasses and pastures of South Africa. I. A guide to the identification of grasses in South Africa. Parov, Cape Province, Central Newsagency. pp. 412–14.

Christian, C. S., Noakes, L. C., Perry, R. A., Slatyer, R. O., Stewart, G. A., and Traves, D. M. (1954). Survey of the Barkly region, Northern Territory and Queensland, 1947–8. *CSIRO Aust., Land Res. Ser.* **3**.

———, Paterson, S. J., Perry, R. A., Slatyer, R. O., Stewart, G. A., and Traves, D. M. (1953). Survey of the Townsville–Bowen region, North Queensland, 1950. *CSIRO Aust., Land Res. Ser.* **2**.

——— and Shaw, N. H. (1951). Protein status of Australian tropical and sub-tropical pastures. *Proc. Spec. Conf. Agric. Comm. Sci. Off. Conf. Aust. 1949*, London, H.M.S.O. pp. 225–40.

——— and ——— (1952). A study of two strains of Rhodes grass (*Chloris gayana* Kunth) and of lucerne (*Medicago sativa* L.) as components of a mixed pasture at Lawes in south-east Queensland. *Aust. J. agric. Res.* **3**: 277–99.

——— and Stewart, G. A. (1953). General report on survey of Katherine–Darwin region, 1946. *CSIRO Aust., Land Res. Ser.* **1**.

——— and ——— (1954). The land-use groups of the Barkly region. *CSIRO Aust., Land Res. Ser.* **3**: 150–80.

Churchward, H. M. (1963). Soil studies at Swan Hill, Victoria. IV. Ground surface history and its expression in the array of soils. *Aust. J. Soil Res.* **1**: 242–55.

Clark, D. P. (1965). On the sexual maturation, breeding, and oviposition behaviour of the Australian plague locust (*Chortoicetes terminifera* Walk.). *Aust. J. Zool.* **13**: 17–45.

——— (1967). A population study of *Phaulacridium vittatum* Sjost. (Acrididae). *Aust. J. Zool.* **15**: 799–872.

Clark, L. R. (1947). An ecological study of the Australian plague locust (*Chortoicetes terminifera* Walk.) in the Bogan–Macquarie outbreak area, N.S.W. *Coun. scient. ind. Res. Aust. Bull.* **226**.

Clark, N. T. (1965). A comparison of the reproductive performance of ewes grazing Dwalganup or Bacchus Marsh subterranean clover or a mixture of lucerne and burr medic before and during mating. *Aust. J. exp. Agric. Anim. Husb.* **5**: 106–9.

Clements, F. W. (1960). Naturally occurring goitrogens. *Br. med. Bull.* **16**: 133–7.

Clinton, B. H. (1968). Grazing management of lucerne. *Agric. Gaz. N.S.W.* **79**: 282–6.

Coaldrake, J. E. (1951). The climate, geology, soils and plant ecology of portion of the County of Buckingham (Ninety-Mile Plain), South Australia. *CSIRO Aust., Bull.* **266**.

——— (1961). Ecosystem of the coastal lowlands ('Wallum') of southern Queensland. *CSIRO Aust., Bull.* **283**.

——— (1964). The sub-tropical environment of eastern Australia: *In* Some concepts and methods in sub-tropical pasture research. *Commw. Bur. Past. Fld Crops, Bull.* **47**.

——— (1967a). *CSIRO Aust., Div. Trop. Past., Annual Report 1966–7.*

——— (1967b). Depth of ploughing in relation to depth of suckering and soil type in the control of root suckers of brigalow (*Acacia harpophylla*). *Aust. J. exp. Agric. Anim. Husb.* **7**: 523–7.

——— and Russell, M. J. (1965). *CSIRO Aust., Div. Trop. Past., Annual Report 1964–5.*

——— and Smith, C. A. (1967). Estimates of animal production from pastures on brigalow land in the Fitzroy Basin, Queensland. *J. Aust. Inst. agric. Sci.* **33**: 52–4.

———, Smith, C. A., Yates, J. J., and Edye, L. A. (1969). Animal production on sown and native pastures on brigalow land in southern Queensland during drought. *Aust. J. exp. Agric. Anim. Husb.* **9**: 47–56.

Cocks, P. W. (1965). Diquat dibromide as a chemical aid to pasture establishment in the lower south-east of South Australia. *Aust. J. exp. Agric. Anim. Husb.* **5**: 203–7.

Cockcroft, B. (1965). Pedology of the Goulburn Valley Area Victoria. *Tech. Bull. Dep. Agric. Vict.* **19**.

Cole, M. M. (1961). *South Africa.* London, Methuen. Fig. 37, p. 61.

Coleman, R. G. (1964). Frosts and low night temperatures as limitations to pasture development in sub-tropical eastern Australia. *CSIRO Aust., Div. Trop. Past., Tech. Pap.* **3**.

Collins, F. V. (1939). Miscellaneous notes and queries on meat inspection in South Australia. *Aust. vet. J.* **15**: 94–103.

Colman, R. L. (1966). Growth curve studies on Kikuyu grass. *Wollongbar agric. Res. Stn, N.S.W., Annual Report 1965–6.* p. 15.

———, Holder, J. M., and Swain, F. G. (1966). Production from dairy cattle on improved pasture in a sub-tropical environment. *Proc. 10th Int. Grassld Congr.*: 499–503.

——— and Wilson, G. P. M. (1960). The effect of floods on pasture plants. *Agric. Gaz. N.S.W.* **71**: 337–47.

Common, I. F. B. (1948). The yellow-winged locust, *Gastrimargus musicus* Fabr., in central Queensland. *Qd J. agric. Sci.* **5**: 153–219.

——— (1954). A study of the ecology of the adult bogong moth, *Agrotis infusa* (Boisd.) (Lepidoptera: Noctuidae), with special reference to its behaviour during migration and aestivation. *Aust. J. Zool.* **2**: 223–63.

Condon, R. W. (1961a). Soils and land forms of the Western Division of N.S.W. *J. Soil Conserv. Serv. N.S.W.* **17**: 31–46.

——— (1961b). Erosion and management problems in western N.S.W. *J. Soil Conserv. Serv. N.S.W.* **17** 86–102.

——— (1968). The determination of grazing capacity on arid grazing lands. CSIRO Aust., Symposium *Land Evaluation*, Canberra, Macmillan.

——— and Stannard, M. E. (1956). Erosion in western New South Wales. Part I. A general description of the western division. *J. Soil Conserv. Serv. N.S.W.* **12**: 192–202.

Conroy, H. L. and Krumpholcz (1964). The prospects for mutton. *Qd Rev. agric. Econ.* **17**: 55.

Cook, L. J. (1930). Pastures and pasture management. *J. Dep. Agric. S. Aust.* **34**: 348–54.

——— (1939). Further results secured in 'top dressing' poor south-eastern lands with phosphatic fertilisers. *J. Dep. Agric. S. Aust.* **42**: 791–808, 851–66.

——— (1948). Lucerne on the red sand soils at Wokurna, 1937–48. *J. Dep. Agric. S. Aust.* **52**: 164–9.

Coop, I. E. and Blakley, R. L. (1949). Metabolism and toxicity of cyanides and cyanogenetic glucosides in sheep. I. Activity in the rumen. *N.Z. Jl Sci. Technol. A.* **30**: 277–91.

Cooper, J. P. (1966). The significance of genetic variation in light interception and conversion for forage-plant breeding. Proc. 10th Int. Grassld Congr.: 715–20.

Costin, A. B. (1954). *A study of the ecosystems of the Monaro region of N.S.W.* Sydney, Government Printer.

——— (1959). Vegetation of high mountains in Australia in relation to land use. *Biogeography and Ecology in Australia* (Series Monographiae Biologicae) **8**: 427–51.

——— (1966). Problems and practice of nature conservation in subalpine and alpine ecosystems of Australia. *Proc. 11th Pac. sci. Congr.*

——— (1967). Management opportunities in Australian high mountain catchments. In *International Symposium on Forest Hydrology* ed. W. E. Sopper and H. W. Lull. London, Pergamon. pp. 565–77.

Cotsell, J. C. (1958). Sheep investigations at Shannon Vale nutrition station with special reference to strategic stocking. *Proc. Aust. Soc. Anim. Prod.* **1**: 24–32.

Cowdrey, W. A. R. (1960). Growing Glycine for feed in the lower Burdekin. *Qd agric. J.* **86**: 677–80.

Cox, W. J. (1968). Rates of superphosphate for cereal grain production in the under 20 inch rainfall areas. *J. Agric. West. Aust.* **9**: 97–100.

Craft, F. A. (1928). The physiography of the Wollondilly River Basin. *Proc. Linn. Soc. N.S.W.* **53**: 618–50.

——— (1933a). The surface history of Monaro, N.S.W. *Proc. Linn. Soc. N.S.W.* **58**: 229–44.

——— (1933b). The coastal tablelands and streams of New South Wales. *Proc. Linn. Soc. N.S.W.* **58**: 437–60.

Crawford, E. J. (1962). Barrel 173—A new strain of medic for the wheatbelt. *J. Dep. Agric. S. Aust.* **65**: 214–21.

Crocker, R. L. (1944). Soil and vegetation relationships on the lower south-east of South Australia. *Trans. R. Soc. S. Aust.* **68**: 144–72.

——— (1946a). An introduction to the soils and vegetation of Eyre Peninsula, South Australia. *Trans. R. Soc. S. Aust.* **70**: 83.

——— (1946b). The Simpson Desert expedition, 1939. Scientific Reports No. 8—The soils and vegetation of the Simpson Desert and its borders. *Trans. R. Soc. S. Aust.* **70**: 235–58.

Crofts, F. C. (1959). The commercial use of nitrogenous fertilisers and autumn sown oats for the production of winter dairy forage. *Report* **4**. University of Sydney, School of Agriculture.

——— (1965). The effect of nitrogen fertiliser on the seasonal production of an irrigated ryegrass-clover pasture at Badgery's Creek. *Aust. J. exp. Agric. Anim. Husb.* **5**: 417–22.

———, Geddes, H. G., and Carter, O. G. (1963). Water harvesting and planned pasture production at Badgery's Creek. *Report* **6**. University of Sydney, School of Agriculture.

Croker, K. P. (1968). Lamb mortality on agricultural research station. *J. Agric. West. Aust.* **9**: 51–5.

Cross, F. C. (1965). Agriculture in South Australia. The central district. *J. Dep. Agric. S. Aust.* **69**: 116–30.

Culey, Alma G. (1961). *Bibliography of beef production in Australia* (*c. 1930–58*). CSIRO Aust., Div. Anim. Health.

——— (1965). *Bibliography of beef production in Australia (Supplement 1959–63)*. CSIRO Aust., Div. Anim. Health.

Cullity, M. (1966). Stocking rates with growing cattle at Wokalup Research Station. *J. Agric. West. Aust.* **7**: 98–105.

——— and Elliot, H. G. (1949). Fertiliser trials on annual pasture. Wokalup Research Station. *J. Dep. Agric. West. Aust.* **26**: 266–79.

Culvenor, C. C. J., Dal Bon, R., and Smith, L. W. (1964). The occurrence of indolealkylamine alkaloids in *Phalaris tuberosa* L. and *P. arundinacea* L. *Aust. J. Chem.* **17**: 1301–4.

Cumming, J. N. (1966). The effects of the 1965–6 drought on sheep numbers, and the expected rate of recovery. *Qd Rev. agric. Econ.* **19**: 169.

Cunningham, I. J. (1960). Molybdate topdressing and animal health. *N.Z. Jl Agric.* **100**: 419–28.

——— and Hartley, W. J. (1959). Rye grass staggers. *N.Z. vet. J.* **7**: 1–7.

Cuthbertson, E. G. (1951). Studies of galvanised burr. 1. Effectiveness of chlorinated phenoxyacetic acid derivatives as controlling agents. *J. Aust. Inst. agric. Sci.* **17**: 199–202.

Daday, H., Peak, J. W., Lainders, T., Cameron, D. G., Campbell, G. B., Crawford, E. J., and Ryan, F. E. (1968). Seasonal growth of an Australian cultivar of creeping rooted lucerne (*Medicago sativa*). *Aust. J. exp. Agric. Anim. Husb.* **8**: (34) 548–54.

Dairy Industry Committee of Enquiry (1960). *Report.* Canberra, Government Printer.

Dann, P. R. (1960). Pastures for the south-west wheat belt. *Agric. Gaz. N.S.W.* **71**: 373–84.

Davenport, N. (1957). More efficient use of pasture for summer grazing. *J. Agric. West. Aust.* **6**: 393–411.

——— (1967). A measure of clover infertility in ewes. *J. Agric. West. Aust.* **8**: 83–8.

Davidson, B. R. (1967). The economic structure of Australian farms. In *Agriculture in the Australian Economy* ed. D. B. Williams. Sydney, Sydney University Press.

Davidson, Dorothy E. (1966). Five new pasture plants for Queensland. *Qd agric. J.* **92**: 460–6.

Davidson, J. L. and Philip, J. R. (1958). Light and pasture growth. In *Climatology and Micrometeorology. Proc. Canberra Symp.* Paris, UNESCO.

Davidson, J. R. (1964). Species and strain production under irrigation at Deniliquin. Results from field trials 1958–60. *CSIRO Aust., Fld stn rec.* **3**(1): 1–12.

——— and Quirk, J. P. (1961). The influence of dissolved gypsum on pasture establishment on irrigated sodic clays. *Aust. J. agric. Res.* **12** (1): 100–10.

Davies, E. B. and Watkinson, J. H. (1966). Uptake of native and applied selenium by pasture species. I. Uptake of Se by browntop, ryegrass, cocksfoot and white clover from Atiamuri sand. *N.Z. Jl agric. Res.* **9**: 317–27.

Davies, H. L. (1962). Studies on time of lambing in relation to stocking in south-western Australia. *Proc. Aust. Soc. Anim. Prod.* **4**: 113–20.

——— (1964). Lambing losses in south-western Australia. *Proc. Aust. Soc. Anim. Prod.* **5**: 107–12.

——— (1968). Studies in pasture management for the breeding ewe. I. Effects on ewe liveweights, evidence of pregnancy toxaemia, lamb birth weights, and neonatal mortality. *Aust. J. agric. Res.* **19**: 605–20.

——— and Bennett, D. (1962). Studies on the oestrogenic potency of subterranean clover (*Trifolium subterraneum* L.) in south-western Australia. *Aust. J. agric. Res.* **13**: 1030–40.

——— and Dudzinski, M. L. (1965). Further studies on oestrogenic activity in strains of subterranean clover (*Trifolium subterraneum* L.) in south-western Australia. *Aust. J. agric. Res.* **16**: 937–50.

——— and Humphries, A. W. (1965). Stocking rate and wool production at Kojonup. 1. Wether sheep. *J. Agric. West. Aust.* **6**: 409–13.

Davies, J. G. (1946). A note on pasture management. *Coun. scient. ind. Res. Aust., Bull.* **201**: 97–104.

——— (1951). Contributions of agricultural research in pastures. *J. Aust. Inst. agric. Sci.* **17**: 54–66.

——— and Andrew, C. S. (1964). Effects of pastures on soil fertility. Paper to ANZAAS.

——— and Edye, L. A. (1959). *Sorghum almum* Parodi—a valuable summer-growing perennial grass. *J. Aust. Inst. agric. Sci.* **25**: 117–27.

——— and Eyles, A. G. (1965). Expansion of Australian pastoral production. *J. Aust. Inst. agric. Sci.* **31**: 77–93.

——— and Shaw, N. H. (1964). General objectives and concepts. *In* Some concepts and methods in subtropical pasture research. *Comm. Bur. Past. Fld Crops, Bull.* **47**: 1–9.

Davies, J. L. (1959). High level erosion surfaces and landscape development in Tasmania. *Aust. Geog.* **7**: 193–203.

——— ed. (1965). *Atlas of Tasmania.* Hobart, Lands and Surveys Department.

——— (1967). Tasmanian landforms and quaternary climates. In *Landform Studies from Australia and New Guinea* ed. J. N. Jennings and J. A. Mabbutt. Canberra, A.N.U. Press. pp. 1–25.

Davies, S. J. J. F. (1968). Aspects of a study of emus in semi-arid Western Australia. *Proc. ecol. Soc. Aust.* **3**: 160–6.

Davis, G. K. (1950). The influence of copper on the metabolism of phosphorus and molybdenum. In *Copper Metabolism: A Symposium on Animal Plant and Soil Relationships* ed. W. D. McElroy and B. Glass. Baltimore, Johns Hopkins University Press. pp. 216–29.

Dawbarn, M. C. and Farr, F. C. (1932). Variations in the dry weight and iodine content of the thyroid glands of sheep under uniform and varying conditions. *Aust. J. exp. Biol. med. Sci.* **10**: 119–42.

De Ley, J. and Rassel, A. (1965). DNA base composition, flagellation and taxonomy of the genus Rhizobium. *J. gen. Microbiol.* **41**: 85–91.

Denton, D. A., Goding, J. R., McDonald, I. R., Sabine, R., and Wright, R. D. (1961). Adaptation of ruminant animals to variation of salt intake. *Proc. Teheran Symp. UNESCO: Arid Zone Res.* **14**: 193–8.

Dewey, D. W., Lee, H. J., and Marston, H. R. (1958). Provision of cobalt to ruminants by means of heavy pellets. *Nature, Lond.* **181**: 1367–71.

De Wit, C. T. (1959). Potential photosynthesis of a crop surface. *Neth. J. agric. Sci.* **7**: 141–9.

——— (1965). Photosynthesis of leaf canopies. *Institute for Biol. and Chem. Res. on Field Crops and Herbage, Wageningen. Agric. Res. Rep.* **663**.

Dexter, B. D. (1967). Flooding and regeneration of River Red Gum, *Eucalyptus camaldulensis* Dehn. *Bull. For. Commn Vic.* **20**.

Diatloff, A. (1968). Nodulation and nitrogen fixation in some Desmodium species. *Qd J. agric. Anim. Sci.* **25**: 165–7.

Dick, A. T. (1952). The effect of diet and of molybdenum on copper metabolism in sheep. *Aust. vet. J.* **28**: 30–3.

——— (1953). The control of copper storage in the liver of sheep by inorganic sulphate and molybdenum. *Aust. vet. J.* **29**: 233–9.

——— (1954). Studies on the assimilation and storage of copper in crossbred sheep. *Aust. J. agric. Res.* **5**: 511–44.

——— (1956). Molybdenum and copper relationships in animal nutrition. In *A Symposium on Inorganic Nitrogen Metabolism* ed. W. D. McElroy and B. Glass. Baltimore, Johns Hopkins University Press. pp. 445–73.

——— and Bull, L. B. (1945). Some preliminary observations on the effect of molybdenum on copper metabolism in herbivorous animals. *Aust. vet. J.* **21**: 70–2.

———, Dunn, A. T., Bull, L. B., and Culvenor, C. C. J. (1963). Vitamin B12 and the detoxification of hepatotoxic pyrrolizidine alkaloids in rumen liquor. *Nature, Lond.* **197**: 207.

———, Moore, C. W. E., and Bingley, J. B. (1953). The copper and molybdenum contents of some pasture species in the Murray Valley. *Aust. J. agric. Res.* **4**: 44–51.

Dirven, J. G. P. and Van Hoof, H. A. (1960). A destructive virus disease of Pangola grass. *Tijdschr. PlZiekt.* **66**: 344–9.

Dodd, A. P. (1927). The biological control of Prickly Pear. *Coun. scient. ind. Res. Aust. Bull.* **34**.

Dodson, M. E. (1959). Oxalate ingestion studies in the sheep. *Aust. vet. J.* **35**: 225–33.

Doing, H. (1966). A comparison of pasture-weed problems in temperate Australia and Europe. *J. Aust. Inst. agric. Sci.* **32**: 302–4.

———, Biddiscombe, E. F., and Knedlhans, S. (1969). Ecology and distribution of the *Carduus nutans* (nodding thistles) in Australia. *Vegetatio* **17**: 313–51.

Donald, C. M. (1959). The production and life span of seed of subterranean clover (*Trifolium subterreaneum* L.). *Aust. J. agric. Res.* **10**: 771–87.

——— (1960a). The influence of climatic factors on the distribution of subterranean clover in Australia. *Herb. Abstr.* **30**: 81–90.

——— (1960b). The impact of cheap nitrogen. *J. Aust. Inst. agric. Sci.* **26**: 319–38.

——— (1964). Phosphorus in Australian agriculture. *J. Aust. Inst. agric. Sci.* **30**: 75–105.

——— (1967). Innovation in agriculture. In *Agriculture in the Australian Economy* ed. D. B. Williams. Sydney, Sydney University Press.

——— and Neal Smith, C. A. (1937). Strain variation in subterranean clover (*Trifolium subterraneum* Linn.). *J. Coun. scient. ind. Res. Aust.* **10**: 277–90.

——— and Williams, C. H. (1954). Fertility and productivity of a podzolic soil as influenced by subterranean clover (*Trifolium subterraneum* L.) and superphosphate. *Aust. J. agric. Res.* **5**: 664–87.

Donaldson, L. E., Harvey, J. M., Beattie, A. W., Alexander, G. I., and Burns, M. A. (1964). Effects of copper and cobalt supplementation on the growth rate and fertility of shorthorn heifers in northern coastal Queensland. *Qd J. agric. Sci.* **21**: 167–79.

———, Ritson, J. B., and Copeman, D. B. (1967). The reproductive efficiency of several north Queensland beef herds. 1. Physiological and management factors and embrionic neonatal losses. *Aust. vet. J.* **43**: 1–6.

Douglas, N. J. and Luck, P. E. (1964). Farmer's guide to tropical pastures in S.E. Queensland. *Qd agric. J.* **90**: 583–94.

Downes, R. G. (1954). Cyclic salt as a dominant factor in the genesis of soils in south-eastern Australia. *Aust. J. agric. Res.* **5**: 448–64.

——— and Sleeman, J. R. (1953). The soils of the Macquarie region, N.S.W. *CSIRO Aust., Soils Publication* **4**.

Downes, R. W., Staples, I. B., Colman, P. H., and Pedley, L. (1967). The effect of daylength and temperature on the growth and reproduction of six strains of Townsville lucerne (*Stylosanthes humilis*). *Aust. J. exp. Agric. Anim. Husb.* **7**: 351–6.

Doyle, R. J., Parkin, R. J., Smith, J. A. C., and Gartrell, J. W. (1965). Molybdenum increases cereal yields on wheat-belt scrubplain. *J. Agric. West. Aust.* **6**: 699–703.

Drake, F. R. and Curnow, B. C. (1967). Sulphur in East Gippsland. *J. Agric. Vict. Dep. Agric.* **65**: 229–33.

——— and Kehoe, J. K. (1954a). Pasture and soil fertility investigations in East Gippsland. *J. Agric. Vict. Dep. Agric.* **52**.: 337–47.

——— and ——— (1954b). Subterranean clover; establishment on acid sandy soil in East Gippsland. *J. Agric. Vict. Dep. Agric.* **52**: 385–8.

Drake, K. P. and Kehoe, J. K. (1956). Potash and clover growth. *Proc. Aust. Plant Nutrition Conference* **1**: 58–64.

Drane, N. T. and Edwards, H. R. (1961). *The Australian Dairy Industry—An Economic Study.* Melbourne, Cheshire.

Dunne, T. C. (1938). *Pasture development in Western Australia: 1931–1936.* Perth, Government Printer.

——— (1955). Potassium for pastures. *J. Agric. West. Aust.* **4**: 607–8.

——— and Elliot, H. G. (1950). Zinc fertilizers for subterranean clover at Kenderup. *J. Dep. Agric. West. Aust.* **27**: 115–17.

———, Smith, S. T., and Carriss, H. G. (1949). Responses of oats to zinc, phosphate and copper on newly cleared light land in Western Australia. *J. Dep. Agric. West. Aust.* **26**: 75–82.

——— and Throssell, G. L. (1948). Responses of wheat to copper and zinc at Dongara. *J. Dep. Agric. West. Aust.* **25**: 43–6.

Du Toit, P. J., Malan, A. I., and Roussouw, S. D. (1930). Studies in mineral metabolism. XII. Phosphorus in the sheep industry. Preliminary report. *Rep. vet. Res. Un. S. Afr.* **16**: 313–26.

Ealey, E. H. M. (1968). Ecology of the euro, *Macropus robustus* (Gould) in north-western Australia. I–IV. *CSIRO Wildl. Res.* **12**: 9–80.

——— and Richardson, T. M. (1960). A successful campaign against the euro. *J. Agric. West. Aust.* **1**: 3–11.

Edye, L. A. (1966). Grasses. *CSIRO Aust., Div. Trop. Past., Annual Report 1965–6.* p. 87.

——— (1967). Yield comparisons of thirty-eight introductions of *Glycine javanica* in swards in three environments. *Aust. J. exp. Agric. Anim. Husb.* **7**: 342–50.

——— and Haydock, K. P. (1967). Breeding creeping-rooted lucerne for the subtropics. *Aust. J. agric. Res.* **18**: 891–901.

———, Humphreys, L. R., Henzell, E. F., and Teakle, L. J. H. (1964). Pasture investigations in the Yalleroi district of Central Queensland. Queensland University Department of Agriculture. *Pap.* **1** (4): 133–72.

——— and Kiers, H. J. (1966). Variation in maturity, stolon development, and frost resistance of *Glycine javanica. Aust. J. exp. Agric. Anim. Husb.* **6**: 380–7.

Elder, R. J. (1965). Webworms damage northern tablelands pasture. *Qd agric. J.* **91**: 566–8.

Elliott, N. M. (1966). The effect of paddock size on animal production. *Proc. Aust. Soc. Anim. Prod.* **6**: 177–8.

Evans, T. R. (1967a). Primary evaluation of grasses and legumes for the northern Wallum of south-east Queensland. *Trop. Grassld.* **1**: 143–52.

——— (1967b). A salinity problem in pasture establishment in the coastal lowlands of southern Queensland. *J. Aust. Inst. agric. Sci.* **33**: 216–18.

——— (1969). Beef production from nitrogen fertilised Pangola grass (*Digitaria decumbens*) on the coastal lowlands of southern Queensland. *Aust. J. exp. Agric. Anim. Husb.* **9**: 282–86.

Everist, S. L. (1935). Inland pastures. Part II. Response during 1934 season of Mitchell and other grasses in western and central Queensland. *Qd agric. J.* **46**: 374–87.

——— (1949). Mulga (*Acacia aneura* F. Muell.) in Queensland. *Qd J. agric. Sci.* **6**: 87–139.

——— (1954). Control of woody plants. *Report Aust. Weed Control Conference.*

——— (1959). Strangers within the gates. *Qd Nat.* **16**: 49–60.

——— (1964). A review of poisonous plants of Queensland. *Proc. R. Soc. Qd* **74**: 1–20.

——— and Young, R. B. (1967). Fodder trees in sheep lands. *Qd agric. J.* **93**: 540–6.

Farmer, Joan N., Everist, S. L., and Moule, G. R. (1947). Studies in the environment of Queensland, Part I—The climatology of semi-arid pastoral areas. *Qd J. agric. Sci.* **4**: 20–59.

Fearn, J. T. (1966). Discussion of paper by Gallagher, Koch and Hoffman (1966). *Aust. vet. J.* **42**: 284–5.

Fels, H. E., Moir, R. J., and Rossiter, R. C. (1959). Herbage intake of grazing sheep in south-western Australia. *Aust. J. agric. Res.* **10**: 237–47.

——— and Neil, H. G. (1968). Effects on reproduction of prolonged grazing of oestrogenic pastures by ewes. *Aust. J. agric. Res.* **19**: 1059–68.

Fenner, F. and Ratcliffe, F. N. (1965). *Myxomatosis.* London, Cambridge University Press.

Fergus, I. F. (1962). The nutrient status of some soils of the brigalow lands. *CSIRO Aust., Div. Soils Report* **1/62**.

Ferguson, W. S., Lewis, A. H., and Watson, S. J. (1943). The teart pastures of Somerset. I. The cause and cure of teartness. *J. agric. Sci.* **33**: 44–51.

Fitzgerald, K. (1967). The Ord River catchment regeneration project. *J. Agric. West. Aust.* **8**: 446–52.

——— (1968). The Ord River regeneration project. 2. Dealing with the problem. *J. Agric. West. Aust.* **9**: 90–5.

Fitzpatrick, E. A. (1963). Estimates of pan evaporation from mean maximum temperature and vapour pressure. *J. appl. Met.* **2**: 780–92.

——— (1964). Seasonal distribution of rainfall in Australia analysed by Fourier methods. *Arch. Met. Geophys. Bioklim.* **13**: 270–86.

——— (1965a). Climate of the Tipperary area. *CSIRO Aust., Land Res. Ser.* **13**: 37–52.

——— (1965b). Climate in relation to pasture and crop growth. In *Climate—Fitzroy Region, Queensland.* Resources Series. Department of National Development, Canberra.

——— (1967a). Climate of the Nogoa–Belyando Area. *CSIRO Aust., Land Res. Ser.* **18**: 68–82.

——— (1967b). Climate of the Isaac–Comet area. *CSIRO Aust., Land Res. Ser.* **19**: 53–67.

——— (1968). Climate of the Dawson–Fitzroy area. *CSIRO Aust., Land Res. Ser.* **21**: 89–104.

——— and Arnold, Jennifer M. (1964). Climate of the west Kimberley area. *CSIRO Aust.' Land Res. Ser.* **9**: 76–102.

———, Slatyer, R. O., and Krishnan, A. I. (1967). Incidence and duration of periods of plant growth in central Australia as estimated from climatic data. *Agric. Met.* **4**: 389–404.

Fitzpatrick, E. N. (1957). Molybdenum for subterranean clover. *J. Agric. West. Aust.* **6**: 65–8.

——— (1958). Pasture development on peaty sands. *J. Agric. West. Aust.* **7**: 505–10.

——— (1961). Rock phosphate as a fertiliser. *J. Agric. West. Aust.* **2** (4th series): 459–60.

——— (1962). Trace elements for cereal crops and pastures. *J. Agric. West. Aust.* **3**: 323–7.

——— and Dunne, T. C. (1956). Potassium for subterranean clover. *J. Agric. West. Aust.* **5** (3rd Series): 321–6.

Flemons, K. F. and Whalley, R. D. (1958). Buffel grass (*Cenchrus ciliaris*). *Agric. Gaz. N.S.W.* **69**: 449–60.

Fletcher, I. C. and Geytenbeek, P. E. (1968). Effect of creep grazing on the growth rate of prime lambs. *Proc. Aust. Soc. Anim. Prod.* **7**: 106–9.

Foley, J. C. (1945). Frost in the Australian region. *Comm. met. Bur. Aust., Bull.* **32**.

Fox, N. F. and Wilson, R. G. (1959). Green panic and its use in pastures. *Qd agric. J.* **85**: 147–57.

Francis, C. M. (1968). 'Oestrogen Free' subterranean clovers—their development and prospects. *J. Agric. West. Aust.* **9**: 152–4.

——— and Millington, A. J. (1965a). Isoflavone mutations in subterranean clover. 1. Their production, characteristics and inheritance. *Aust. J. agric. Res.* **16**: 565–73.

——— and ——— (1965b). Varietal variation in the isoflavone content of subterranean clover: its estimation by a microtechnique. *Aust. J. agric. Res.* **16**: 557–64.

——— and ——— (1965c). Wether bioassay of annual pasture legumes. IV. The oestrogenic activity of annual medic pastures. *Aust. J. agric. Res.* **16**: 927–35.

———, ———, and Bailey, E. T. (1967). The distribution of oestrogenic isoflavones in the genus *Trifolium*. *Aust. J. agric. Res.* **18**: 47–54.

Francis, W. D. (1929). *Australian rain-forest trees.* Brisbane, Government Printer.

Frankel, O. H. (1954). Invasion and evolution of plants in Australia and New Zealand. *Caryologia* **6** (Suppl.): 600–19.

Franklin, M. C. (1961). The cattle industry. In *The development of northern Australia.* Sydney, University of New South Wales. pp. 58–79.

——— (1962). Drought. In *The simple fleece* ed. A. Barnard. Melbourne, Melbourne University Press.

———, Reid, R. L., and Johnstone, I. L. (1948). Studies on dietary and other factors affecting the serum-calcium levels of sheep. *Comm. scient. ind. Res. Org., Bull.* **240**.

Freer, M. (1959). Utilization of irrigated pastures by dairy cows. I. Comparison of rotational and strip grazing. *J. agric. Sci.* **52**: 129–36.

French, M. H. (1957). Nutritional value of tropical grasses and fodders. *Herb. Abstr.* **27**: 1–9.

French, R. J., Matheson, W. E., and Clarke, A. L. (1968). Soils and agriculture of the northern and Yorke Peninsula regions of South Australia. *Bull. Dep. Agric. S. Aust.*

Fricke, E. F. (1945a). Molybdenum deficiency in the North East. *Tasm. J. Agric.* **16**: 1–4.

——— (1945b). Molybdenum trials on pastures in north western districts. *Tasm. J. agric.* **16**: 109–11.

Frith, H. J. (1964). Mobility of the red kangaroo *Megaleia rufa.* *CSIRO Aust., Wildl. Res.* **9**: 1–19.

Fulmer, H. L. (1918). Influence of carbonates of magnesium and calcium on bacteria of certain Wisconsin soils. *J. agric. Res.* **12**: 463–504.

Gallagher, C. H. (1964). *Nutritional factors and enzymological disturbances in animals.* London, Crosby Lockwood & Son.

———, Koch, J. H., and Hoffman, H. (1966). Diseases of sheep due to ingestion of *Phalaris tuberosa. Aust. vet. J.* **42**: 279–84.

Galloway, R. W. (1963). Glaciation in the Snowy Mountains: a re-appraisal. *Proc. Linn. Soc. N.S.W.* **88** (2): 180–98.

——— (1967a). Geomorphology of the Nogoa–Belyando area. *CSIRO Aust., Land Res. Ser.* **18**: 97–114.

——— (1967b). Pre-basalt, sub-basalt and post-basalt surfaces of the Hunter Valley, New South Wales. In *Landform Studies from Australia and New Guinea* ed. J. N. Jennings and J. A. Mabbutt. Canberra, A.N.U. Press. pp. 293–314.

———, Gunn, R. H., and Story, R. Lands of the Mitchell-Normanby area, Queensland. *CSIRO Aust., Land Res. Ser.* **26** (in press).

Gardiner, M. R. (1963). A review of white muscle disease investigations in W.A. *J. Agric. West. Aust.* **4**: 633–8.

——— (1967). Lupinosis. *Adv. vet. Sci.* **11**: 85–138.

———, Armstrong, J., Fels, H., and Glencross, R. N. (1962). A preliminary report on selenium and animal health in Western Australia. *Aust. J. exp. Agric. Anim. Husb.* **2**: 261–9.

——— and Gorman, R. C. (1963). Further observations on plant selenium levels in Western Australia. *Aust. J. exp. Agric. Anim. Husb.* **3**: 284–9.

Gardner, C. A. (1944). The vegetation of Western Australia with special reference to the climate and soils. *J. R. Soc. West. Aust.* **28**: 11–87.

——— and Bennetts, H. W. (1956). *The Toxic Plants of Western Australia.* Perth, W.A. Newspapers Ltd.

Gartner, J. A. (1966). The effects of different rates of fertiliser nitrogen on the growth, nitrogen uptake and botanical composition of tropical grass swards. *Proc. 10th Int. Grassld Congr.*: 223–7.

Gartrell, J. W. (1966). Field responses of cereals to molybdenum. *Nature, Lond.* **209**: 1050.

Gates, C. T., Haydock, K. P., Claringbold, J. P., and Robins, M. F. (1966). Growth of Sorghum varieties of three Sorghum species at different levels of salinity. *Aust. J. exp. Agric. Anim. Husb.* **6**: 161–9.

———, Wilson, J. R., and Shaw, N. H. (1966). Growth and chemical composition of Townsville lucerne (*Stylosanthes humilis*). 2. Chemical composition, with special reference to cations, as affected by the principal constituent elements of molybdenised superphosphate. *Aust. J. exp. Agric. Anim. Husb.* **6**: 266–76.

Geddes, H. J. (1964). Water harvesting. In *Water Resources, Use and Management.* Melbourne, Melbourne University Press.

Gentilli, J. (1956). *Weather and climate in Western Australia.* 3rd rev. ed., Perth, W.A. Government Tourist & Publicity Bureau.

George, J. M. (1966). The use of an organic iodine preparation for controlling goitre in lambs born in winter, spring and summer. *Proc. Aust. Soc. Anim. Prod.* **6**: 403–4.

———, Farleigh, E. A., and Harris, A. N. A. (1966). Occurrence of goitre in summer born lambs of different breeds. *Aust. vet. J.* **42**: 1–4.

Gill, E. D. (1955). The Australian 'arid period'. *Aust. J. Sci.* **17**: 204–6.

Gillard, P. (1967). Coprophagous beetles in pasture ecosystems. *J. Aust. Inst. agric. Sci.* **33**: 30–4.

Gladstones, J. S. (1966). Naturalised subterranean clover (*Trifolium subterraneum* L.) in Western Australia: the strains, their distributions, characteristics, and possible origins. *Aust. J. Bot.* **14**: 329–54.

——— (1968). Pastures in Western Australia. In *Pasture improvement in Australia* (ed. B. Wilson), Sydney, Murray, pp. 210–36.

———, Leach, B. J., Drover, D. P., and Asher, C. J. (1964). Field studies on the potassium and phosphorus nutrition of lupins. *Aust. J. exp. Agric. Anim. Husb.* **4**: 158–64.

Godwin, K. O. and Fraser, F. J. (1966). Abnormal electrocardiograms, blood pressure changes, and some aspects of the histopathology of selenium deficiency in lambs. *Q. Jl exp. Physiol.* **51**: 94–102.

Gooding, C. D. (1963). Wallaby control in the Kimberleys. *J. Agric. West. Aust.* **4** (4th series): 607–9.

——— and Long, J. L. (1958). The Kimberley wallaby menace: water poisoning experiments 1955–7. *J. Agric. West. Aust.* **7** (3rd series): 173–8.

Goss, Olga M. and Shipton, W. A. (1965). Nodulation of legumes on new light land. 1. Survival of rhizobia on inoculated pelleted seed held for varying periods before sowing into dry soil. *J. Agric. West. Aust.* **6**: 616–21.

Graham, P. H. (1964). The application of computer techniques to the taxonomy of the root-nodule bacteria of legumes. *J. gen. Microbiol.* **35**: 511–17.

Gray, S. G. (1962). Hot water seed treatment for *Leucaena glauca* (L.) Benth. *Aust. J. exp. Agric. Anim. Husb.* **2**: 178–80.

——— (1967a). General and specific combining ability in varieties of *Leucaena leucocephala* (Lam.) De Wit. *Aust. J. agric. Res.* **18**: 71–6.

——— (1967b). Inheritance of growth habit and quantitative characters in intervarietal crosses in *Leucaena leucocephala* (Lam.) De Wit. *Aust. J. agric. Res.* **18**: 63–70.

——— (1967c). The components of variation in an intervarietal cross in *Leucaena leucocephala* (Lam.) De Wit. *Aust. J. agric. Res.* **18**: 77–83.

Green, R. J. (1956). Micronutrient deficiencies in sheep and cattle and their distribution in Tasmania. *J. Aust. Inst. agric. Sci.* **22**: 40–4.

Greenup, L. R. (1967). The Sitona weevil—a pest of lucerne (*Sitona humeralis*). *Agric. Gaz. N.S.W.* **78**: 528–9.

Greenwood, E. A. N., Davies, H. Lloyd, and Watson, E. R. (1967). Growth of an annual pasture on virgin land in south-western Australia including effect of stocking rate and nitrogen fertiliser. *Aust. J. agric. Res.* **18**: 447–59.

———, Goodall, D. W., and Titmanis, Z. V. (1965). A measurement of nitrogen deficiency in grass swards. *Pl. Soil* **23**: 97–116.

Gregory, C. M., Senior, B. R., and Galloway, M. C. (1967). The geology of the Connemara, Jundah, Canterbury, Windorah, and Adavale 1 : 250,000 sheet areas. Commonwealth Bureau of Mineral Resources.

Greig-Smith, R. (1899). The nodule organism of the Leguminosae. *Proc. Linn. Soc. N.S.W.* **24**: 653–73.

Griffiths, M. E. and Barton, A. A. (1966). The ontogeny of the stomach in the pouch young of the red kangaroo. *CSIRO Wildl. Res.* **11**: 169–86.

——— and Parker, R. D. (1966). The plants eaten by sheep and by kangaroos grazing together in a paddock in south-western Queensland. *CSIRO Wildl. Res.* **11**: 145–68.

Grof, B. (1957). Notes on Biloela buffel grass. *Qd agric. J.* **83**: 111–18.

——— (1961). Two pasture grasses show promise. *Qd agric. J.* **87**: 741–2.

——— (1967). Grass species sward trial. *Agrostology Tech. Annual Report 1967*, Queensland Department of Primary Industries, p. 10.

Gruen, F. H. (1953). Stocking rates in the Berriquin and Wakool irrigation districts. *Rev. Mktg agric. Econ.* **21**: 113–40.

——— *et al.* (1968). *Long term projections of agricultural supply and demand: Australia, 1965 to 1980.* U.S. Department of Agriculture, Economic Research Service.

———, Ward, L. E., and Powell, A. A. (1967). Changes in supply of agricultural products. In *Agriculture in the Australian Economy* ed. D. B. Williams. Sydney, Sydney University Press.

——— and Waring, E. J. (1958). A survey of small North Coast dairy farms. *Rev. Mktg agric. Econ.* **26**: 5.

Gunn, R. H. (1967). Soils of the Isaac-Comet area. *CSIRO Aust., Land Res. Ser.* **19**: 89–107.

———, Galloway, R. W., Pedley, L., and Fitzpatrick, E. A. (1967). Lands of the Nogoa-Belyando area, Queensland. *CSIRO Aust., Land Res. Ser.* **18**: 1–190.

Hacker, J. B. (1966). Cytological investigations in the *Setaria sphacelata* complex. *Aust. J. agric. Res.* **17**: 297–301.

——— (1967). The maintenance of strain purity in the *Setaria sphacelata* complex. *J. Aust. Inst. agric. Sci.* **33**: 265–7.

——— (1968). Polyploid structure in the *Setaria sphacelata* complex. *Aust. J. Bot.* **16**: 539–44.

Haigh, F. B. (1964). Irrigation potential and problems. In *Water Resources, Use and Management*. Melbourne, Melbourne University Press. pp. 21–35.

Hall, W. T. K. (1964). Plant toxicoses of tropical Australia. *Aust. vet. J.* **40**: 176–82.

Hallsworth, E. G., Robertson, Gwen K., and Gibbons, F. R. (1955). Studies in pedogenesis in New South Wales. VII. The gilgai soils. *J. Soil Sci.* **6**: 1–31.

Hamilton, D. (1968). Is it profitable to graze cattle and sheep together? *Pwr Fmg* **77**: 34–7.

——— and Ruth, G. (1968). Bloat on *Dolichos lablab*. *Trop. Grassld.* **2**: 135–6.

Harris, W. J. (1939). The physiography of the Echuca district. *Proc. R. Soc. Vict.* **51**: 45–60.

Hartley, W. (1949). Plant collecting expedition to subtropical South America 1947–48. *Coun. scient. ind. Res. Aust. Div. Pl. Ind. Divisional Report* **7**.

Hartley, W. J. (1963). Selenium and ewe fertility. *Proc. N.Z. Soc. Anim. Prod.* **23**: 20–7.

Harvey, J. M. (1952a). Copper deficiency in ruminants in Queensland. *Aust. vet. J.* **28**: 209–15.

——— (1952b). Chronic endemic fluorosis of Merino sheep in Queensland. *Qd J. agric. Sci.* **9**: 47–141.

——— (1953). Further studies of fluorosis in Merino sheep. *Qd J. agric. Sci.* **10**: 109-24.

Hastings, A. and Drake, A. D. (1960). Inoculation and pelleting of clover seed. *N.Z. Jl agric.* **101**: 619-21.

——— and ——— (1962). Further tests with materials for pelleting inoculated clover seeds. *N.Z. Jl Agric.* **104**: 331-3.

Hatch, M. D. and Slack, C. R. (1966). Photosynthesis by sugar-cane leaves. A new carboxylation reaction and the pathway of sugar formation. *Biochem. J.* **101**: 103-11.

———, ———, and Johnson, Hilary S. (1967). Further studies on a new pathway of photosynthetic carbon dioxide fixation in sugar-cane and its occurrence in other plant species. *Biochem. J.* **102**: 417-22.

Hayman, D. L. (1960). The distribution and cytology of the chromosome races of *Themeda australis* in southern Australia. *Aust. J. Bot.* **8**: 58-68.

Hays, J. (1967). Land surfaces and laterites in the north of the Northern Territory. In *Landform studies from Australia and New Guinea* ed. J. N. Jennings and J. A. Mabbutt. Canberra, A.N.U. Press. pp. 182-210.

Hayward, C. R. and Russell, J. S. (1967). Aspects of pasture growth on solodic soils—Property of Mr Hayward. *Trop. Grassld.* **1**: 203-5.

Heathcote, R. L. (1969). Land tenure systems in Australia's arid lands: past and present. In *Arid Lands of Australia*, ed. R. A. Perry and R. O. Slatyer. Canberra, A.N.U. Press.

Hegarty, M. P. and Pound, A. W. (1968). Indospicine, a new hepatotoxic amino-acid from *Indigofera spicata*. *Nature, Lond.* **217**: 354-5.

———, Schinckel, P. G., and Court, R. D. (1964). Reaction of sheep to the consumption of *Leucaena glauca* Benth. and to its toxic principle mimosine. *Aust. J. agric. Res.* **15**: 153-67.

Heinrichs, D. H. (1954). Developing creeping-rooted alfalfa for pasture. *Can. J. agric. Sci.* **34**: 269-80.

Hely, F. (1965). Survival studies with *Rhizobium trifolii* on seed of *Trifolium incarnatum* L. inoculated for aerial sowing. *Aust. J. agric. Res.* **16**: 575-89.

———, Bergersen, F. J., and Brockwell, J. (1957). Microbial antagonism in the rhizosphere as a factor in the failure of inoculation of subterranean clover. *Aust. J. agric. Res.* **8**: 24-44.

Henzell, E. F. (1962). Nitrogen fixation and transfer by some tropical and temperate pasture legumes in sand culture. *Aust. J. exp. Agric. Anim. Husb.* **2**: 132-40.

——— (1963). Nitrogen fertiliser responses of pasture grasses in south-eastern Queensland. *Aust. J. exp. Agric. Anim. Husb.* **3**: 290-9.

——— (1968). Sources of nitrogen for Queensland pastures. *Trop. Grassld.* **2**: 1-17.

———, Fergus, I. F., and Martin, A. E. (1966). Accumulation of soil nitrogen and carbon under a *Desmodium uncinatum* pasture. *Aust. J. exp. Agric. Anim. Husb.* **6**: 157-60.

——— and Oxenham, D. J. (1964). Seasonal changes in the nitrogen content of three warm-climate pasture grasses. *Aust. J. exp. Agric. Anim. Husb.* **4**: 336-44.

——— and Stirk, G. B. (1963). Effects of nitrogen deficiency and soil moisture stress on growth of pasture grasses at Samford, south-east Queensland. *Aust. J. exp. Agric. Anim. Husb.* **3**: 300-13.

Herd, R. P. (1961-2). Hypomagnesaemia in cattle. *Proc. Vict. vet. Soc.* 35-7.

——— (1966). Grass tetany in sheep. *Aust. vet. J.* **42**: 160-4.

——— and Peebles, R. M. (1962). Hypomagnesaemia and grass tetany in sheep. *Aust. vet. J.* **38**: 455-6.

———, Schuster, N., and Coltman, M. (1965). Prevention of hypomagnesaemia and grass tetany. *Aust. vet. J.* **41**: 142-6.

Hesketh, J. D. (1963). Limitations to photosynthesis responsible for differences among species. *Crop Sci.* **3**: 493-6.

Higgins, E. S., Richert, D. A., and Westerfeld, W. W. (1956). Molybdenum deficiency and tungstate inhibition studies. *J. Nutr.* **59**: 539-59.

Higgs, E. D. (1958). Choosing sub clover strains for your farm. *J. Dep. Agric. S. Aust.* **61**: 267-72.

——— and Burton, M. V. (1955). Land development on southern Yorke Peninsula. *J. Dep. Agric. S. Aust.* **59**: 114-21.

Highett, S. L. (1956). The influence of calcium, phosphorus, manganese and vitamin D on heifer fertility. *Proc. 3rd Int. Congr. Anim. Reprod.*: 116-23.

Hilder, E. J. (1954). Some aspects of sulphur as a nutrient for pastures in New England soils. *Aust. J. agric. Res.* **5**. 39-54.

——— (1956). Seasonal pasture production. *Proc. Aust. Soc. Anim. Prod.* **1**: 38-44.

——— (1964). The distribution of plant nutrients by sheep at pasture. *Proc. 5th Bienn. Conf. Aust. Soc. Anim. Prod.*: 241-2.

——— (1966). Rate of turnover of elements in soils: the effects of stocking rate. *Wool Technology and Sheep Breeding.* **13**: 11-16.

——— and Mottershead, B. E. (1963). The distribution of plant nutrients through free-grazing sheep. *Aust. J. Sci.* **26**: 88-9.

——— and Spencer, K. (1954). The influence of sulphur on a natural *Medicago* pasture. *J. Aust. Inst. agric. Sci.* **20**: 171-6.

Hills, E. S. (1953). The hydrology of arid and sub-arid Australia with special reference to underground water. In *Reviews of Research on Arid Zone Hydrology*. Paris, UNESCO. pp. 179-202.

——— (1956). A contribution to the morphotectonics of Australia. *J. geol. Soc. Aust.* **3**: 1-15.

Hingston, F. J. (1959). The loss of applied phosphorus and sulphur from soils under pasture in W.A. *J. Aust. Inst. agric. Sci.* **25**: 209-13.

Hoen, K. and Oram, R. N. (1967). Establishment of perennial pasture grasses under a cover crop in a Mediterranean type environment. *Aust. J. exp. Agric. Anim. Husb.* **7**: 241-8.

Holder, J. M. (1967). Milk production from tropical pastures. *Trop. Grassld.* **1**: 135-41.

Holland, A. A. (1962). The effects of indigenous saprophytic fungi upon nodulation and establishment of subterranean clover. In *Antibiotics in Agriculture* ed. M. Woodbine. London, Butterworths. pp. 147-64.

——— (1966). Studies on microbial antagonism in the establishment of clover pasture. 1. The number of species and percentage frequency of occurrence of the major fungi. *Pl. Soil* **25**: 238-48.

——— and Moore, C. W. E. (1962). The vegetation and soils of the Bollon district. *CSIRO Aust. Div. Pl. Ind., Tech. Pap.* **15**: 1–31.

——— and Parker, C. A. (1966). Studies on microbial antagonism in the establishment of clover pasture. II. The effect of saprophytic soil fungi upon *Rhizobium trifolii* and the growth of subterranean clover. *Pl. Soil* **25** (3): 329–40.

Hopkins, L. L., jr, Pope, A. L., and Baumann, C. A. (1964). Contrasting nutritional responses to vitamin E and selenium in lambs. *J. Anim. Sci.* **23**: 674–81.

Hopkirk, C. S. M. (1935). Staggers in livestock. *N.Z. Jl Agric.* **51**: 18–21.

Horrocks, D. (1964a). Sodium and potassium balances and growth on high and low sodium diets. I. The addition of sodium to a low energy hay diet. *J. agric. Sci.* **63**: 369–72.

——— (1964b). Sodium and potassium balances and growth on high and low sodium diets. II. The feeding of protein-rich concentrates in addition to sodium. *J. agric. Sci.* **63**: 373–5.

Hosking, W. J. (1957a). Trace elements in the West Gippsland region. *J. Agric. Vict. Dep. Agric.* **55**: 205–12.

——— (1957b). Pasture improvement in the Cockatoo–Yarra Junction area. *J. Agric. Vict. Dep. Agric.* **55**: 789–95.

——— (1965). Potash for pastures. *J. Agric. Vict. Dep. Agric.* **63**: 121–7.

——— *et al.* (1961). Pasture topdressing trials in South Gippsland; Toora series–1960. *J. Agric. Vict. Dep. Agric.* **59**: 382–4.

Hounam, C. E. (1963). Estimates of solar radiation over Australia. *Australian Meteorological Magazine* **43**: 1–14.

Hoveland, C. S. (1960). Sorghum grass and perennial sweet sorgrass for Alabama. *Auburn University agric. Exp. Stn Ala. Progress Report* **78**.

Hubble, G. D. (1954). Some soils of the coastal lowlands north of Brisbane, Queensland. 1. Morphology classification and chemical data. *CSIRO Aust., Div. Soils Divisional Report* **1/54**.

——— (1961). Soils. In *Introducing Queensland.* Brisbane, Government Printer. pp. 27–37.

——— (1964). The sub-tropical environment of eastern Australia—Soils. *In* Some concepts and methods of sub-tropical pasture research. *Comm. Bur. Past. Fld Crops Bull.* **47**.

Huffaker, C. B. (1967). A comparison of the status of biological control of St. John's wort in California and Australia. *Mushi* 39 (Suppl.): 51–73.

Hughes, J. D. and Searle, P. G. E. (1964). Observations of the residual value of accumulated phosphorus in a red loam. *Aust. J. agric. Res.* **15**: 377–83.

Hume, I. D., Somers, M., and McKeown, N. R. (1968). Nutritive evaluation of two strains of mature subterranean clover. *Aust. J. exp. Agric. Anim. Husb.* **8**: 295–300.

Humphreys, L. R. (1967a). Townsville lucerne: history and prospect. *J. Aust. Inst. agric. Sci.* **33**: 3–13.

——— (1967b). Buffel grass (*Cenchrus ciliaris*) in Australia. *Trop. Grassld.* **1**: 123–34.

——— and Robinson, A. R. (1966). Sub-tropical grass growth. I. Relationships between carbohydrate accumulation and leaf area in growth. *Div. Pl. Ind. Bull.* **354**. Queensland Department of Primary Industries.

Humphries, A. W. (1962). The growth of some perennial grasses in waterlogged soil. 1. The effect of waterlogging on the availability of nitrogen and phosphorus to the plant. *Aust. J. agric. Res.* **13**: 414–25.

Hurst, E. (1942). *The Poison Plants of N.S.W.* Sydney, N.S.W. Poison Plants Committee.

Hutchings, R. J. (1967). Factors affecting the establishment of spring-sown *Phalaris tuberosa*. *Aust. J. exp. Agric. Anim. Husb.* **7**: 255–8.

Hutchinson, R. J. (1966). A note on wool production responses to fodder conservation in pastoral systems. *J. Br. Grassld. Soc.* **21**: 303–4.

Hutton, E. M. (1960). Flowering and pollination in *Indigofera spicata, Phaseolus lathyroides, Desmodium uncinatum*, and some other tropical pasture legumes. *Emp. J. exp. Agric.* **28**: 235–43.

——— (1961). Inter-variety variation in Rhodes grass (*Chloris gayana* Kunth). *J. Br. Grassld Soc.* **16**: 23–9.

——— (1962). Siratro—a tropical pasture legume bred from *Phaseolus atropurpureus*. *Aust. J. exp. Agric. Anim. Husb.* **2**: 117–25.

——— (1965). A review of the breeding of legumes for tropical pastures. *J. Aust. Inst. agric. Sci.* **31**: 102–9.

——— and Beall, L. B. (1957). Root-knot nematode resistance in two pasture species of Phaseolus. *J. Aust. Inst. agric. Sci.* **23**: 158.

——— and Bonner, I. A. (1960). Dry matter and protein yields in four strains of *Leucaena glauca* Benth. *J. Aust. Inst. agric. Sci.* **26**: 276–7.

——— and Coote, J. N. (1966). Tannin content of some tropical legumes. *J. Aust. Inst. agric. Sci.* **32**: 139–40.

——— and Gray, S. G. (1959). Problems in adapting *Leucaena glauca* as a forage for the Australian tropics. *Emp. J. exp. Agric.* **27**: 187–96.

——— and ——— (1967). Hybridisation between the legumes *Desmodium intortum, D. uncinatum*, and *D. sandwicense*. *J. Aust. Inst. agric. Sci.* **33**: 122–3.

——— and Grylls, N. E. (1956). Legume 'little leaf' a virus disease of sub-tropical pasture species. *Aust. J. agric. Res.* **7**: 85–97.

——— and Guerassimoff, J (1966). Problems in breeding the legume *Indigofera spicata* for tropical pastures. *Euphytica* **15**: 353–61.

Hutton, J. T. and Leslie, T. I. (1958). Accession of non-nitrogenous ions dissolved in rain water to soils in Victoria. *Aust. J. agric. Res.* **9**: 492–507.

Isbell, R. F. (1957). The soils of the Inglewood–Talwood–Tara–Glenmorgan region, Queensland. Brisbane, Department of Public Lands *Tech. Bull.* **5**.

——— (1962). Soils and vegetation of the brigalow lands, eastern Australia. *CSIRO Aust., Soils and Land Use, Series* **43**.

———, Thompson, C. H., Hubble, G. D., Beckmann, G. G., and Paton, T. R. (1967). *Atlas of Australian soils. Sheet 4.* Brisbane–Charleville–Rockhampton–Clermont area. With explanatory data. Melbourne, CSIRO and Melbourne University Press.

———, Webb, A. A., and Murtha, G. G. (1968). *Atlas of Australian soils. Sheet 7.* North Queensland. With explanatory data. Melbourne, CSIRO and Melbourne University Press.

Jackson, E. A. (1957). Soil features in arid regions with particular reference to Australia. *J. Aust. Inst. agric. Sci.* **23**: 196–208.

——— (1962). Soil studies in central Australia: Alice Springs–Hermannsburg–Rodinga areas. *CSIRO Aust., Soil Publ.* **19**.

——— (1966). Phosphorus fertiliser research in Australia. *CSIRO Aust., Bull.* **284**.

James, J. W. (1960a). Erosion survey of the Paroo–Upper Darling region. Part II. Land form and soils. *J. Soil Conserv. Serv. N.S.W.* **16**: 41–53.

——— (1960b). Erosion survey of the Paroo–Upper Darling region. Part III. Vegetation and pastures. *J. Soil Conserv. Serv. N.S.W.* **16**: 185–206.

Jefferies, B. C. and Dreaver, R. W. (1962). Grazing management systems in fat lamb production. *Proc. Aust. Soc. Anim. Prod.* **4**: 109–12.

Jenkins, C. F. H. (1958). Insect pests and their control: pasture cockchafers. *Dep. Agric. West. Aust. Bull.* **2544**.

——— (1965). The black beetle. *Dep. Agric. West. Aust. Bull.* **3292**.

Jenkins, G. N. (1967). Fluoride. *Wld. Rev. Nutr. Diet.* **7**: 138–203.

Jennings, J. N. and Sweeting, M. M. (1963). The limestone ranges of the Fitzroy Basin, Western Australia. *Bonn. geogr. Abh. Heft* **32**.

Jensen, R. C. (1967). A review of the Australian dairying industry. *Lincoln College N.Z. Agricultural Economics Paper* **423**.

Jessup, R. W. (1951). The soils, geology, and vegetation of north-western South Australia. *Trans. R. Soc. S. Aust.* **74**: 189–273.

Johns, R. K. (1962). The sediments of the Lake Eyre basin, evaporites and brines, their constitution and age. *Geol. Surv. S. Aust. Rept. Invest.* **24**. Part 1: 1–69.

Johnson, R. W. (1962). Clearing the scrub. *Qd agric. J.* **88**: 736–50.

——— (1964). *Ecology and control of brigalow in Queensland.* Brisbane, Government Printer.

——— (1965). Influence of age and environment on control of brigalow. *Proc. 2nd Aust. Weeds Conf.* **1**: 2–5, 2–6.

Johnstone, R. N. (1933). Grass tetany. *J. Agric. Vict. Dep. Agric.* **31**: 396–7, 400.

Jones, R. J. (1964). East-African plants and research of potential value to Queensland. *J. Aust. Inst. agric. Sci.* **30**: 278.

——— (1965). The use of cyclodiene insecticides as liquid seed dressings to control bean fly (*Melanagromyza phaseoli*) in species of Phaseolus and *Vigna marina* in south eastern Queensland. *Aust. J. exp. Agric. Anim. Husb.* **5**: 458–65.

——— (1967). *CSIRO Aust., Div. Trop. Past. Annual Report 1966–7.* p. 42.

———, Griffiths Davies, J., and Waite, R. B. (1967). The contribution of some tropical legumes to pasture yields of dry matter and nitrogen at Samford, south-eastern Queensland. *Aust. J. exp. Agric. Anim. Husb.* **7**: 57–65.

———, ———, ———, and Fergus, I. F. (1968). The production and persistence of grazed irrigated pasture mixtures in south-eastern Queensland. *Aust. J. exp. Agric. Anim. Husb.* **8**: 177–89.

Jones, R. M. (1966). Scald reclamation studies in the Hay district. Part I. Natural reclamation of scalds. *J. Soil Conserv. Serv. N.S.W.* **22**: 147–60.

——— and Muirhead, W. A. (1966). Species trials in the semi-arid southwest of New South Wales. 1. Grasses and legumes. *J. Soil Conserv. Serv. N.S.W.* **22**: 102–11.

Jutson, J. T. (1934). The physiography (geomorphology) of Western Australia. *Bull. geol. Surv. West. Aust.* **95**.

Kawanabe, Sukeo (1968). Temperature responses and systematics of the Gramineae. *Proc. Jap. Soc. Plant Taxon.* **2**: 17–20.

Kehoe, J. K. and Curnow, B. C. (1963). Root growth of subterranean clover on some acid sandy soils in Victoria. *Aust. J. exp. Agric. Anim. Husb.* **3**: 11–16.

Kelly, J. H. (1952). Report on the beef cattle industry in northern Australia. *Bur. Agric. Econ. Aust.*

Kendrew, W. G. (1961). *The climates of the continents.* 5th ed. New York, Oxford University Press. p. 608.

Key, K. H. L. (1938). The regional and seasonal incidence of grasshopper plagues in Australia. *Coun. scient. ind. Res. Aust. Bull.* **117**.

King, D. (1960). The sand ridge deserts of South Australia and related aeolian landforms of the arid cycles. *Trans. R. Soc. S. Aust.* **83**: 99–108.

King, L. C. (1951). The cyclic land-surfaces of Australia. *Proc. R. Soc. Vict.* **62**: 79–95.

Kingsland, Alison M. (1950). An economic survey of the productivity of dairy farms on the red basaltic soils of the far north coast of New South Wales. *Rev. Mktg agric. Econ.* **18**: 95–120.

Kipps, E. H. (1947). The calcium/manganese ratio in relation to the growth of lucerne at Canberra, A.C.T. *J. Coun. scient. ind. Res. Aust.* **20**: 176–89.

Kirsch, J. A. W. and Poole, W. E. (1967). Serological evidence for speciation in the grey kangaroo *Macropus giganteus* Shaw 1790 (Marsupialia: Macropodidae). *Nature, Lond.* **215**: 1097–8.

Kleinig, C. R. (1965). Emergence of *Medicago tribuloides* on moderately acid soils. *Aust. J. agric. Res.* **16**: 311–19.

——— (1966). Mats of unincorporated organic matter under irrigated pastures. *Aust. J. agric. Res.* **17**: 327–33.

——— and Loveday, J. (1962). Responses of pasture legumes to zinc on calcareous soils in the Riverina N.S.W. *Aust. J. exp. Agric. Anim. Husb.* **2**: 228–90.

Knott, S. G. and McCray, C. W. R. (1959). Two naturally occurring outbreaks of selenosis in Queensland. *Aust. vet. J.* **35**: 161–5.

Kondos, A. C. and McClymont, G. L. (1967). Pharmacology and toxicology of carbon tetrachloride in the sheep. IV. Reduction and augmentation of toxicity by selenium. *Aust. J. agric. Res.* **18**: 667–82.

Koppen, W. (1931). *Grundriss der Klimakunde.* Berlin, Walter de Gruyter.

Kretschmer, A. E. (1965). *Stylosanthes humilis*, a summer-growing self-regenerating annual legume for use in Florida permanent pastures. *Proc. Soil Crop Sci. Soc. Fla.* **25**: 248–62.

——— (1966). Four years' results with Siratro (*Phaseolus atropurpureus* D.C.) in south Florida. *Proc. Soil Crop Sci. Soc. Fla.* **26**: 238–45.

Krishnaswamy, N. and Raman, V. S. (1953). Cytogenetical studies in the interspecific hybrid of *Pennisetum typhoides*, Stapf and Hubbard x *Pennisetum* *purpureum* Schumach. *Proc. 1st Scient. Workers Conf. Coimbatore 1951*: 43–71.

———, ———, and Chandrasekharan, P. (1956). An interspecific hybrid of grain sorghum and Johnson grass—*S. halepense* (2n = 20) × *S. roxburghii* (2n = 20). *Curr. Sci.* **25**: 195–7.

Kyneur, G. W. (1960). Glycine on the Atherton Tableland. *Qd agric. J.* **86**: 507–13.

Lange, R. T. (1961). Nodule bacteria associated with the indigenous Leguminosae of south-western Australia. *J. gen. Microbiol.* **26**: 351–9.

——— and Parker, C. A. (1960). The symbiotic performance of Lupin bacteria under glasshouse and field conditions. *Pl. Soil* **13** (2): 137–46.

Langford-Smith, T. (1960). The dead river systems of the Murrumbidgee. *Geogrl Rev.* **50**: 368–89.

——— and Dury, G. H. (1965). Distribution, character, and attitude of the duricrust in the northwest of New South Wales and the adjacent areas of Queensland. *Am. J. Sci.* **263**: 170–90.

Lavers, D. W. (1951). Grass tetany or oat tetany. *Qd agric. J.* **73**: 116–18.

Lee, H. J. (1951). Cobalt and copper deficiencies affecting sheep in South Australia. *J. Dep. Agric. S. Aust.* **54**: 475–90, 527–32.

——— (1956a). The toxicity of *Phalaris tuberosa* to sheep and cattle and the preventive role of cobalt. *Proc. 7th Int. Grassld. Congr.*: 387–95.

——— (1956b). The influence of copper deficiency on the fleeces of British breeds of sheep. *J. agric. Sci.* **47**: 218–23.

——— (1963). Cobalt deficiency. In *Animal Health, Production and Pasture* ed. A. N. Worden, K. C. Sellers, and D. E. Tribe. London, Longmans, Green. pp.662–80.

——— and Kuchel, R. E. (1953). The aetiology of phalaris staggers in sheep. I. Preliminary observations on the preventive role of cobalt. *Aust. J. agric. Res.* **4**: 88–99.

———, ———, and Trowbridge, R. F. (1956). The aetiology of phalaris staggers in sheep. II. The toxicity to sheep of three types of pasture containing *Phalaris tuberosa*. *Aust. J. agric. Res.* **7**: 333–44.

———, ———, Good, B. F., and Trowbridge, R. F. (1957). The aetiology of phalaris staggers in sheep. IV. The site of preventive action and its specificity to cobalt. *Aust. J. agric. Res.* **8**: 502–11.

——— and Moule, G. R. (1947). Copper deficiency affecting sheep in Queensland. *Aust. vet. J.* **23**: 303–9.

Leeper, G. W. (1966). *The Australian environment*. Melbourne, CSIRO and Melbourne University Press.

Legg, S. P. and Sears, L. (1960). Zinc sulphate treatment of parakeratosis in cattle. *Nature, Lond.* **186**: 1061–2.

Leigh, J. H. and Mulham, W. E. (1964). The performance of introduced dryland species on three soil types in the southern Riverine Plain. *CSIRO Aust., Div. Pl. Ind. Fld Stn Rec.* **3** (2): 9–20.

——— and ——— (1965). *Pastoral plants of the Riverine Plain.* Brisbane, Jacaranda Press.

———, Wilson, A. D., and Mulham, W. E. (1968). A study of merino sheep grazing a cotton bush (*Kochia aphylla*)-grassland (*Stipa variabilis-Danthonia caespitosa*) community on the Riverine Plain. *Aust. J. agric. Res.* **19**: 947–61.

Leslie, J. K. (1963). Nutrient responses on a cypress pine sand. *Qd J. agric. Sci.* **20**: 191–4.

——— and Hart, J. (1967). Key for using nitrogen fertiliser in grain crops. *Qd agric. J.* **93**: 331–4.

———, Mackenzie, J., and Glasby, T. J. (1967). Species and mineral nutrition studies on deep sands of solodic associations—a progress report. *Trop. Grassld.* **1**: 187–94.

Lightfoot, L. C., Smith, S. T., and Malcolm, C. V. (1964). Saltland survey, 1962. Report of a survey of soil salinity in the agricultural areas of Western Australia. *J. Agric. West. Aust.* **5**: 397–410.

Lightfoot, R. J., Croker, K. P., and Neil, H. G. (1967). Failure of sperm transport in relation to ewe infertility following prolonged grazing on oestrogenic pastures. *Aust. J. agric. Res.* **18**: 755–65.

——— and McGarry, W. L. (1966). Stocking rates on light land—Wongan Hills Research Station. *J. Agric. West. Aust.* **7**: 432–40.

Lindner, H. R. (1967). Study of the fate of phyto-oestrogens in the sheep by determination of isoflavones and coumestrol in plasma and adipose tissue. *Aust. J. agric. Res.* **18**: 305–33.

Lindsay, D. R. and Francis, C. M. (1968). Cervical mucus measurement in ovariectomized ewes as a bioassay of synthetic and phyto-oestrogens. *Aust. J. agric. Res.* **19**: 1069–76.

Lines, E. W. (1935). The effect of the ingestion of minute quantities of cobalt by sheep affected with 'Coast disease': a preliminary note. *J. Coun. scient. ind. Res. Aust.* **8**: 117–19.

Lines, G. E. (1961). Establishing pastures on deep sands in the South East. *J. Agric. S. Aust.* **64**: 369–70.

Litchfield, W. H. (1962). Soils of the Alice Springs area. *CSIRO Aust., Land Res. Ser.* **6**: 185–207.

——— (1963). Soils of the Wiluna–Meekatharra area. *CSIRO Aust., Land Res. Ser.* **7**: 123–42.

——— and Mabbutt, J. A. (1962). Hardpan soils of semi-arid Western Australia. *J. Soil Sci.* **13**: 148–59.

Littler, J. W. (1968). Wheat nutrition and crop rotation. *Qd agric. J.* **94**: 508–10.

——— and Price, M. J. (1967). Correction of sulphur deficiency in lucerne in the Warwick district, Queensland. *Qd J. Agric. Anim. Sci.* **24**: 159–71.

Loneragan, J. F. (1960). The legume—Rhizobium symbiosis. *J. Aust. Inst. agric. Sci.* **26**: 26–31.

——— and Dowling, E. J. (1958). The interaction of calcium and hydrogen ions in the nodulation of subterranean clover. *Aust. J. agric. Res.* **9**: 464–72.

———, Meyer, D., Fawcett, R. G., and Anderson, A. J. (1955). Lime pelleted clover seeds for nodulation on acid soils. *J. Aust. Inst. agric. Sci.* **21**: 264–5.

Loper, G. M. and Hanson, C. H. (1964). Influence of controlled environmental factors and two foliar pathogens on coumestrol in alfalfa. *Crop Sci.* **4**: 480–2.

Loveday, J. and Scotter, R. D. (1966). Emergence responses of subterranean clover to dissolved gypsum in relation to soil properties and evaporative conditions. *Aust. J. Soil Res.* **4**: 55.

Luck, P. E. (1965). *Dolichos axillaris*—Prospects in Queensland. *CSIRO Aust., Div. Pl. Ind., Plant Introduction Rev.* **1** (3): 50a–51a.

——— and Douglas, N. J. (1966). Dairy pasture research and development in the near north coast centred on Cooroy, Queensland. *Proc. Trop. Grassld. Soc. Aust.* **6**: 35–53.

Ludlow, M. M. and Wilson, G. L. (1967). Studies on the productivity of tropical pasture plants. I. Growth analysis, photosynthesis, and respiration of Hamil grass and Siratro in a controlled environment. *Aust. J. agric. Res.* **19**: 35–45.

Mabbutt, J. A. (1962). The geomorphology of the Alice Springs area. *CSIRO Aust., Land Res. Ser.* **6**: 163–84.

——— (1963). Wanderrie banks: micro-relief patterns in semiarid Western Australia. *Bull. geol. Soc. Am.* **74**: 529–40.

——— (1966). Landforms of the western Macdonnell Ranges. In *Essays in Geomorphology* ed. G. H. Dury. London, Heinemann. pp. 83–119.

——— (1968). Aeolian landforms in central Australia. *Aust. Geog. Studies* **6**: 139–50.

McArthur, W. M. and Bettenay, E. (1960). Development and distribution of soils of the Swan Coastal Plain, W.A. *CSIRO Aust., Soil Publ.* **16**.

——— and Spencer, K. (1963). Morphology as a guide to plant nutrient status in the soils of the Dorrigo Plateau. In *New England Essays* ed. R. F. Warner, Armidale, University of New England. p. 33.

McBarron, E. J. (1967). Poison plants and animal health. *Proc. Weed Soc. N.S.W.* **1**: 11-1, 11-4.

McCalla, T. M. (1937). Behaviour of legume bacteria (Rhizobium) in relation to exchangeable calcium and hydrogen ion concentration of the colloidal fraction of the soil. *Res. Bull. Mo. agric. Exp. Stn* **256**: 1–44.

McClelland, T. H. (1965). Some economic aspects of the Australian casein industry. *Quart. Rev. agric. Econ. (Aust.).* **18**: 84–95.

McClymont, G. L. (1943). Grass tetany. A cattle disease often associated with flush growth. *Agric. Gaz. N.S.W.* **54**: 484, 490.

——— (1954). Minerals and licks for sheep. *Agric. Gaz. N.S.W.* **65**: 567–70, 572, 646–51.

McColl, J. C. (1963). Dairy farming with less water. *Australas. Irrig. Past. Improver* **9** (1): 17–21.

McCray, C. W. R. and Hurwood, I. S. (1963). Selenosis in north-western Queensland associated with a marine Cretaceous formation. *Qd J. agric. Sci.* **20**: 475–98.

McDonald, G. T. (1968). Recent pasture development on the northern tablelands of N.S.W. *Aust. Geogr.* **10**: 382–91.

McDonald, I. W. (1942a). The occurrence of uncomplicated cobalt deficiency of sheep in South Australia. *Aust. vet. J.* **18**: 107–15.

——— (1942b). A 'staggers' syndrome in sheep and cattle associated with grazing on *Phalaris tuberosa*. *Aust. vet. J.* **18**: 182–9.

——— (1946). Studies on the etiology of 'phalaris staggers' in sheep: a preliminary report. *Aust. vet. J.* **22**: 91–4.

——— (1968). The nutrition of grazing ruminants. *Nutr. Abstr. Rev.* **38**: 381–400.

McEwan, T. (1964). Isolation and identification of the toxic principle of *Gastrolobium grandiflorum*. *Nature, Lond.* **201**: 827.

McFarlane, J. D. (1965). The influences of seasonal pasture production and grazing management on seasonal wool growth. *Aust. J. exp. Agric. Anim. Husb.* **5**: 252–61.

McKay, D. H. (1967a). The small farm problem in Australia. *Aust. J. agric. econ.* **11**: 115.

——— (1967b). Agriculture in the economy. In *Agriculture in the Australian Economy* ed. D. B. Williams. Sydney, Sydney University Press.

McKee, H. S. (1964). Legume seed collection in tropical America, July 1963-February 1964. *CSIRO Aust., Div. Pl. Ind., Plant Introduction Rev.* **1**: 4a–5a.

Mackenzie, J. (1966). Legumes can grow in cypress pine country. *Qd agric. J.* **92**: 154–6.

McKenzie, R. M. (1967). The sorption of cobalt by manganese minerals in soils. *Aust. J. Soil. Res.* **5**: 235–46.

——— and Taylor, R. M. (1968). The association of cobalt with manganese oxide minerals in soils. *Trans. 9th Int. Congr. Soil Sci.* **2**: 577–84.

McKeown, N. R. (1962). Effect of Dwalganup and Geraldton strains of subterranean clover on lactation in wether sheep. *Aust. J. Sci.* **24**: 457.

McKnight, T. (1949). Efficiency of isolates of Rhizobium in the cowpea group, with proposed additions to this group. *Qd J. agric. Sci.* **6**: 61–76.

McLachlan, K. D. (1952). The occurrence of sulphur deficiency on a soil of adequate phosphorus status. *Aust. J. agric. Res.* **3**: 125–7.

——— (1953). Effects of lime and copper on subterranean clover grown on acid soil. *Aust. J. agric. Res.* **4**: 151–9.

——— (1960). Rock phosphate and superphosphate compared as pasture fertilisers on acid soils. *Aust. J. agric. Res.* **11**: 513–23.

——— (1963). Soil phosphorus and the pasture response to a current application of superphosphate. *Aust. J. exp. Agric. Anim. Husb.* **3**: 184–9.

——— (1968). Stocking rate and the superphosphate requirements of sown pasture on an acid soil. *Aust. J. exp. Agric. Anim. Husb.* **8**: 33–9.

——— and Norman, B. W. (1962). Effects of previous superphosphate applications on the pasture environment and the response by pasture to a current dressing. *Aust. J. agric. Res.* **13**: 836–52.

——— and ——— (1964). The influence of rate and frequency of superphosphate application on pasture yield. *Aust. J. exp. Agric. Anim. Husb.* **4**: 152–7.

——— and ——— (1966). Observations on the superphosphate requirements of two grazing experiments. *Aust. J. exp. Agric. Anim. Husb.* **6**: 22–4.

McMullen, F. (1966). The plant nutrient status of granite soils from the Bendemeer area of New South Wales. *Aust. J. exp. Agric. Anim. Husb.* **6**: 17–21.

McTaggart, A. (1936). A survey of the pastures of Australia. *Coun. scient. ind. Res. Aust. Bull.* **9**.

——— (1937). Stylosanthes. *J. Coun. scient. ind. Res. Aust.* **10**: 201–3.

——— (1942). Plant introduction. I. A review with notes on outstanding species. *Coun. scient. ind. Res. Aust., Pamph.* **114**.

Madge, P. E. (1958). The ecology of *Oncopera fasciculata* (Walker) (Lepidoptera: Hepialidae) in South Australia. *Aust. J. Zool.* **6**: 19–26.

Madigan, C. T. (1936). The Australian sand-ridge deserts. *Geogrl Rev.* **26**: 205–27.

Maelzer, D. A. (1962). The emergence as a pest of *Aphodius tasmaniae* Hope (Scarabaeidae) in pastures in the lower south-east of South Australia. *Aust. J. Zool.* **10**: 95–112.

——— (1964). Rainfall and changes in abundance of *Aphodius tasmaniae* Hope (Coleoptera: Scarabaeidae) in the lower south-east of South Australia. *Aust. J. Zool.* **12**: 263–78.

Malcolm, C. V. (1961). Salty seepages can be productive. *J. Agric. West. Aust.* **2** (10): 863–4.

——— and Smith, S. T. (1965). Puccinellia outstanding saltland grass. *J. Agric. West. Aust.* **6** (3): 153–6.

Malikides, E, S. and Waring, E. J. (1967). Investment and change in the Australian sheep industry: a review of the post-war period. *Q. Rev. agric. Econ.* **20**: 177.

Mann, A. P. (1959). Harbinger medic—an early medic for the central and northern Mallee. *J. Agric. Vict. Dep. Agric.* **57**: 489–91.

Mann, J. (1967). *The Harrisia Cactus.* Brisbane, Government Printer.

Mann, P. P., Gorddard, B. J., Glencross, R. N., and Fitzpatrick, E. N. (1966). Stocking rate and rate of superphosphate in a higher rainfall area. *J. Agric. West. Aust.* **7**: 482-8.

't Mannetje, L. (1964). The use of some African clovers as pasture legumes in Queensland. *Aust. J. exp. Agric. Anim. Husb.* **4**: 22–5.

——— (1965). The effect of photoperiod on flowering, growth habit, and dry matter production in four species of the genus *Stylosanthes* Sw. *Aust. J. agric. Res.* **16**: 767–71.

——— (1967a). Pasture improvement in the Eskdale district of south-eastern Queensland. *Trop. Grassld.* **1**: 9–19.

——— (1967b). A re-examination of the taxonomy of the genus rhizobium and related genera using numerical analysis. *Antonie van Leeuwenhoek* **33**: 477–91.

———, Shaw, N. H., and Elich, T. W. (1963). The residual effect of molybdenum fertiliser on improved pastures on a prairie-like soil in sub-tropical Queensland. *Aust. J. exp. Agric. Anim. Husb.* **3**: 20–5.

Margetts, S. W., Stubb, A., and Newman, R. J. (1961). Pasture improvement, Shire of Portland. *J. Agric. Vict. Dep. Agric.* **59**: 225–31.

Marrett, P. L. (1963). Ferrous sulphate corrects iron deficiency in south-east soils. *J. Dep. Agric. S. Aust.* **66**: 373–5.

Marriott, S. J. (1955). Buffel grass. *J. Aust. Inst. agric. Sci.* **21**: 277–8.

——— and Anderssen, K. B. (1953). Buffel grass (*Cenchrus ciliaris* L.). *Qd agric. J.* **76**: 3–9.

——— and Winchester, W. J. (1951). Green Panic grass. *Qd agric. J.* **73**: 19–24.

Marshall, K. C. (1964). Survival of root-nodule bacteria in dry soils exposed to high temperatures. *Aust. J. agric. Res.* **15**: 273–81.

———, Mulcahy, M. J., and Chowdhury, M. C. (1963). Second-year clover mortality in Western Australia—a microbiological problem. *J. Aust. Inst. agric. Sci.* **29**: 160–4.

——— and Roberts, F. J. (1963). Influence of fine particle materials on survival of *Rhizobium trifolii* in sandy soil. *Nature, Lond.* **198**: 410–11.

Marston, H. R. (1935). Problems associated with 'coast disease' in South Australia. *J. Coun. scient. ind. Res. Aust.* **8**: 111–16.

——— (1939). Ruminant nutrition. *A. Rev. Biochem.* **8**: 557–78.

——— (1955). Wool growth. In *Progress in the Physiology of Farm Animals* ed. J. Hammond. vol. 2. London, Butterworths. pp. 543–81.

——— and Lee, H. J. (1952). Cobalt in the nutrition of ruminants: response of cobalt-deficient sheep to massive doses of vitamin B_{12}. *Nature, Lond.* **170**: 791.

———, ———, and McDonald, I. W. (1948). Cobalt and copper in the nutrition of sheep (2). *J. agric. Sci.* **38**: 222–8.

———, Thomas, R. G., Murnane, D., Lines, E. W., McDonald, I. W., Moore, H. O., and Bull, L. B. (1938). Studies on Coast Disease of sheep in South Australia. *Coun. scient. ind. Res. Aust. Bull.* **113**.

Martin, C. J. and Peirce, A. W. (1934). Studies on the phosphorus requirements of sheep. I. The effect on young Merino sheep of a diet deficient in phosphorus but containing digestible proteins and vitamins. *Coun. scient. ind. Res. Aust. Bull.* **77**.

Martin, G. J. (1954). Species and strains of pasture plants. Part 2. *Tasm. J. Agric.* **25**: 315–22.

——— (1960). The relative importance of legume species in improved pastures. *J. Aust. Inst. agric. Sci.* **26**: 38–41.

——— (1963). Using pasture species to extend the growing season. *Tasm. J. Agric.* **34**: 67–71.

Martyn, E. J. (1958). Corbie and winter corbie. *Tasm. Dep. Agric. Pamph.* **24**.

Mears, P. T. (1967). Tropical pastures in the Richmond–Tweed region of New South Wales—Recent experiences and future development. *Trop. Grassld.* **1**: 98–105.

Meigs, P. (1953). World distribution of arid and semi-arid homoclimes. In *Reviews of Research on Arid Zone Hydrology.* Paris, UNESCO. pp. 203–10.

Merrilees, D. (1968). Man the destroyer; late Quaternary changes in the Australian marsupial fauna. *J. R. Soc. West. Aust.* **51**: 1–24.

Michael, P. W. (1964). The identity and origin of varieties of *Oxalis pes-caprae* L. naturalised in Australia. *Trans. R. Soc. S. Aust.* **88**: 167–73.

——— (1965a). Physiological comparisons between the pentaploid and tetraploid varieties of *Oxalis pes-caprae. Proc. 2nd Aust. Weeds Conf.* **1**: 5–1, 5–5.

——— (1965b). Studies on *Oxalis pes-caprae* L. in Australia. I. Quantitative studies on oxalic acid during the life cycle of the pentaploid variety. *Weed Res.* **5**: 123–32.

——— (1965c). Studies on *Oxalis pes-caprae* L. in Australia. II. The control of the pentaploid variety. *Weed Res.* **5**: 133–40.

——— (1968a). Perennial and annual pasture species in the control of *Silybum marianum. Aust. J. exp. Agric. Anim. Husb.* **8**: 101–5.

——— (1968b). Control of the biennial thistle, *Onopordum*, by amitrole and five perennial grasses. *Aust. J. exp. Agric. Anim. Husb.* **8**: 332–9.

Micheli, R. A., Booth, A. N., Livingston, A. L., and Bickoff, E. M. (1962). Coumestrol, plant phenolics and synthetic oestrogens: a correlation of structure and activity. *J. mednl pharm. Chem.* **5**: 321–35.

Miles, J. F. (1947). The pastoral and agricultural growing season in north-eastern Australia. *J. Aust. Inst. agric. Sci.* **13**: 41–9.

——— (1949). Plant introduction trials in central coastal

Queensland 1936–46. *CSIRO Aust., Div. Pl. Ind., Divl. Report* **6**.

Milford, R. (1960). Nutritional values for 17 sub-tropical grasses. *Aust. J. agric. Res.* **11**: 138–48.

——— (1967). Nutritive values and chemical composition of seven tropical legumes and lucerne grown in sub-tropical south-eastern Queensland. *Aust. J. exp. Agric. Anim. Husb.* **7**: 540–5.

——— and Haydock, K. P. (1965). The nutritive value of protein in sub-tropical pasture species grown in south-east Queensland. *Aust. J. exp. Agric. Anim. Husb.* **5**: 13–17.

——— and Minson, D. J. (1968). The digestibility and intake of six varieties of Rhodes grass (*Chloris gayana*). *Aust. J. exp. Agric. Anim. Husb.* **8**: 413–18.

Miller, H. P. (1967). The effect of pre-treatment of native pasture and sowing rate on establishment of Townsville lucerne on Tippera clay loam at Katherine, N.T. *Aust. J. exp. Agric. Anim. Husb.* **7**: 515–17.

Miller, J. K. and Miller, W. J. (1962). Experimental zinc deficiency and recovery of calves. *J. Nutr.* **76**: 467–74.

Millikan, C. R. (1938). A preliminary note on the relation of zinc to disease in cereals. *J. Agric. Vict. Dep. Agric.* **36**: 409–16.

——— (1953a). Relative effects of zinc and copper deficiencies on lucerne and subterranean clover. *Aust. J. biol. Sci.* **6**: 164–77.

——— (1953b). Nutritional disorders in subterranean clover. *Dep. Agric. Vict. Tech. Bull.* **11**.

——— (1958). Nutrient deficiency symptoms in lucerne and some pasture legumes. *J. Agric. Vict. Dep. Agric.* **56**: 511–31.

Millington, A. J. (1960). Subterranean clover varieties for the wheatbelt of Western Australia. *Proc. 8th Int. Grassld. Congr.* Pap. **2A/4**.

———, Burvill, G. H., and Marsh, B. a'B. (1951). Salt tolerance, germination and growth tests under controlled salinity conditions. *J. Dep. Agric. West. Aust.* **28**: 198–210.

——— and Francis, C. M. (1966). Oestrogenic activity in some annual species of *Medicago. Proc. Aust. Cer. Past. Breed. Conf.*: 13–15.

———, ———, and Davies, H. L. (1966). Isoflavone mutations in subterranean clover. II. Assessment of oestrogenic activity by ewe bioassay. *Aust. J. agric. Res.* **17**: 901–6.

———, ———, and McKeown, N. R. (1964). Wether bioassay of annual pasture legumes. 1. Oestrogenic activity in *Medicago tribuloides* Desr. var. Cyprus, relative to four strains of *Trifolium subterraneum* L. *Aust. J. agric. Res.* **15**: 520–6.

Milthorpe, E. J. (1943). *Vegetable matter in the New South Wales wool clip.* Sydney, Central Wool Committee Testing House.

Minson, D. J. (1967). The voluntary intake and digestibility, in sheep, of chopped and pelleted *Digitaria decumbens* (pangola grass) following a late application of fertiliser nitrogen. *Br. J. Nutr.* **21**: 587–97.

——— and Milford, R. (1966). The energy values and nutritive value indices of *Digitaria decumbens*, *Sorghum almum*, and *Phaseolus atropurpureus*. *Aust. J. agric. Res.* **17**: 411–23.

——— and ——— (1968). The nutritional value of four tropical grasses when fed as chaff and pellets to sheep. *Aust. J. exp. Agric. Anim. Husb.* **8**: 270–6.

Mitchell, K. J. (1956). Growth of pasture species under controlled environment. I. Growth at various levels of constant temperature. *N.Z. Jl Sci. Technol.* **38A**: 203–16.

Moffett, M. L. and Colwell, R. R. (1968). Adansonian analysis of the Rhizobiaceae. *J. gen. Microb.* **51**: 245–66.

Moore, C. W. E. (1953a). The vegetation of the south-eastern Riverina, New South Wales. 1. The climax communities. *Aust. J. Bot.* **1**: 485–547.

——— (1953b). The vegetation of the south-eastern Riverina, New South Wales. 2. The disclimax communities. *Aust. J. Bot.* **1**: 548–67.

——— (1956). Observations on the autecology of *Heliotropium europaeum* L. in New South Wales and Victoria. *CSIRO Aust., Div. Pl. Ind. Tech. Pap.* **7**.

——— (1957). A study of some soil properties in relation to the invasion of native pastures by *Bothriochloa ambigua* S. T. Blake. *Aust. J. Bot.* **5**: 44–51.

Moore, R. M. (1959). Ecological observations on plant communities grazed by sheep in Australia. *Biogeography and Ecology in Australia* (Series Monographiae Biologicae) **8**: 500–13.

——— (1962). The effect of sheep grazing on Australian vegetation. In *The simple fleece*, ed. A. Barnard. Melbourne, Melbourne University Press.

——— (1966). Man as a factor in the dynamics of plant communities. *Proc. Ecol. Soc. Aust.* **1**: 106–10.

——— (1967a). Interaction between the grazing animal and its environment. *Proc. 9th Int. Congr. Anim. Prod.*: 188–95.

——— (1967b). The naturalisation of alien plants in Australia. *I.U.C.N. Publs. new ser.* **9**: 82–97.

———, Arnold, G. W., Hutchings, R. J., and Chapman, H. W. (1961). Poisoning of Merino sheep on *Phalaris tuberosa* L. pastures. *Aust. J. Sci.* **24**: 88–9.

———, Barrie, Nancy, and Kipps, E. H. (1946). Grazing management: continuous and rotational grazing by Merino sheep. *Coun. scient. ind. Res. Aust., Bull.* **201**.

——— and Biddiscombe, E. F. (1964). The effects of grazing on grasslands. In *Grasses and grasslands* ed. C. Barnard. London, Macmillan. p. 221.

——— and Cashmore, A. B. (1942). The control of St. John's wort (*Hypericum perforatum* L. var. *angustifolium* D.C.) by competing pasture plants. *Coun. scient. ind. Res. Aust. Bull.* **151**.

——— and Hutchings, R. J. (1967). Mortalities among sheep grazing *Phalaris tuberosa. Aust. J. exp. Agric. Anim. Husb.* **7**: 17–21.

——— and Robertson, J. A. (1964). Studies on skeleton weed—competition from pasture plants. *CSIRO Aust., Fld Stn Rec.* **3**: 69–72.

——— and ——— (1967). *CSIRO Aust., Div. Trop. Past. Annual Report.*

———, Williams, J. D., and Chia, J. (1967). Factors affecting concentrations of dimethylated indolealkylamines in *Phalaris tuberosa* L. *Aust. J. biol. Sci.* **20**: 1131–40.

Morgan, A. (1947). Salt land reclamation at Tragowal. *J. Dep. Agric. Vict.* **45**: 111.

——— and Garland, K. (1954). Salt land reclamation at Swan Hill. *J. Dep. Agric. Vict.* **52**: 268–70.

Morley, F. H. W. (1960). Natural selection and variation in plants. *Cold Spring Harb. Symp. Quant. Biol.* **24**: 47–56.

——— (1961). Subterranean clover. *Adv. Agron.* **13**: 57–123.

———, Axelsen, A., and Bennett, D. (1964). Effects of grazing red clover (*Trifolium pratense* L.) during the joining season on ewe fertility. *Proc. Aust. Soc. Anim. Prod.* **5**: 58–61.

———, ———, and ——— (1966). Recovery of normal fertility after grazing on oestrogenic red clover. *Aust. vet. J.* **42**: 204–6.

———, Brock, R. D., and Davern, C. I. (1956). Subspeciation in *Trifolium subterraneum*. *Aust. J. biol. Sci.* **9**: 1–17.

——— and Evans, L. T. (1959). Flower initiation in *Trifolium subterraneum* L. II. Limitations by vernalisation, low temperatures, and photoperiod, in the field at Canberra. *Aust. J. agric. Res.* **10**: 17–26.

——— and Katznelson, J. (1965). Colonisation in Australia by *Trifolium subterraneam* L. In *The genetics of colonising species.* New York, Academic Press. pp. 269–82.

——— and Ward, M. A. (1966). Drought feeding economics and a national drought fodder reserve. *J. Aust. Inst. agric. Sci.* **32** (1): 11–19.

Morris, J. G. (1968). Survival feeding for beef cattle during drought. *Proc. Aust. Soc. Anim. Prod.* **7**: 22–39.

Mouldon, J. O. and Jenkins, E. L. (1968). Road transport of beef cattle in northern Australia. *Q. Rev. agric. Econ.* **21**: 87.

Moule, G. R., Braden, A. W. H., and Lamond, D. R. (1963). The significance of oestrogens in pasture plants in relation to animal production. *Anim. Breed. Abstr.* **31**: 139–57.

———, Sutherland, A. K., and Harvey, J. M. (1959). Occurrence and correction of copper deficiency of sheep in north-western Queensland. *Qd J. agric. Sci.* **16**: 93–119.

——— and Young, R. B. (1950). Cobalt deficiency of sheep in Queensland. *Qd agric. J.* **71**: 277–80.

Moxon, A. L., Rhian, M. A., Anderson, H. D., and Olson, O. E. (1944). Growth of steers on seleniferous range. *J. Anim. Sci.* **3**: 299–309.

Moye, D. V. and Spencer, K. (1962). The relative boron requirements of lucerne and subterranean clover. *CSIRO Aust., Fld Stn Rec.* **1**: 26–9.

Mulcahy, M. J. (1967). Landscapes, laterites and soils in southwestern Australia. In *Landform Studies from Australia and New Guinea* ed. J. N. Jennings and J. A. Mabbutt. Canberra, A.N.U. Press.

Munns, D. N. (1965a). Soil acidity and growth of a legume. I. Interactions of lime with nitrogen and phosphate on growth of *Medicago sativa* L. and *Trifolium subterraneum* L. *Aust. J. agric. Res.* **16**: 733–41.

——— (1965b). Soil acidity and growth of a legume. II. Reactions of aluminium and phosphate in solution and effects of aluminium, phosphate, calcium and pH on *Medicago sativa* L. and *Trifolium subterraneum* L. in solution culture. *Aust. J. agric. Res.* **16**: 743–55.

Murguia, J. L. and Date, R. A. (1965). The use of pellets in the oversowing of pasture legumes. *Proc. 9th Int. Grassld Congr.* **1**: 279–82.

Murtagh, G. J. and Wilson, G. P. M. (1962). Glycine: a summer-growing legume. *Agric. Gaz. N.S.W.* **73**: 634–7.

Myers, K. and Poole, W. E. (1963). A study of the biology of the wild rabbit *Oryctolagus cuniculus* (L.) in confined populations. IV. The effects of rabbit grazing on sown pastures. *J. Ecol.* **51**: 435–51.

Myers, L. F. (1962a). Irrigated pastures. In *The simple fleece* ed. A. Barnard. Melbourne, Melbourne University Press.

——— (1962b). Irrigation and the wool industry. *Wool Technol. Sheep Breed.* **9**: 27–9.

——— (1967). Assessment and integration of special purpose pastures. *Aust. J. agric. Res.* **18**: 235–44.

——— and Baxter, R. I. (1963). Irrigation frequency, water use and pasture production. *Proc. 3rd Aust. Grassld. Conf.* **13**: 3.

——— and Moore, R. M. (1952). The effect of fertilisers on a winter weed population. *J. Aust. Inst. agric. Sci.* **18**: 152–5.

——— and Squires, V. R. (1964). A comparison of two phalaris species and an interspecific hybrid in flood irrigated swards at Deniliquin, N.S.W. *CSIRO Aust., Fld Stn Rec.* 3(2): 1–8.

——— and ——— (1968). Some effects of cutting for hay on production of irrigated annual pastures in the following year. *Aust. J. exp. Agric. Anim. Husb.* **8**: 197–202.

Mylrea, P. J. (1958). Copper-molybdenum-sulphate-manganese interaction and the copper status of cattle. *Aust. J. agric. Res.* **9**: 373–84.

Narayan, K. N. (1955). Cytogenetic studies of apomixis in Pennisetum. *Proc. Ind. Acad. Sci. Sect. B.* **41**: 196–208.

Naveh, Z. (1967). Mediterranean ecosystems and vegetation types in California and Israel. *Ecology* **48**: 445–59.

Neal-Smith, C. A. (1942). The comparative grazing values of top-dressed natural and sown pastures in the middle south-east of South Australia. *J. Agric. S. Aust.* **45**: 485–96.

——— and Johns, D. E. (1967). Australian plant exploration 1947–67. *CSIRO Aust., Div. Pl. Ind. Plant Introduction Rev.* **4**: 1–6.

Newman, R. J. (1955). Molybdenum deficiency in central highlands and upper Goulburn regions and adjoining districts. *J. Agric. Vict. Dep. Agric.* **53**: 451–63.

——— (1956). Plant nutrient deficiencies in Victorian pasture soils. *J. Agric. Vict. Dep. Agric.* **54**: 337–45.

——— (1963). The fertiliser requirements of old top-dressed perennial pasture. *3rd Aust. Grassld. Conf.*: 5–7.

——— (1966). Problems of grassland establishment and maintenance on hill country in Victoria. *Proc. 10th Int. Grassld. Congr.*: 875–8.

———, Allen, B. F., and Cook, M. G. (1962). The effect of nitrogen on winter pasture production in southern Victoria. *Aust. J. exp. Agric. Anim. Husb.* **2**: 20–4.

——— and Makeham, J. P. (1960). Pasture improvement in the Heytesbury forest. *J. Agric. Vict. Dep. Agric.* **58**: 137–47.

Newsome, A. E. (1966). The influence of food on breeding in the red kangaroo in central Australia. *CSIRO Aust., Wildl. Res.* **11**: 187–96.

Nicholson, F. J., Weir, R., Barkus, B., and Atkinson, W. T. (1960). Nitrogen fertilisers on pastures. Farm production trials in the Tumut-Adelong District. *Agric. Gaz. N.S.W.* **71**: 548–56.

Nilsson, A. (1961). On the *in vitro* metabolism of the plant oestrogen biochanin A in rumen fluid. *Ark. Kemi* **17**: 305–10.

——— (1962). Demethylation of the plant oestrogen formononetin to daidzein in rumen fluid. *Ark. Kemi* **19**: 549–50.

———, Hill, J. L., and Davies, H. L. (1967). An *in vitro* study of formononetin and biochanin A metabolism in rumen fluid from sheep. *Biochim. Biophys. Acta* **148**: 92–8.

Noble, J. C. (1962). Gypsum in irrigation. Water improves pasture establishment. *Agric. Gaz. N.S.W.* **73**: 449–52, 478–82.

Norman, M. J. T. (1959). Influence of fertilisers on the yield and nodulation of Townsville lucerne (*Stylosanthes sundaica* Taub.) at Katherine, N.T. *CSIRO Aust., Div. Land Res. Reg. Surv. Tech. Pap.* **5**.

——— (1960). Grazing and feeding trials with beef cattle at Katherine, N.T. *CSIRO Aust., Div. Land Res. Reg. Surv. Tech. Pap.* **12**.

——— (1962). Performance of pasture grasses in mixtures with Townsville lucerne at Katherine, N.T. *Aust. J. exp. Agric. Anim. Husb.* **2**: 221–7.

——— (1963a). The short-term effects of time and frequency of burning on native pastures at Katherine, N.T. *Aust. J. exp. Agric. Anim. Husb.* **3**: 26–9.

——— (1963b). The pattern of dry matter and nutrient content changes in native pastures at Katherine, N.T. *Aust. J. exp. Agric. Anim. Husb.* **3**: 119–24.

——— (1965a). The response of birdwood grass—Townsville lucerne pasture to phosphate fertilisers at Katherine, N.T. *Aust. J. exp. Agric. Anim. Husb.* **5**: 120–4.

——— (1965b). Seasonal performance of beef cattle on native pasture at Katherine, N.T. *Aust. J. exp. Agric. Anim. Husb.* **5**: 227–31.

——— (1966). Katherine Research Station 1956–64; A review of published work. *CSIRO Aust., Div. Land Res. Tech. Pap.* **28**.

——— (1968). The performance of beef cattle on different sequences of Townsville lucerne and native pasture at Katherine, N.T. *Aust. J. exp. Agric. Anim. Husb.* **8**: 21–5.

——— and Arndt, W. (1959). Performance of beef cattle on native and sown pastures at Katherine, N.T. *CSIRO Aust., Div. Land Res. Reg. Surv. Tech. Pap.* **4**.

——— and Begg, J. E. (1968). Bulrush millet (*Pennisetum typhoides*) (Burm. S & H) at Katherine, N.T. A review. *J. Aust. Inst. agric. Sci.* **34**: 59–68.

Norris, D. O. (1956). Legumes and the Rhizobium symbiosis. *Emp. J. exp. Agric.* **24**: 247–70.

——— (1958a). A red strain of Rhizobium from *Lotononis bainesii* Baker. *Aust. J. agric. Res.* **9**: 629–32.

——— (1958b). Lime in relation to the nodulation of tropical legumes. In *Nutrition of the Legumes* ed. E. G. Hallsworth. London, Butterworths. pp. 164–82.

——— (1959). The role of calcium and magnesium in the nutrition of Rhizobium. *Aust. J. agric. Res.* **10**: 651–98.

——— (1964). Some concepts and methods in subtropical pasture research. In *Legume bacteriology, Comm. Bur. Past. Fld Crops, Bull.* **47**: 102–17, 186–98.

——— (1965). Acid production by Rhizobium. A unifying concept. *Pl. Soil* **22**: 143–66.

——— (1966a). Rhizobium relationships in legumes. *Proc. 9th Int. Grassld. Congr.* **2**: 1087–92.

——— (1966b). The legumes and their associated Rhizobium. In *Tropical Pastures* ed. W. Davies and C. L. Skidmore. London, Faber and Faber. pp. 89–105.

——— (1967). The intelligent use of inoculants and lime pelleting for tropical legumes. *Trop. Grassld.* **1**: 107–21.

——— and 'tMannetje, L. (1964). The symbiotic specialisation of African *Trifolium* spp. in relation to their taxonomy and their agronomic use. *E. Afr. agric. For. J.* **29**: 214–35.

Norris, K. R. (1948). Seasonal severity of the attack of the red-legged earth mite (*Halotydeus destructor*) on subterranean clover. *J. Coun. scient. ind. Res. Aust.* **21**: 7–15.

Norrish, K. (1957). Some phosphate minerals of soils. *2nd Aust. Conf. Soil Sci.* **1**: 17 (1–15).

——— and Sweatman, T. R. (1962). The relationship between weathering status and the occurrence of gorceixite in podzolic soils of the Barossa Valley, South Australia. *3rd Aust. Conf. Soil Sci.* **2**: 66 (1–8).

Northcote, K. H. (1960). *Atlas of Australian soils.* Sheet 1. Port Augusta–Adelaide–Hamilton area. With explanatory data. Melbourne, CSIRO and Melbourne University Press.

——— (1962). *Atlas of Australian soils.* Sheet 2. Melbourne–Tasmania area. With explanatory data. Melbourne, CSIRO and Melbourne University Press.

——— (1966). *Atlas of Australian soils.* Sheet 3. Sydney–Canberra–Bourke–Armidale area. With explanatory data. Melbourne, CSIRO and Melbourne University Press.

——— (1968). *Atlas of Australian soils.* Sheet 8. Northern part of Northern Territory. With explanatory data. Melbourne, CSIRO and Melbourne University Press.

———, Bettenay, E., Churchward, H. M., and McArthur, W. M. (1967). *Atlas of Australian soils.* Sheet 5. Perth–Albany–Esperance area. With explanatory data. Melbourne, CSIRO and Melbourne University Press.

———, Isbell, R. F., Webb, A. A., Murtha, G. G., Churchward, H. M., and Bettenay, E. (1968). *Atlas of Australian soils.* Sheet 10. Central Australia. With explanatory data. Melbourne, CSIRO and Melbourne University Press.

Nunn, W. M. and Suijdendorp, H. (1954). Station management—the value of 'deferred grazing'. *J. Agric. West. Aust.* **3**: 385–7.

O'Brien, T. P. (1964). Problems in the control of the bracken fern of Victoria. *J. Aust. Inst. agric. Sci.* **30**: 119–27.

Oelrichs, P. B. and McEwan, T. (1962). The toxic principle of *Acacia georginae*. *Qd J. agric. Sci.* **19**: 1–16.

Oertel, A. C. and Prescott, J. A. (1944). A spectrochemical examination of some ironstone gravels from Australian soils. *Trans. R. Soc. S. Aust.* **68**: 173–6.

Oldfield, J. E., Fox, C. W., Bahn, A. V., Bickoff, E. M., and Kohler, G. O. (1966). Coumestrol in alfalfa as a factor in growth and carcass quality in lambs. *J. Anim. Sci.* **25**: 167–74.

———, Muth, O. H., and Schubert, J. R. (1960). Selenium and vitamin E as related to growth and white muscle disease in lambs. *Proc. Soc. exp. Biol. Med.* **103**: 799–800.

Ollier, C. D. (1967). Landforms of the newer volcanic province of Victoria. In *Landform Studies from Australia and New Guinea* ed. J. N. Jennings and J. A. Mabbutt. Canberra, A.N.U. Press. pp. 315–39.

Oram, R. N. (1965). Sowing Moroccan phalaris in spring in the wheatbelt of southern N.S.W. *CSIRO Aust., Fld Stn Rec.* **4**(2): 59–62.

Ott, E. A., Smith, W. H., Stob, M., Parker, H. E., and Beeson, W. M. (1965). Zinc deficiency syndrome in the young calf. *J. Anim. Sci.* **24**: 735–41.

Ozanne, P. G. (1968). Comparative effects of nutrient supply on the growth of pasture plants. *Aust. Grassld. Conf.* **1**: 19, 20.

———, Greenwood, E. A. N., and Shaw, T. C. (1963). The cobalt requirement of subterranean clover in the field. *Aust. J. agric. Res.* **14**: 39–50.

———, Keay, J., and Biddiscombe, E. F. (1969). The comparative applied phosphate requirements of eight annual pasture species. 1. Effects of level of applied phosphorus. *Aust. J. agric. Res.* **20**: 809–18.

———, Kirton, D. J., and Shaw, T. C. (1961). The loss of phosphorus from sandy soils. *Aust. J. agric. Res.* **12**: 409–23.

——— and Shaw, T. C. (1967). Phosphate sorption by soils as a measure of the phosphate requirement for pasture growth. *Aust. J. agric. Res.* **18**: 601–12.

———, ———, and Kirton, D. J. (1965). Pasture responses to traces of zinc in phosphate fertilisers. *Aust. J. exp. Agric. Anim. Husb.* **5**: 29–33.

Paltridge, T. B. (1942). Plant introduction. 2. Preliminary selection and evaluation of pasture species at Lawes, Queensland. *Coun. scient. ind. Res. Aust., Pamph.* **114**.

——— (1955). Studies on sown pastures for south-eastern Queensland. *CSIRO Aust., Bull.* **274**: 108.

Parberry, N. W. (1946). The problem of declining fertility in red laterite soils. Importance of regular mineral income experiments on the effect of added phosphate and liming materials. *Agric. Gaz. N.S.W.* **57**: 291–8.

Parker, C. A. (1968). On the evolution of symbiosis in legumes. In *Fest. Hans. Lauritz Jensen*, ed. Henriksen. Lemvig, Gadgaard Neilsens Bogtrykkeri. pp. 107–16.

——— and Oakley, A. E. (1965). Reduced nodulation of lupins and serradella due to lime pelleting. *Aust. J. exp. Agric. Anim. Husb.* **5**: 144–6.

Parkin, R. J. (1966). Rate of stocking rate of fertiliser in the Chapman Valley. *J. Agric. West. Aust.* **7**: 464–70.

Parle, J. (1964). Some aspects of the nodulation problem occurring in the Wither Hills. *Proc. N.Z. Grassld. Ass.*: 123–8.

Parodi, L. R. (1943). Una nueva especie de 'Sorghum' cultivada en la Argentina. *Revta argent. Agron.* **10**: 361–72.

Paton, D. F. (1956a). Pasture responses to potash molybdenum and superphosphate on cressy shaley clay-loam. *Tasm. J. Agric.* **27**: 329–38.

——— (1956b). The occurrence and significance of potassium deficiency in Tasmanian pastures. *Tasm. J. Agric.* **27**: 189–204.

——— (1956c). Investigations of trace element deficiencies in pasture in Tasmania. *J. Aust. Inst. agric. Sci.* **22**: 33–6.

——— (1957). Responses to seed inoculation of pasture legumes in Tasmania. *Tasm. J. Agric.* **28**: 389–98.

——— (1960). Problems in legume establishment with special reference to nodulation and nutrition. *J. Aust. Inst. agric. Sci.* **26**: 32–7.

——— and Loneragan, J. F. (1960). An effect of lime on residual phosphorus in soil. *Aust. J. agric. Res.* **11**: 524–9.

Payne, W. J. A. (1966) Nutrition of ruminants in the tropics. *Nutr. Abstr. Rev.* **36**: 653–70.

Pearce, G. A. (1963). Dormancy in *Homeria breyniana* (L.) Lewis. *Weed Res.* **3**: 215–29.

Peart, G. R. (1968). A comparison of rotational grazing and set stocking of dryland lucerne. *Proc. Aust. Soc. Anim. Prod.* **7**: 110–13.

Pedley, L. (1967). Vegetation of the Nogoa–Belyando area. *CSIRO Aust., Land Res. Ser.* **18**: 138–69.

Peirce, A. W. (1952). Studies on fluorosis of sheep. I. The toxicity of water-borne fluoride for sheep maintained in pens. *Aust. J. agric. Res.* **3**: 326–40.

——— (1954). Studies on fluorosis of sheep. II. The toxicity of water-borne fluoride for mature grazing sheep. *Aust. J. agric. Res.* **5**: 545–54.

——— (1959). Studies on fluorosis of sheep. III. The toxicity of water-borne fluoride for the grazing sheep throughout its life. *Aust. J. agric. Res.* **10**: 186–98.

——— (1966). Studies on salt tolerance of sheep. VI. The tolerance of wethers in pens for drinking waters of the types obtained from underground sources in Australia. *Aust. J. Agric. Res.* **17**: 209–18.

——— and Jones, G. B. (1968). Studies on selenium in the nutrition of sheep. *Aust. J. exp. Agric. Anim. Husb.* **8**: 277–87.

Pels, S. (1964). The present and ancestral Murray River System. *Australian Geographical Studies* **2**: 111–19.

Perry, R. A. (1960). Pasture lands of the Northern Territory, Australia. *CSIRO Aust., Land Res. Ser.* **5**: 1–55.

——— (1962). Natural pastures of the Alice Springs area. *CSIRO Aust., Land Res. Ser.* **6**: 240–57.

——— (1964). Land use in the Leichhardt–Gilbert area. *CSIRO Aust., Land Res. Ser.* **11**: 192–213.

——— (1967). The need for rangelands research in Australia. *Proc. ecol. Soc. Aust.* **2**: 1–14.

——— (1968). Australia's arid rangelands. *Ann. arid zone* **7**: 43–9.

———. Vegetation of the Ord–Victoria area. *CSIRO Aust., Land Res. Ser.* (in press).

———. Pasture lands of the Ord–Victoria area. *CSIRO Aust., Land Res. Ser.* (in press).

——— and Christian, C. S. (1954). Vegetation of the Barkly region. *CSIRO Aust., Land Res. Ser.* **3**: 78–112.

——— and Lazarides, M. (1962). Vegetation of the Alice

Springs area. *CSIRO Aust., Land Res. Ser.* **6**: 208–36.

——— and ——— (1964). Vegetation of the Leichhardt–Gilbert area. *CSIRO Aust., Land Res. Ser.* **11**: 152–91.

———, Sleeman, J. R., Twidale, C. R., Prichard, C. E., Slatyer, R. O., Lazarides, M., and Collins, F. H. (1964). General report on lands of the Leichhardt–Gilbert area, Queensland, 1953–54. *CSIRO Aust., Land Res. Ser.* **11**: 1–224.

Philpotts, Helen (1967). The effect of soil temperature on nodulation of cowpeas (*Vigna sinensis*). *Aust. J. exp. Agric. Anim. Husb.* **7**: 372–6.

Piper, C. S. (1938). A copper deficiency in plants at Robe, South Australia. 2. The occurrence of 'Reclamation Disease' in cereals in South Australia. *Coun. scient. ind. Res. Aust. Pamph.* **78**.

——— (1942). Investigations on copper deficiency in plants. *J. agric. Sci.* **32**: 143–78.

Pittman, H. A. J. (1935). Leguminous crops and their use in the building up of soil fertility. *J. Dep. Agric. West. Aust.* **12**: 105–16.

——— (1944). *Commonwealth of Australia Patent Specifications* **127**: 817.

Powrie, J. K. (1960). A field response by subterranean clover to cobalt fertiliser. *Aust. J. Sci.* **23**: 198–9.

——— (1963). The phosphorus requirement of pastures on siliceous sands. *3rd Aust. Grassld. Conf.* **5**: 8–11.

Prescott, J. A. (1931). The soils of Australia in relation to vegetation and climate. *Coun. sci. ind. Res. Aust. Bull.* **52**.

——— (1934). Single value climatic factors. *Trans. R. Soc. S. Aust.* **58**: 48–61.

——— (1949). Climatic expressions and generalised climatic zones in relation to soils and vegetation. *Proc. Br. Comm. Sci. Conf.*, Adelaide.

Pritchard, A. J. (1962). The cytology and reproduction of *Paspalum yaguaronense* (Henr.). *Aust. J. agric. Res.* **13**: 206–11.

——— (1964). Comparative trials with *Sorghum almum* and other forage sorghums in south-east Queensland. *Aust. J. exp. Agric. Anim. Husb.* **4**: 6–14.

——— (1965a). Inheritance patterns in hybrids between *Sorghum almum* Parodi and perennial sweet sudan grass. *Aust. J. agric. Res.* **16**: 525–32.

——— (1965b). *Sorghum almum. CSIRO Aust., Div. Trop. Past. Annual Report 1964–5.* p. 64.

——— (1967). Apomix in *Brachiaria decumbens* Stapf. *J. Aust. Inst. agric. Sci.* **33**: 264–5.

——— and Wutoh, J. G. (1964). Chromosome numbers in the genus Glycine L. *Nature, Lond.* **202**: 322.

Prunster, R. W. (1940). Notes on the control of blackberry, Watsonia, bracken and ragwort in Victoria. *J. Coun. scient. ind. Res. Aust.* **13**: 178–80.

Pryor, L. D. (1939). The vegetation of the Australian Capital Territory. A study of the Synecology. M.Sc. Thesis, University of Adelaide.

——— (1954). *Vegetation of the A.C.T.* ANZAAS Handbook.

——— (1959). Species distribution and association in Eucalyptus. *Biogeography and Ecology in Australia.* (Series Monographiae Biologicae) **8**: 461–71.

Pulsford, M. F., Rae, R., and Irving, E. A. (1966). Unthriftiness of lambs and weaners in the spring and early summer in South Australia. *Aust. vet. J.* **42**: 165–8.

Quinlivan, B. J., Francis, C. M., and Poole, M. L. (1968). The certified strains of subterranean clover—their origin, potential use and identification. *J. Agric. West. Aust.* **9**: 161–77.

Ratcliffe, F. N. (1959). The rabbit in Australia. *Biogeography and Ecology in Australia* (Series Monographiae Biologicae) **8**: 545–64.

——— and Calaby, J. H. (1958). Rabbit. In *The Australian Encyclopaedia.* Sydney, Angus & Robertson. **7**: 340–7.

Redrup, J. (1966). An approach to the commercial production of the seeds of tropical pasture plants. *Proc. 9th Int. Grassld. Congr.*: 521–6.

Riceman, D. S. (1945). Mineral deficiency in plants on the soils of the Ninety-mile Desert in South Australia. I. Preliminary investigations on the Laffer Sand near Keith. *J. Coun. scient. ind. Res. Aust.* **18**: 336–48.

——— (1948a). Mineral deficiency in plants on the soils of the Ninety-mile Plain in South Australia. 2. Effect of zinc, copper, and phosphate on subterranean clover and lucerne grown on Laffer Sand, near Keith. *Coun. scient. ind. Res. Aust. Bull.* **234**.

——— (1948b). Mineral deficiency in plants on the soils of the Ninety-mile Plain in South Australia. 5. Effect of growth and removal of a crop treated with zinc and copper upon pasture established subsequently on Laffer Sand, near Keith. *J. Coun. scient. ind. Res. Aust.* **21**: 229–35.

——— and Donald, C. M. (1938). A copper deficiency in plants at Robe, South Australia. 1. Preliminary investigations on the effect of copper and other elements on the growth of plants in a 'coasty' calcareous sand at Robe, South Australia. 2. The occurrence of 'Reclamation Disease' in cereals in South Australia. *Coun. scient. ind. Res. Aust. Pamph.* **78**.

Ridpath, M. G. and Meldrum, G. K. (1968a). Damage to oat crops by the Tasmanian native hen *Tribonyx mortierii. CSIRO Aust., Wildl. Res.* **13**: 25–43.

——— and ——— (1968b). Damage to pastures by the Tasmanian Native Hen *Tribonyx mortierii. CSIRO Aust., Wildl. Res.* **13**: 11–24.

Rimington, C. and Quin, J. I. (1934). Studies on the photosensitisation of animals in South Africa. VII. The nature of photosensitising agent in Geeldikkop. *Onderstepoort J. vet. sci. Anim. Ind.* **3**: 137–57.

Rixon, A. J. (1966). Soil fertility changes in a red-brown earth under irrigated pastures. 1. Changes in organic carbon, carbon/nitrogen ratio, cation exchange capacity and pH. *Aust. J. agric. Res.* **17**: 303–16.

——— (1969). The influence of annual and perennial pastures on soil fertility as shown by the yield and quality of a subsequent wheat crop. *Aust. J. agric. Res.* **20** (2): 243–55.

——— and Bridge, B. J. (1967). Soil fertility changes in a red-brown earth under irrigated pastures. II. Water relations of the mat and surface soil. *Aust. J. agric. Res.* **18**: 741–53.

Roark, B. and Donald, C. M. (1954). The control of onion weed by competing pasture plants. *Aust. Weed Control Conf. Report.*

Robards, G. E. and Peart, G. R. (1967). Outstanding results from rotationally grazed lucerne. *Agric. Gaz. N.S.W.* **78**: 14.

Roberts, F. J. (1966). The effects of sand type and fine particle amendments on the emergence and growth of subterranean clover (*Trifolium subterraneum* L.) with particular reference to water relations. *Aust. J. agric. Res.* **17**: 657–72.

———, Fitzpatrick, E. N., Toms, W. J., Greenwood, E. A. N., and Oliver, G. (1966). The prospects for nitrogen fertilisers in Western Australia. *J. Aust. Inst. agric. Sci.* **32** (2): 72–92.

Robertson, J. A. (1965). Chemical control of *Eremophila mitchellii. Aust. J. exp. Agric. Anim. Husb.* **5**: 299–304.

——— (1966). The effect of basal injections of 2, 4, 5-T on mature trees of *Eucalyptus populnea. Aust. J. exp. Agric. Anim. Husb.* **6**: 344–9.

Roche, D. (1961). White muscle disease. *Tasm. J. Agric.* **32**: 22–4.

Roe, R. (1963). *CSIRO Aust., Div. Trop. Past. Annual Report, 1962–3.* Brisbane. p. 13.

——— and Allen, G. M. (1945). Studies on the Mitchell grass association in south-western Queensland. I. The effect of grazing on the Mitchell grass pasture. *Coun. scient. ind. Res. Aust., Bull.* **185**.

———, Southcott, W. H., and Turner, Helen Newton (1959). Grazing management of native pastures in the New England region of New South Wales. *Aust. J. agric. Res.* **10**: 530–54.

Rogers, A. L. and Bailey, E. T. (1963). Salt tolerance trials with forage plants in south-western Australia. *Aust. J. exp. Agric. Anim. Husb.* **3**: 125–30.

Rogers, V. R. (1961). Lucerne variety trials at Deniliquin N.S.W. *Aust. J. exp. Agric. Anim. Husb.* **1**: 60–6.

Rose, A. L., Gardner, C. A., McConnell, J. D., and Bull, L. B. (1957). Field and experimental investigation of 'Walkabout' disease of horses (Kimberley horse disease) in Northern Australia: Crotalaria poisoning in horses. Parts I and II. *Aust. vet. J.* **33**: 25–33, 49–62.

Rosenfeld, I. and Beath, O. A. (1964). *Selenium: geobotany, biochemistry, toxicity and nutrition.* New York, Academic Press.

Rossiter, R. C. (1947). The effect of potassium on the growth of subterranean clover and other pasture plants on Crawley sand. 1. Pot culture experiments. 2. Field plot experiments. *J. Coun. scient. ind. Res. Aust.* **20** (3): 379–401.

——— (1951). Studies on the nutrition of pasture plants in the south-west of Western Australia. 1. The effect of copper, zinc and potassium on the growth of the Dwalganup strain of *Trifolium subterraneanum* L. on sandy soils. *Aust. J. agric. Res.* **2**: 1–13.

——— (1952a). Studies on the nutrition of pasture plants in the south-west of Western Australia. III. The effect of sulphur on the growth of subterranean clover (*Trifolium subterraneum* L.). *Aust. J. agric. Res.* **3**: 7–15.

——— (1952b). The effect of grazing on a perennial veldt grass–subterranean clover pasture. *Aust. J. agric. Res.* **3**: 148–59.

——— (1955a). The influence of soil type on phosphate toxicity in subterranean clover (*Trifolium subterraneum* L.). *Aust. J. agric. Res.* **6**: 1–8.

——— (1955b). Strain reaction to potassium deficiencies in subterranean clover (*Trifolium subterraneum* L.). *Aust. J. agric. Res.* **6**: 9–14.

——— (1958). Utilisation of annual pastures in a Mediterranean environment with special reference to autumn deferment. *Proc. Aust. Agrostology Conference* **1**: 56/1–15.

——— (1964). The effect of phosphate supply on the growth and botanical composition of annual type pasture. *Aust. J. agric. Res.* **15**: 61–76.

——— (1966a). The success or failure of strains of *Trifolium subterraneum* L. in a Mediterranean environment. *Aust. J. agric. Res.* **17**: 425–46.

——— (1966b). Ecology of the Mediterranean annual-type pasture. *Adv. Agron.* **18**: 1–56.

——— (1967). Physiological and ecological studies on the oestrogenic isoflavones in subterranean clover (*T. subterraneum* L.). IV. Effects of zinc deficiency in clover seedlings. *Aust. J. agric. Res.* **18**: 39–46.

——— (1969). Physiological and ecological studies on the oestrogenic isoflavones in subterranean clover (*T. subterraneum* L.). VI. Effects of defoliation including grazing. *Aust. J. agric. Res.* **20**: 25–35.

——— and Beck, A. B. (1966a). Physiological and ecological studies on the oestrogenic isoflavones in subterranean clover (*T. subterraneum* L.). I. Effects of temperature. *Aust. J. agric. Res.* **17**: 29–37.

——— and ——— (1966b). Physiological and ecological studies on the oestrogenic isoflavones in subterranean clover (*T. subterraneum* L.). II. Effects of phosphate supply. *Aust. J. agric. Res.* **17**: 447–56.

——— and ——— (1967). Physiological and ecological studies on the oestrogenic isoflavones in subterranean clover (*T. subterraneum* L.). III. Effects of light. *Aust. J. agric. Res.* **18**: 23–37.

———, Curnow, D. H., and Underwood, E. J. (1948). The effect of cobalt sulphate on the cobalt content of subterranean clover at three stages of growth. *J. Aust. Inst. agric. Sci.* **14**: 9–14.

——— and Ozanne, P. G. (1955). The short term effects of rock phosphate and superphosphate on subterranean clover pasture. *Aust. J. agric. Res.* **6**: 553–64.

——— and Pack, R. J. (1956). The effect of protection from grazing on the botanical composition of an annual-type subterranean clover pasture. *J. Aust. Inst. agric. Sci.* **22**: 71–3.

Roughley, R. J. (1962). Some aspects of Rhizobium research and service in the N.S.W. Dept. of Agriculture. *Agric. Gaz. N.S.W.* **73**: 260–2.

Rowan, J. N. and Downes, R. G. (1963). *A Study of the land in North-western Victoria.* Victoria, Soil Conservation Authority.

Russell, F. C. and Duncan, D. L. (1956). Minerals in pasture: deficiencies and excesses in relation to animal health. *2nd Ed. Tech. Commun. Comm. Bur. Anim. Nutr.* **15**.

Russell, J. S. (1960a). Soil fertility changes in the long-term experimental plots at Kybybolite, South Australia. 1. Changes in pH, total nitrogen, organic carbon, and bulk density. *Aust. J. agric. Res.* **11**: 902–26.

——— (1960b). Soil fertility changes in the long-term experimental plots at Kybybolite, South Australia. II. Changes in phosphorus. *Aust. J. agric. Res.* **11**: 927–47.

——— (1961). Soil fertility changes in the long-term experimental plots at Kybybolite, South Australia. III. Changes in cation exchange capacity and exchangeable cations. *Aust. J. agric. Res.* **12**: 273–85.

——— (1966). Plant growth on a low calcium status solodic soil in a subtropical environment. I. Legume species, calcium carbonate, zinc, and other minor element interactions. *Aust. J. agric. Res.* **17**: 673–86.

——— (1967). Aspects of pasture growth on solodic soils. *Trop. Grassld.* **1** (2): 199–203.

——— (1968). Implications of the effect of nitrogen on daily pasture growth rates in the semi-arid sub-tropics. *J. Aust. Inst. agric. Sci.* **34**: 169–70.

Russell, M. J., Coaldrake, J. E., and Sanders, A. M. (1967). Comparative effectiveness of some insecticides, repellents and seed-pelleting in the prevention of ant removal of pasture seeds. *Trop. Grassld.* **1**: 153–66.

Ruschel, Alaides P., Alvahydro, R., and Penteado, A. F. (1962). Influência do cálcio do magnesio e da acidez sôbre o Rhizobium phaseoli em meio de cultura. *Comm. Tec. 16. Inst. Ec. exp. Agric. M.A., Rio de Janeiro.*

Rutherford, G. K. (1964). Soils of the West Kimberley area. *CSIRO Aust., Land Res. Ser.* **9**: 119–39.

Rutherford, J. (1958). Integration of irrigation and dryland farming in the southern Murray Basin. I. Need for reappraising the concept. *Rev. Mktg agric. Econ.* **26**: 227–83.

——— (1959). Integration of irrigation and dryland farming in the southern Murray Basin. II. Results of research in a 'field study area' 1956–8. *Rev. Mktg agric. Econ.* **27**: 146–233.

Ryan, F. E. (1965). Seed and superphosphate rates for new dairy pastures. *J. Agric. West. Aust.* **6**: 211-13.

St George-Grambauer, T. D. (1957). Plants poisonous to livestock. *J. Dep. Agric. S. Aust.* **60**: 253–64, 294–8.

Samuel, G. and Piper, C. S. (1929). Manganese as an essential element for plant growth. *Ann. appl. Biol.* **16**: 493–524.

Santhirasegaram, K., Coaldrake, J. E., and Salih, M. H. (1966). Yield of a mixed sub-tropical pasture in relation to frequency and height of cutting and leaf-area index. *Proc. 10th Int. Grassld. Conf.*: 125–9.

Saubert, Synnöve and Scheffler, J. G. (1967a). Strain variation and host specificity of Rhizobium. II. Host specificity of *Rhizobium trifolii* on European clovers. *S. Afr. J. agric. Sci.* **10**: 85–93.

——— and ——— (1967b). Strain variation and host specificity of Rhizobium. III. Host specificity of *Rhizobium trifolii* on African clovers. *S. Afr. J. Agric. Sci.* **10**: 357–64.

Saunders, G. W. (1967). Funnel ants (*Aphaenogaster* spp., Formicidae) as pasture pests in north Queensland. *Int. Bull. Ent. Res.* **57**: 327–477.

Schinckel, P. G. (1948). Infertility in ewes grazing subterranean clover pastures. Observations on breeding behaviour following transfer to 'sound' country. *Aust. vet. J.* **24**: 289–94.

Schofield, J. L. (1941). Introduced legumes in north Queensland. *Qd agric. J.* **56**: 378–88.

——— (1944). The effects of season and frequency of cutting on the productivity of various grasses under coastal conditions in northern Queensland. *Qd J. agric. Sci.* **1** (4): 2–58.

——— (1945). Tropical legumes in south-eastern Queensland. *Qd agric. J.* **61**: 133–43.

Schumm, S. A. (1963). A tentative classification of alluvial river channels. *U.S. Geol. Surv. Circ.* **477**.

——— (1967). Paleohydrology: the application of modern hydrologic data to problems of the ancient past. *Proc. Int. Hydrology Symposium* **1**: 185–93.

Scobie, G. M. (1968). Economic aspects of replacement policies in Merino sheep flocks. *Q. Rev. agric. Econ.* **21**: 126–139.

——— and Rowe, A. H. (1967). Trends in the size distribution of Australian sheep flocks. *Q. Rev. agric. Econ.* **20**: 127–141.

Scott, B. J., Evans, L. H., and Noble, J. C. (1968). Gypsum for problem soils in southern New South Wales. *Agric. Gaz. N.S.W.* **79**: 493–8.

Sedgley, R. H. (1962). Physical effects of gypsum on some Riverine soils. *3rd Aust. Conf. Soil Science*, Pap. **55**.

Setchell, B. P. and Dickinson, D. A. (1966). Effect of iodised oil and iodate on thyroid iodine concentrations in lambs with some observations on aetiology of naturally occurring goitre. *Proc. Aust. Soc. Anim. Prod.* **6**: 405–6.

———, Dickinson, D. A., Lascelles, A. K., and Bonner, R. B. (1960). Neonatal mortality in lambs associated with goitre. *Aust. vet. J.* **36**: 159–64.

———, Harris, A. N. A., Farleigh, E. A., and Clarke, F. L. (1962). Further studies in lambs in N.S.W. on the growth response to selenium and the prevention of muscular dystrophy with selenium and vitamin E. *Aust. vet. J.* **38**: 62–5.

Sharkey, M. J. and Hedding, R. R. (1964). The relationship between changes in body weight and wool production in sheep at different stocking rates on annual pastures in southern Victoria. *Proc. Aust. Soc. Anim. Prod.* **5**: 284–90.

Sharman, G. B. (1959). Marsupial Reproduction. In *Biogeography and Ecology in Australia* (Series Monographiae Biologicae) **8**: 332–68.

Shaw, N. H. (1957). Bunch spear grass dominance in burnt pastures in south-eastern Queensland. *Aust. J. agric. Res.* **8**: 325–34.

——— (1961). Increased beef production from Townsville lucerne (*Stylosanthes sundaica* Taub.) in the spear grass pastures of central coastal Queensland. *Aust. J. exp. Agric. Anim. Husb.* **1**: 73–80.

——— (1967a). Brian Pastures. *CSIRO Aust., Div. Trop. Past. Annual Report 1966–7*: 15–6.

——— (1967b). CSIRO Pasture Research—Brian Pastures. *Trop. Grassld.* **1**: 76–7.

——— and Bisset, W. J. (1955). Characteristics of a bunch spear grass (*Heteropogon contortus* (L.) Beauv.) pasture grazed by cattle in sub-tropical Queensland. *Aust. J. agric. Res.* **6**: 539–52.

———, Elich, T. W., Haydock, K. P., and Waite, R. B. (1965). A comparison of seventeen introductions of *Paspalum* species and naturalised *P. dilatatum* under cutting at Samford, south-eastern Queensland. *Aust. J. exp. Agric. Anim. Husb.* **5**: 423–32.

———, Gates, C. T., and Wilson, J. R. (1966). Growth and chemical composition of Townsville lucerne (*Stylosanthes humilis*). I. Dry matter yield and nitrogen content in response to superphosphate. *Aust. J. exp. Agric. Anim. Husb.* **6**: 150–6.

Shelton, J. N. (1956). The performance of beef cattle in North Queensland. *Proc. Aust. Soc. Anim. Prod.* **1**: 130–7.

Shipton, W. A. and Parker, C. A. (1967). Nodulation of lime-pelleted lupins and serradella when inoculated with peat and agar cultures. *Aust. J. exp. Agric. Anim. Husb.* **7**: 259–62.

Shutt, D. A. (1967). Interaction of genistein with oestradiol in the reproductive tract of the ovariectomised mouse. *J. Endocr.* **37**: 231–2.

——— and Braden, A. W. H. (1968). The significance of equol in relation to the oestrogenic responses in sheep ingesting clover with a high formononetin content. *Aust. J. agric. Res.* **19**: 545.

———, ———, and Lindner, H. R. (1969). Plasma coumestrol levels in sheep following administration of synthetic coumestrol or ingestion of medic hay (*Medicago littoralis*). *Aust. J. agric. Res.* **20**: 65–9.

Sillar, D. I. (1967). Effect of shade on growth of Townsville lucerne (*Stylosanthes humilis* H.B.K.) *Qd J. Agric. Anim. Sci.* **24**: 237–40.

——— (1969). Townsville lucerne in Queensland. *Qd agric. J.* **95**: 2–11.

Simnett, K. I. and Spray, G. H. (1965). The effect of a low-cobalt diet in rabbits. *Br. J. Nutr.* **19**: 119–23.

Simpson, J. R. (1962). Mineral nitrogen fluctuations in soils under improved pasture in southern New South Wales. *Aust. J. agric. Res.* **13**: 1059–72.

——— (1965). The effects of nitrogenous fertilisers on the winter growth of pastures in a tablelands environment. *Aust. J. exp. Agric. Anim. Husb.* **5**: 208–17.

———, Lipsett, J., and Fisher, H. J. (1968). The growth of three pasture legumes on a coarse textured podzolic soil in the upper Shoalhaven Valley. *CSIRO Aust., Fld Stn Rec.* **7**: 83–94.

Skene, J. K. M., Hosking, W. J., Leverington, K. C., Russell, J. S., and Williams, C. H. (1965). A survey of soil and plant tissue testing activities in Australia. *Aust. Soc. Soil Sci. Report by Soil Testing Sub-Committee.*

Skerman, K. D. (1962). Observations on selenium deficiency of lambs in Victoria. *Proc. Aust. Soc. Anim. Prod.* **4**: 22–7.

Skerman, P. J. (1953). Some agricultural features of the central highlands region of Queensland. *Qd agric. J.* **76**: 139–49, 187–201.

——— (1958). Heatwaves and their significance in Queensland's primary industries. *Arid Zone Res. UNESCO* **11**: 195–8.

Skipton, W. A. and Parker, C. A. (1967). Nodulation of lime-pelleted lupins and serradella when inoculated with peat and agar cultures. *Aust. J. exp. Agric. Anim. Husb.* **7**: 259–62.

Slatyer, R. O. (1960). Agricultural climatology of the Katherine area, N.T. *CSIRO Aust., Div. Land Res. Reg. Surv. Tech. Pap.* **13**.

——— (1962). Climate of the Alice Springs area. *CSIRO Aust., Land Res. Ser.* **6**: 109–28.

——— (1964). Climate of the Leichhardt–Gilbert area. *CSIRO Aust., Land Res. Ser.* **11**: 90–104.

———. Climate of the Ord–Victoria area. *CSIRO Aust., Land Res. Ser.* (in press).

——— and Christian, C. S. (1954). Climate of the Barkly region. *CSIRO Aust., Land Res. Ser.* **3**: 17–33.

Sleeman, J. R. (1964). Soils of the Leichhardt–Gilbert area. *CSIRO Aust., Land Res. Ser.* **11**: 129–51.

Sloan, W. J. S., Owens, A. J., and Johnston, M. A. (1962). Report of the North Queensland Land Classification Committee, 1960–1. Brisbane. Government Printer.

Smith, B. S. W., Field, A. C., and Suttle, N. F. (1968). Effect of intake of copper, molybdenum and sulphate on copper metabolism in the sheep. III. Studies with radioactive copper in male castrated sheep. *J. comp. Path. Ther.* **78**: 449–61.

Smith, C. A. (1968). *CSIRO Aust., Div. Trop. Past. Annual Report 1967–8.*

Smith, D. F. (1968a). The growth of barley grass (*Hordeum leporinum*) in annual pasture. 1. Germination and establishment in comparison with other annual species. *Aust. J. exp. Agric. Anim. Husb.* **8**: 478–83.

——— (1968b). The growth of barley grass (*Hordeum leporinum*) in annual pasture. 2. Growth comparisons with Wimmera rye grass (*Lolium rigidum*). *Aust. J. exp. Agric. Anim. Husb.* **8**: 484–90.

Smith, S. E., Koch, B. A., and Turk, K. L. (1951). The response of cobalt-deficient lambs to liver extract and vitamin B_{12}. *J. Nutr.* **44**: 455–64.

Smith, S. T. (1961). Soil salinity in Western Australia. *J. Agric. West. Aust.* **2**: 757–60.

——— and Malcolm, C. V. (1959). Bringing wheatbelt salt land back into production. *J. Agric. West. Aust.* **8**: 263–7.

Snieszko, S. F. (1941). The influence of lime on nodulation and growth of canning peas. *Cann. Age* **22**: 49–50.

Snyder, L. A., Hernandez, Alice R., and Warmke, H. E. (1955). The mechanism of apomixis in *Pennisetum ciliare*. *Bot. Gaz.* **116**: 209–21.

Southcott, W. H. (1945). Congenital goitre in lambs in Tasmania. *Aust. vet. J.* **21**: 35–6.

———, Hill, M. K., Watkin, B. R., and Wheeler, J. L. (1968). Effect of paddock size, stocking rate, anthelmintics and trace elements on the weight gain of young cattle. *Proc. Aust. Soc. Anim. Prod.* **7**: 118–22.

———, Roe, R., and Turner, Helen Newton (1962). Grazing management of native pastures in the New England region of New South Wales. II. The effect of size of flock on pasture and sheep production with special reference to internal parasites and grazing behaviour. *Aust. J. agric. Res.* **13**: 880–93.

Specht, R. L. (1951). A reconnaissance survey of the soils and vegetation of the hundreds of Tatiara, Wirrega and Stirling, County Buckingham, South Australia. *Trans. R. Soc. S. Aust.* **74**: 79–107.

——— (1963). Dark Island heath (Ninety-mile Plain, South Australia). VII. The effect of fertilisers on composition and growth, 1950–60. *Aust. J. Bot.* **11**: 67–94.

——— and Perry, R. A. (1948). Plant ecology of part of the Mount Lofty Ranges. *Trans. R. Soc. S. Aust.* **72**: 91–132.

Speck, N. H. (1963). Vegetation of the Wiluna–Meekatharra area. *CSIRO Aust., Land Res. Ser.* **7**: 143–61.

——— (1968). Vegetation of the Dawson–Fitzroy area. *CSIRO Aust., Land Res. Ser.* **21**: 157–73.

———, Fitzgerald, K., and Perry, R. A. (1964). The pasture lands of the west Kimberley area. *CSIRO Aust. Land Res. Ser.* **9**: 175–91.

——— and Lazarides, M. (1964). Vegetation and pastures of the west Kimberley area. *CSIRO Aust., Land Res. Ser.* **9**: 140–74.

———, Bradley, J., Lazarides, M., Patterson, R. A., Slatyer, R. O., Stewart, G. A., and Twidale, C. R. (1960). The lands and pastoral resources of the north Kimberley area, W.A. *CSIRO Aust., Land Res. Ser.* **4**.

———, Wright, R. L., Sweeney, F. C., Perry, R. A., Fitzpatrick, E. A., Nix, H. A., Gunn, R. H., and Wilson, I. B. (1968). Lands of the Dawson–Fitzroy area, Queensland. *CSIRO Aust., Land Res. Ser.* **21**.

———, ———, van de Graaff, R. H. M., Fitzpatrick, E. A., Mabbutt, J. A., and Stewart, G. A. (1965). General report on lands of the Tipperary area, Northern Territory, 1961. *CSIRO Aust., Land Res. Ser.* **13**.

Spencer, D. (1950). The effect of calcium and soil pH on nodulation of *T. subterraneum* L. clover on a yellow podzol. *Aust. J. agric. Res.* **1**: 374–81.

Spencer, K. (1966). Soil properties in relation to the sulphur and phosphorus status of some basaltic soils. *Aust. J. Soil. Res.* **4**: 115–30.

——— and Barrow, N. J. (1963). A survey of the plant nutrient status of the principal soils of the northern tablelands of New South Wales. *CSIRO Aust., Div. Pl. Ind. Tech. Pap.* **19**.

———, Bouma, D., and Moye, D. V. (1969a). The assessment of the phosphorus and sulphur status of subterranean clover pastures. I. Environmental factors and pasture responses. *Aust. J. exp. Agric. Anim. Husb.* **9**: 310–19.

———, ———, and ——— (1969b). The assessment of the phosphorus and sulphur status of subterranean clover pastures. II. Soil tests. *Aust. J. exp. Agric. Anim. Husb.* **9**: 320–8.

Sprivulis, R. (1966). The first year of a cattle stocking rate trial at Pardelup. *J. Agric. West. Aust.* **7**: 107–15.

Stace, H. C. T., Hubble, G. D., Brewer, R., Northcote, K. H., Sleeman, J. R., Mulcahy, M. J., and Hallsworth, E. G. (1968). *A Handbook of Australian Soils.* Glenside, S.A., Rellim.

Stannard, M. E. (1958). Erosion survey of the south-west Cobar peneplain. II. Soils and vegetation. *J. Soil Conserv. Serv. N.S.W.* **14**: 30–45.

——— (1962). Erosion survey of the central east Darling region. Part II. Soils. *J. Soil Conserv. Serv. N.S.W.* **18**: 173–82.

——— (1963). Erosion survey of the central east Darling region. Part III. Vegetation. *J. Soil Conserv. Serv. N.S.W.* **19**: 17–28.

Staples, I. B. (1967). A promising new legume. *Qd agric. J.* **92**: 388–92.

Steindl, D. R. L. (1941). Legume inoculation in Queensland canefields. Efficiency of strains of nitrogen-fixing bacteria. *Bureau Sugar Experiment Stations Qd Tech. Commun.* **2**.

Stephens, C. G. (1946). Pedogenesis following the dissection of lateritic regions in southern Australia. *Coun. sci. ind. Res. Aust. Bull.* **206**.

——— (1951). The influence of pedological age and parent material on the nutritional status of certain Australian soils. *Proc. Br. Comm. scient. Conf., Specialist Conf. Agriculture, 1949*, pp. 51–7.

——— (1950). Comparative morphology and genetic relationships of certain Australian, North American, and European soils. *J. Soil Sci.* **1**: 123–49.

——— (1953). *A manual of Australian soils.* Melbourne, CSIRO Aust. publ.

——— and Donald, C. M. (1958). Australian soils and their responses to fertilisers. *Adv. Agron.* **10**: 167–256.

Stewart, G. A. (1954). Soils of the Barkly region. *CSIRO Aust., Land Res. Ser.* **3**: 65–77.

———. Soils of the Ord–Victoria area. *CSIRO Aust., Land Res. Ser.* (in press).

Stewart, W. D. P. (1966). *Nitrogen fixation in plants.* University of London, Athlone Press.

Stocker, G. C. and Sturtz, J. D. (1966). The use of fire to establish Townsville lucerne in the Northern Territory. *Aust. J. exp. Agric. Anim. Husb.* **6**: 277–9.

Stonard, P. (1968). Fine-stem stylo, a legume of promise. *Qd agric. J.* **94**: 478–84.

Storr, G. M. (1968). Diet of kangaroos (*Megaleia rufa* and *Macropus robustus*) and Merino sheep near Port Hedland, Western Australia. *J. R. Soc. West. Aust.* **51**: 25–32.

Story, R. (1967). Vegetation of the Isaac-Comet region. *CSIRO Aust., Land Res. Ser.* **19**: 108–38.

———, Galloway, R. W., Gunn, R. H., and Fitzpatrick, E. A. (1967). Lands of the Isaac-Comet area, Queensland. *CSIRO Aust., Land Res. Ser.* **19**.

Strang, J. (1955). A pasture response to applications of sodium molybdate. *J. Aust. Inst. agric. Sci.* **21**: 179–80.

——— (1960). Pasture management for the south coast. *Agric. Gaz. N.S.W.* **71**: 113–16.

——— (1963). Potash deficiency in south coast pastures. *Agric. Gaz. N.S.W.* **74**: 52–4.

Strickland, R. W. Seed production and testing problems in tropical and sub-tropical pasture species. *Proc. 15th Int. Seed Testing Congr.* (in press).

Strong, T. H. (1937). The influence of host plant species in relation to the effectiveness of the Rhizobium of clovers. *J. Coun. scient. ind. Res. Aust.* **10**: 12–16.

Suijdendorp, H. (1953). Buffel and birdwood grasses. Two useful perennials. *J. Agric. West. Aust.* **2**: 492–3.

Sutherland, D. N. (1952). Copper deficiency in cattle in Queensland. *Aust. vet. J.* **28**: 204–8.

——— (1959). Factors affecting the performance of beef cattle on unimproved pastures in Queensland. *Aust. vet. J.* **35**: 129–34.

——— (1961). The beef cattle industry in Queensland. In *Introducing Queensland.* Brisbane, Government Printer. pp. 61–5.

——— (1967). The beef cattle industry in northern Australia. *World Rev. Anim. Prod.* **3**: 32–7.

Suttle, N. F. and Field, A. C. (1967). The effects of feeding a diet of low copper content to lambs. *Proc. Nutr. Soc.* **26**: 15–16.

Sweeney, F. C. (1968). Soils of the Dawson-Fitzroy area. *CSIRO Aust., Land Res. Ser.* **21**: 135–56.

Synge, R. L. M. and White, E. P. (1959). Sporidesmin: a substance from *Sporidesmium bakeri* causing lesions characteristic of facial eczema. *Chemy Ind.* **49**: 1546–7.

Takahashi, M. and Ripperton, J. C. (1949). Koa Haola (*Leucaena glauca*). Its establishment, culture, and utilisation as a forage crop. *University of Hawaii agric. Exptl Stn Bull.* **100**.

Tanaka, A., Kwano, K., and Yamaguchi, J. (1966). Photosynthesis, respiration and plant type of the tropical rice plant. *Tech. Bull. Int. Rice Res. Inst.* **7**: 1–46.

Taylor, K. L. (1958). Insect pests of pastures. *Proc. Aust. Agrostology Conference.*

Taylor, R. M., McKenzie, R. M., and Norrish, K. (1964). The mineralogy and chemistry of manganese in some Australian soils. *Aust. J. Soil Res.* **2**: 235–48.

Taylor, T. G. (1907). The Lake George senkungsfeld, a study of the evolution of Lakes George and Bathurst, N.S.W. *Proc. Linn. Soc. N.S.W.* **32**: 325–45.

Teakle, L. J. H. (1937). Saline soils of Western Australia and their utilisation. *J. Dep. Agric. West. Aust.* **14** (2nd Ser.): 313–24.

——— (1945). Experiments with phosphatic fertilisers 1943 and 1944. *J. Dep. Agric. West. Aust.* **22** (2nd Ser.): 100–217.

——— and Cariss, H. G. (1944). Experiments with serpentine superphosphate and phosphatic guano as fertilisers for the wheat crop. *J. Dep. Agric. West. Aust.* **21** (2nd Ser.): 143–8.

———, Morgan, E. T., and Turton, A. G. (1941). Experiments with micro-elements for the growth of crops in Western Australia. III. Experiments with pastures, vegetables and other crops in the Albany District. *J. Dep. Agric. West. Aust.* **18**: 96–125.

Tennant, D. (1968). Aspects of seed development and production in subterranean clover (*Trifolium subterraneum* L.). Ph.D. Thesis, University of Western Australia.

Thain, R. I. (1955). Cobalt deficiency in sheep and cattle. *Tasm J. Agric.* **26**: 154–64.

——— (1966). Bovine infertility possibly caused by subterranean clover. Further report and herd histories. *Aust. vet. J.* **42**: 199–203.

——— (1968). Residual herd infertility in cattle. *Aust. vet. J.* **44**: 218–22.

——— and Robinson, E. G. (1968). The high isoflavone content of red leaves in the Mt Barker strain of subterranean clover. *Aust. J. Sci.* **31**: 121–2.

Theiler, A. and Green, H. H. (1932). Aphosphorosis in ruminants. *Nutr. Abstr. Rev.* **1**: 359–85.

———, ———, and Du Toit, P. J. (1927). Minimum mineral requirements in cattle. *J. agric. Sci.* **17**: 291–314.

Thornthwaite, C. W. (1948). An approach toward a rational classification of climate. *Geog. Rev.* **38**: 35–94.

Thornton, R. H. and Percival, J. C. (1959). A hepatotoxin from *Sporidesmium bakeri* capable of producing facial eczema diseases in sheep. *Nature, Lond.* **183**: 63.

Tindale, N. B. (1959). Ecology of primitive Aboriginal man in Australia. *Biogeography and Ecology in Australia* (Series Monographiae Biologicae) **8**: 3651.

Tisdall, A. L. (1961). Australian water policy. *J. Aust. Inst. agric. Sci.* **27**: 55–60.

Tiver, N. S. (1955). Deficiencies in South Australian soils. *J. Dep. Agric. S. Aust.* **59**: 100–13.

——— (1958a). Lessons from ten years land development—Scrub to pasture in the south-east. *J. Dep. Agric. S. Aust.* **62**: 117–34.

——— (1958b). Fertilisers on deep sands—New facts about applying lime, trace elements. *J. Dep. Agric. S. Aust.* **62**: 141–3, 153.

Tomlinson, A. R., Gooding, C. D., and Harrison, L. A. (1954). The wallaby menace in the Kimberleys. Control experiments June–October 1953. *J. Agric. West. Aust.* **3** (3rd Ser.): 609–17.

Toms, J. (1958). Manganese deficiency of subterranean clover in Western Australia. *J. Agric. West. Aust.* **7**: 215–16.

Toms, W. J. and Fitzpatrick, E. N. (1961). Potassium deficiency in medium rainfall areas. *J. Agric. West. Aust.* **2** (9): 763–73.

Torssell, B. W. R., Begg, J. E., Rose, C. W., and Byrne, G. F. (1968). Stand morphology of Townsville lucerne (*Stylosanthes humilis*): seasonal growth and root development. *Aust. J. exp. Agric. Anim. Husb.* **8**: 533–43.

Tow, P. G. (1960). Some ways of establishing Glycine. *Qd agric. J.* **86**: 425–7.

——— (1967). Controlled climate comparisons of a tropical grass and legume. *Neth. J. agric. Sci.* **15**: 141–54.

Tribe, D. E. and Peele, L. (1963). Body composition of the kangaroo *Macropus* sp. *Aust. J. Zool.* **11**: 273–89.

Trumble, H. C. (1935). The relation of pasture development to environmental factors in South Australia. *J. Dep. Agric. S. Aust.* **38**: 1460–87.

——— (1937). The climatic control of agriculture in South Australia. *Trans. R. Soc. S. Aust.* **61**: 41–62.

——— (1939). Barrel medic (*Medicago tribuloides*, Desr.) as a pasture legume. *J. Dep. Agric. S. Aust.* **42**: 953–8.

——— and Donald, C. M. (1938a). The relation of phosphate to the development of seeded pasture on a podzolised sand. *Coun. scient. ind. Res. Aust. Bull.* **116**.

——— and ——— (1938b). Soil factors in relation to the distribution of subterranean clover and some alternative legumes. *J. Aust. Inst. agric. Sci.* **4**: 206–8.

——— and Ferres, H. M. (1946). Responses of herbage legumes to applied nutrients on some southern Australian soils and their dependence on external factors. *J. Aust. Inst. agric. Sci.* **12**: 32–43.

Tulloch, D. (1967). The distribution, density and social behaviour of the water buffalo *Bubalus bubalis* (Lydekker) in the Northern Territory. M.Agr.Sc. Thesis, University of Queensland.

Turnbull, K. E., Braden, A. W. H., and George, J. M. (1966). Fertilisation and early embryonic losses in ewes that had grazed oestrogenic pastures for 6 years. *Aust. J. agric. Res.* **17**: 907–17.

———, Shutt, D. A., and Braden, A. W. H. (1967). Increase in chloride content of cervical mucus as a simple test for impending ovulation and for oestrogenic stimulation in ewes. *Aust. J. exp. Agric. Anim. Husb.* **7**: 314–7.

Twidale, C. R. (1966). Geomorphology of the Leichhardt–Gilbert area of north-west Queensland. *CSIRO Aust., Land Res. Ser.* **16**: 115–28.

——— (1967). Hillslopes and pediments in the Flinders Ranges, South Australia. In *Landform Studies from Australia and New Guinea* ed. J. N. Jennings and J. A. Mabbutt. Canberra, A.N.U. Press. pp. 95–117.

Underwood, E. J., Beck, A. B., and Shier, F. L. (1939). Further experiments on the incidence and control of pica in sheep in the botulism areas of Western Australia. *Aust. J. exp. Biol. med. Sci.* **17**: 183–92.

——— and Filmer, J. F. (1935). Enzootic marasmus: the determination of the biologically potent element (cobalt) in limonite. *Aust. vet. J.* **11**: 84–92.

———, Shier, F. L., and Beck, A. B. (1940). Experiments in the feeding of phosphorus supplements to sheep in Western Australia. *J. Dep. Agric. West. Aust.* **17** (2nd Ser.): 388–405.

———, ———, and Harvey, R. J. (1937). An investigation into the composition of Western Australian wheat belt pastures and stubbles. *J. Dep. Agric. West. Aust.* **14** (2nd Ser.): 442–7.

——— and ——— (1951). The permanence of the oestrogenic effects of subterranean clover grazing on the ewe. *Aust. vet. J.* **27**: 63–7.

Uvarov, B. P. (1964). Problems of insect ecology in developing countries. *J. appl. Ecol.* **1**: 159–68.

van Dijk, D. C. (1959). Soil features in relation to erosional history in the vicinity of Canberra. *CSIRO Aust., Soil Publ.* **13**.

Vimpany, I. A. (1967). Soil testing for potassium. *J. Aust. Inst. agric. Sci.* **33**: 296–301.

Vincent, J. M. (1941). Serological studies of the root-nodule bacteria. I. Strains of *Rhizobium meliloti*. *Proc. Linn. Soc. N.S.W.* **66**: 145–54.

——— (1942). Serological studies of the root nodule bacteria. II. Strains of *Rhizobium trifolii*. *Proc. Linn. Soc. N.S.W.* **67**: 82–6.

——— (1954). The root nodule bacteria of pasture legumes. *Proc. Linn. Soc. N.S.W.* **79**: 4–32.

——— (1956). Strains of rhizobia in relation to clover establishment. *Proc. 7th Int. Grassld. Congr.*: 179–89.

——— (1958). Survival of the root nodule bacteria. In *Nutrition of the legumes* ed. E. G. Hallsworth. London, Butterworths. pp. 108–23.

——— (1962a). Australian studies of the root nodule bacteria. A review. *Proc. Linn. Soc. N.S.W.* **87**: 8–38.

——— (1962b). Influence of calcium and magnesium on the growth of Rhizobium. *J. gen. Microb.* **28**: 653–64.

——— (1965). Environmental factors in the fixation of nitrogen by legumes. In Agronomy Series No. 10, *Soil Nitrogen*. American Society of Agronomy, pp. 384–435.

——— (1967). Symbiotic specificity. *Aust. J. Sci.* **29**: 192–7.

Voisey, A. H. (1956). Erosion surfaces around Armidale, New South Wales. *J. R. Soc. N.S.W.* **90**: 128–33.

Wadham, S. M. and Wood, G. L. (1964). *Land utilisation in Australia*, 4th ed. Melbourne, Melbourne University Press.

Walker, A. J. K. (1954). Control of bulbous perennials with particular reference to the Cape tulip (*Homeria* spp.). *Aust. Weed Control Conf. Report*: 115–28.

Walker, D. J., Harris, A. N. A., Farleigh, E. A., Setchell, B. P., and Littlejohns, I. R. (1961). Muscular dystrophy in lambs in N.S.W. *Aust. vet. J.* **37**: 172–5.

Wallace, M. M. H. (1954). The effect of DDT and BHC on the population of the lucerne flea, *Sminthurus viridis* (L.) (Collembola), and its control by predatory mites, *Biscirus* spp. (Bdellidae). *Aust. J. agric. Res.* **5**: 148–55.

——— (1963). Seed treatment with systemic insecticides for control of red-legged earth mite (*Halotydeus destructor*). *Aust. J. exp. Agric. Anim. Husb.* **3**: 357–64

——— (1968). The ecology of *Sminthurus viridis* (L.) (Collembola). I. Processes influencing numbers in pastures in Western Australia. *Aust. J. Zool.* **15**: 1173–206.

——— and Mahon, J. A. (1952). Webworm damage to pastures in the south-west of Western Australia. *J. Aust. Inst. agric. Sci.* **18** (2): 91–4.

——— and ——— (1963). The effect of insecticide treatment on the yield and botanical composition of sown pastures in Western Australia. *Aust. J. exp. Agric. Anim. Husb.* **3**: 39–50.

Walter, H. and Leith, H. (1967). *Klimadiagramm Weltatlas*. Jena, Gustav Fischer Verlag.

Walsh, S. R. (1959). Improved pastures will fatten cattle in far north. *Qd agric. J.* **85**: 576–92.

Waring, E. J. (1959). Supplementary irrigation of pastures in humid areas. *Rev. Mktg agric. Econ.* **27** (4): 239–54.

Warmke, H. E. (1954). Apomixis in *Panicum maximum*. *Am. J. Bot.* **41**: 5–11.

Warren Wilson, J. (1967). Effects of seasonal variation in radiation and temperature on net assimilation and growth rates in an arid climate. *Ann. Bot.* **31**: 41–57.

Waterhouse, D. F. (1967). The entomological control of weeds in Australia. *Mushi* **39** (Suppl.): 109–18.

Watson, A. S. (1967). The effects of breed, sex and age distribution of Australian sheep population on drought losses and drought recovery. *Proceedings of Bankers' Conference on Drought*, Sydney.

Watson, E. R. (1963). The influence of subterranean clover pasture on soil fertility. I. Short term effects. *Aust. J. agric. Res.* **14**: 796–807.

——— and Lapins, P. (1964). The influence of subterranean clover pasture on soil fertility. II. The effect of certain management systems. *Aust. J. agric. Res.* **15**: 885–94.

Watson, K. A. (1967). Land clearing—techniques and cost. *Proc. Weed Soc. N.S.W.* **1**: 8–1, 8–4.

Webb, L. J. (1948). Guide to the medicinal and poisonous plants of Queensland. *Coun. scient. ind. Res. Aust. Bull.* **232**.

——— (1959). A physiognomic classification of Australian rain forests. *J. Ecol.* **47**: 551–70.

Webster, I. D. and Whan, R. B. (1967). The effect of vegetable fault on the price paid for wool. *Proc. Weed Soc. N.S.W.* **1**: 10–1, 10–9.

Wells, G. J. (1967). Research into skeleton weed control in the Mallee. *J. Agric. Vict. Dep. Agric.* **65**: 277–83, 320–2.

West, O. (1952). Promising new grasses for seeded pastures in southern Rhodesia. *Rhodesia Agric. J.* **49**: 89–95.

Wetherall, R. S. (1963). Plant nutrition studies in the Hunter Valley. *Agric. Gaz. N.S.W.* **74**: 83–9.

Wetselaar, R. (1967). Estimation of nitrogen fixation by four legumes in a dry monsoonal area of north-western Australia. *Aust. J. exp. Agric. Anim. Husb.* **7**: 518–22.

——— and Norman, M. J. T. (1960). Soil and crop nitrogen at Katherine, N.T. *CSIRO Aust., Div. Land Res. Reg. Sur. Tech. Pap.* **10**.

Wheeler, J. L. (1965). The improvement of winter feed in year-long grazing programmes. *Proc. 9th Int. Grassld. Congr.*: 975–80.

White, L. D., Lightfoot, R. J., and Glencross, R. N. (1966). The Avondale stocking rate experiment. *J. Agric. West. Aust.* **7**: 442–55.

White, R. E. (1967). Nutrient requirements of white clover based pastures on a krasnozem basalt at Maleny, south-eastern Queensland. *Aust. J. exp. Agric. Anim. Husb.* **7**: 509–14.

Whitehead, D. C. (1966). Nutrient minerals in grassland herbage. *Comm. Bur. Past. Fld Crops* Mimeo.

Whitehouse, F. W. (1944). The natural drainage of some very flat monsoonal lands. *Aust. Geog.* **4**: 183–96.

Whiteman, P. C. (1968). The effects of temperature on the vegetative growth of six tropical legume species. *Aust. J. exp. Agric. Anim. Husb.* **8**: 528–32.

Whittet, J. N. (1964). *Pastures of New South Wales.* Sydney, Department of Agriculture.

Wilcox, D. G. and Speck, N. H. (1963). Pastures and pasture lands of the Wiluna–Meekatharra area. *CSIRO Aust., Land Res. Ser.* **7**: 162–77.

Wild, A. (1958). The phosphate content of Australian soils. *Aust. J. agric. Res.* **9**: 193–204.

Wilkie, W. J. (1966). Beef cattle and production in Western Australia. *J. Agric. West. Aust.* **7**: 343–50.

Wilkins, Jean (1967). The effect of high temperatures on certain root nodule bacteria. *Aust. J. agric. Res.* **18**: 299–304.

Williams, C. H. (1950). Studies on soil phosphorus. II. The nature of native and residual phosphorus in some South Australian soils. *J. agric. Sci.* **40**: 243–56.

——— (1962). Changes in nutrient availability in Australian soils as a result of biological activity. *J. Aust. Inst. agric. Sci.* **28**: 196–205.

——— (1968). Seasonal fluctuations in mineral sulphur under subterranean clover pasture in southern New South Wales. *Aust. J. Soil Res.* **6**: 131–9.

——— and Donald, C. M. (1957). Changes in organic matter and pH in a podzolic soil as influenced by subterranean clover and superphosphate. *Aust. J. agric. Res.* **8**: 179–89.

——— and Hines, H. J. G. (1940). The toxic principles of *Salvia reflexa*. *Aust. vet. J.* **16**: 14–20.

——— and Lipsett, J. (1960). The build-up of available potassium under subterranean clover pastures on a podzolic soil. *Aust. J. agric. Res.* **11**: 473–84.

——— and Simpson, J. R. (1965). Some effects of cultivation and waterlogging on the availability of phosphorus in pasture soils. *Aust. J. agric. Res.* **16**: 413–27.

Williams, D. B. (ed.) (1967). *Agriculture in the Australian Economy.* Sydney, Sydney University Press.

Williams, O. B. (1955). Studies in the ecology of the Riverine Plain. I. The gilgai microrelief and associated flora. *Aust. J. Bot.* **3**: 99–112.

——— (1956). Studies in the ecology of the Riverine Plain. II. Plant-soil relationships in three semi-arid grasslands. *Aust. J. agric. Res.* **7**: 127–39.

——— (1961). Studies in the ecology of the Riverine Plain. III. Phenology of a *Danthonia caespitosa* Gaudich. grassland. *Aust. J. agric. Res.* **12**: 247–59.

——— (1963). Row pastures for a semi-arid environment. *CSIRO Aust., Fld Stn Rec.* **2**(2): 41–54.

——— (1964). A relationship between forage availability and wool growth-rates for high and low producing sheep. *Proc. Aust. Soc. Anim. Prod.* **5**: 280–3.

——— (1968). Studies in the ecology of the Riverine Plain. IV. Basal area and density changes in *Danthonia caespitosa* Gaudich. in a natural pasture grazed by sheep. *Aust. J. Bot.* **16**: 565–78.

——— and Schinckel, P. G. (1962). Seasonal variations in wool growth and liveweight in several environments. *Proc. Aust. Soc. Anim. Prod.* **4**: 38–52.

Williams, R. J. (1955). Vegetation regions. In *Atlas of Australia.* Canberra, Commonwealth Department of National Development.

——— (1966). Preliminary report on the CSIRO plant collecting mission to Brazil and adjacent countries 1965. *CSIRO Aust., Div. Pl. Ind. Plant Introduction Review* **3**: 18–26.

Williamson, W. H. (1964). The development of underground water resources. In *Water resources, use and management.* Melbourne, Melbourne University Press. pp. 195–211.

Willoughby, W. M. (1954). Some factors affecting grass–clover relationships. *Aust. J. agric. Res.* **5**: 157–80.

——— (1958). A relationship between pasture availability and animal production. *Proc. Aust. Soc. Anim. Prod.* **2**: 42–5.

——— (1959). Limitations to animal production imposed by seasonal fluctuations in pasture and by management procedures. *Aust. J. agric. Res.* **10**: 248–68.

Wilson, A. A. (1964). Hypomagnesaemia and magnesium metabolism. *Vet. Rec.* **76**: 1382–92.

Wilson, A. D. (1966a). The growth rate of weaner sheep on irrigated pastures. *Proc. Aust. Soc. Anim. Prod.* **6**: 179–81.

——— (1966b). The intake and excretion of sodium by sheep fed on species of *Atriplex* (saltbush) and *Kochia* (bluebush). *Aust. J. agric. Res.* **17**: 155–63.

——— and Hindley, N. L. (1968). The value of the seed, pods and dry tops of subterranean clover (*Trifolium subterraneum*) in the summer nutrition of sheep. *Aust. J. exp. Agric. Anim. Husb.* **8**: 168–71.

Wilson, G. P. M. and Murtagh, G. J. (1962). Lablab—new forage crop for the north coast. *Agric. Gaz. N.S.W.* **73**: 460–2.

Wilson, R. G. (1961). Sowing pastures in south-west Queensland. *Qd agric. J.* **87**: 214–25.

——— (1963). Bambatsi grass for Downs and Brigalow. *Qd agric. J.* **89**: 118–19.

Wood, J. G. (1929). Floristics and ecology of the mallee. *Trans. R. Soc. S. Aust.* **53**: 359–78.

——— (1937). *The vegetation of South Australia.* Adelaide, Government Printer.

Wopfner, H. and Twidale, C. R. (1967). Geomorphological history of the Lake Eyre Basin. In *Landform Studies from Australia and New Guinea* ed. J. N. Jennings and J. A. Mabbutt. Canberra, A.N.U. Press. pp. 118–43.

Wright, R. L. (1964). Geomorphology of the West Kimberley area. *CSIRO Aust., Land Res. Ser.* **9**: 101–18.

Wutoh, J. G., Hutton, E. M., and Pritchard, A. J. (1968a). The effects of photoperiod and temperature on flowering in *Glycine javanica*. *Aust. J. exp. Agric.*

Anim. Husb. **8**: 544–7.

———, ———, and ——— (1968b). Combining ability in *Glycine javanica*. *Aust. J. agric. Res.* **19**: 411–18.

———, ———, and ——— (1968c). Inheritance of flowering time, yield, and stolon development in *Glycine javanica* L. *Aust. J. exp. Agric. Anim. Husb.* **8**: 317–22.

Wynne, K. N. and McClymont, G. L. (1956). Copper–molybdenum–sulphate interaction in induction of ovine hypocupraemia and hypocuprosis. *Aust. J. agric. Res.* **7**: 45–56.

Yates, J. J., Edye, L. A., Davies, J. G., and Haydock, K. P. (1964). Animal production from a *Sorghum almum* pasture in south-east Queensland. *Aust. J. exp. Agric. Anim. Husb.* **4**: 326–35.

Young, N. D., Fox, N. F., and Burns, M. A. (1959). A study of three important pasture mixtures in the Queensland sub-tropics: Progress report, 1955–8. *Qd J. agric. Sci.* **16**: 199–215.

Zimmer, W. J. (1937). The flora of the far north-west of Victoria. *For. Commw. Vict. Bull.* **2**.

INDEX

Designed by Arthur Stokes
Text set in 10 on 11 pt Monotype Times Roman
by The Universities Press Pty Ltd Melbourne
and printed on Provincial Georgian Offset 89 g.s.m. paper
by Halstead Press Pty Ltd Sydney

THE AUTHORS

C. S. Andrew
P. M. Barrow
A. W. H. Braden
W. W. Bryan
J. E. Coaldrake
R. W. Condon
A. B. Costin
J. Griffiths Davies
C. M. Donald
E. A. Fitzpatrick
H. J. Frith
Fred H. G. Gruen
W. J. Hosking
G. D. Hubble
E. M. Hutton
J. H. Leigh
J. A. Mabbutt
Ian W. McDonald
P. W. Michael
R. Milton Moore
L. F. Myers
R. J. Newman
H. A. Nix
M. J. T. Norman
D. O. Norris
P. G. Ozanne
D. F. Paton
F. B. Pearson
R. A. Perry
R. C. Rossiter
N. H. Shaw
M. E. Sullivan
M. M. H. Wallace
C. H. Williams
W. M. Willoughby

Jacket design by Arthur Stokes
Jacket photographs by courtesy of CSIRO

Printed in Australia