Northern Australia: Progress and prospects Volume 2

Floodplains research

Edited by
Deborah Wade-Marshall and Peter Loveday

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CONTENTS

Appendices:

CONTENTS VOLUME 1 -
CONTEMPORARY ISSUES IN DEVELOPMENT

LIST OF PARTICIPANTS

Dr Jon Altman
Department of Political and Social Change
Research School of Pacific Studies
Australian National University
GPO Box 4
CANBERRA ACT 2601

Dr Ross Babbage
Strategic and Defence Studies Centre
Research School of Pacific Studies
Australian National University
GPO Box 4
CANBERRA ACT 2601

Dr Marilyn Ball
North Australia Research Unit
Australian National University
PO Box 41321
CASUARINA NT 5792

Dr John Chappell
Department of Biogeography & Geomorphology
Research School of Pacific Studies
Australian National University
GPO Box 4
CANBERRA ACT 2601

Dr Lorraine Corner
Department of Demography, RSSS/
Population & Manpower Studies Centre
Indonesian Institute of Sciences (LIPI)
Jakarta
INDONESIA

Dr Don Dayananda
North Australia Research Unit
Australian National University
PO Box 41321
CASUARINA NT 5792

Mr Michael Dillon
10 Cowan Street
DOWNER ACT 2602

Dr Max Finlayson
Alligator Rivers Region Research Institute
Office of the Supervising Scientist
PMB JABIRU NT 5796

Dr James J. Fox
Department of Anthropology
Research School of Pacific Studies
Australian National University
GPO Box 4
CANBERRA ACT 2601

Mr Dan Gillespie
Australian National Parks & Wildlife Service
GPO Box 1260
DARWIN NT 5794

Mr David Hegarty
Strategic and Defence Studies Centre
Research School of Pacific Studies
Australian National University
GPO Box 4
CANBERRA ACT 2601

Professor John H. Holmes
Department of Geography
University of Queensland
ST LUCIA Qld 4067

Dr Rhys Jones
Department of Prehistory
Research School of Pacific Studies
Australian National University
GPO Box 4
CANBERRA ACT 2601

Col J.O. Langtry
Strategic and Defence Studies Centre
Research School of Pacific Studies
Australian National University
GPO Box 4
CANBERRA ACT 2601

Mr Andrew McWilliam
Department of Anthropology
Research School of Pacific Studies
Australian National University
GPO Box 4
CANBERRA ACT 2601

Dr Betty Meehan
Division of Anthropology
Australian Museum
PO Box A285
SYDNEY SOUTH NSW 2621

Professor Henry Nix
Director
CRES
Australian National University
GPO Box 4
CANBERRA ACT 2601

Dr Ciaran O'Faircheallaigh*
North Australia Research Unit
Australian National University
PO Box 41321
CASUARINA NT 5792

*Present address:
School of Administration
Griffith University
NATHAN Q 4111

Dr Owen Stanley
Business Faculty
New South Wales Institute of Technology
PO Box 123
BROADWAY NSW 2007

Dr John Taylor
North Australia Research Unit
Australian National University
PO Box 41321
CASUARINA NT 5792

Dr Colin Woodroffe*
North Australian Research Unit
Australian National University
PO Box 41321
CASUARINA NT 5789

*Present address:
Department of Geography
University of Woolongong
WOLLONGONG NSW 2500

Dr Elspeth Young
Australian Defence Force Academy
CAMPBELL ACT 2601

PREFACE

The conference on north Australian studies, held in Darwin in November 1987, was the second on this subject held by the Australian National University's Research School of Pacific Studies. The first was held in Canberra in 1978 and Rhys Jones edited the proceedings in a volume entitled Northern Australia: Options and Implications (Research School of Pacific Studies, 1980).

The theme of the conference was expansive and papers were presented on northern defence, the Northern Territory economy, Aborigines and the economy, Indonesia, northern Australia and Timor, the prehistory of north Australia, the wetlands and tidal floodplains, the ecophysiology of mangroves. Some of these were topics at the 1978 conference, some were new but all reflected work done by staff of the School, either in Canberra or Darwin or by people who have close connections with the work of the School either in the past or in present times.

The conference ran over three days and participants generally thought that it was very successful. The coverage given to it by media, both locally in Darwin and nationally, helped to make the northern research of the School more widely known.

Professor John Holmes was invited to prepare an overview of the conference at its close and in these proceedings his paper has been brought forward as an introduction to the two volumes. It appears only in volume 1.

The papers, although presented in an order similar to that in which they were originally given, have been split into two volumes for ease of production. This enabled us to make one or two changes to the order of the papers to group together in one volume those of principally social science interest while those of more natural science interest fall in the second volume. There is however overlap between the two: the modern economy of the north, for example, is largely shaped by physical determinants such as pastoral capacity and mineral formation; defence depends on an intimate knowledge of the coasts and rivers and of the people who inhabit the area; Aboriginal interaction with the contemporary economy is still shaped by the traditions built up in a landscape which is one of the oldest inhabited in the world.

As editors we must note that two of the papers from the conference reached us after the deadline for receipt of copy for publication. It was impossible to edit them or to retype them and rather than exclude them from the collection we included them as unedited appendices in this volume. Unfortunately one other paper which provoked considerable discussion, Professor Henry Nix's on Agricultural Futures, did not reach us in written form at all and we hope that it will eventually be published elsewhere.

CHANGING MANGROVE AND WETLAND HABITATS OVER THE LAST 8000 YEARS, NORTHERN AUSTRALIA AND SOUTHEAST ASIA

Colin Woodroffe

The morphology of river estuaries or deltas, and associated depositional landforms, reflect processes operating upon them. They may be river dominated, tidally-dominated, dominated by wave energy, or intermediate and responding to more than one of the above (Wright 1985). Form is rarely constant, and the study of landform changes is termed morphodynamics. Coastal morphodynamics in northern Australia has been reviewed by Chappell and Thom (1986).

Two broad patterns of Holocene coastal sedimentation can be recognised. Where the coastline is relatively straight and shallow, without structural embayments, coastal progradation occurs, and suites of landforms build out progressively. This has occurred on chenier plains (i.e. Karumba, Rhodes 1982; Princess Charlotte Bay, Chappell and Grindrod 1984; Broad Sound, Cook and Polach 1973), or river deltas on the southern Gulf of Carpentaria (i.e. McArthur River). However, where the coastline is highly indented, and the pre-Holocene topography contains numerous drowned valley systems, estuarine infill has predominated over coastal progradation.

Along the coast of the seasonally-wet tropics of northern Australia are a series of estuarine systems. These can be divided, on the basis of structure, hydrodynamics and mangrove floristics, into: i) structurally-controlled drainage systems (i.e. NW Kimberley); ii) tidal rivers which meander across extensive Holocene plains; iii) harbours and large embayments; and iv) short coastal inlets with minor catchments (Wells 1985). The second category, meandering tidal rivers, occur where estuarine infill has led to the establishment of widespread plains, supporting a variety of wetland habitats. The wetland habitats represent important resources, both in traditional Aboriginal economies and, in view of the diverse and abundant wildlife they support, in tourist-oriented management of areas such as the Kakadu National Park. Mangrove forests are also very productive and support detritus-based estuarine food webs, on which much of the north Australian fisheries are presently based. Several of these river systems have been the focus of the 'mangrove and tidal rivers project' at NARU, and it is these systems which are the subject of this paper.

A model of the evolution of the tidal river and plains of the South Alligator River has been reported by Woodroffe et al. (1986). Morphological similarity between that river and several others in the Northern Territory indicate that other river systems have undergone a similar pattern of development (Chappell and Woodroffe 1985). In this volume Chappell (1988) has shown how geomorphological dynamics of the lower Daly, South Alligator and Adelaide river systems differ as a function of the interaction between sediment supply and fluviatile and tidal flows.

Changes in the extent and distribution of mangrove and wetland habitats have occurred as a response to geomorphological changes. In this paper development of the freshwater wetland habitats on the floodplains of the South Alligator estuarine system over the last 8000 years is examined. The model of estuarine development has application to other systems in a similar tectonic and climatic setting on the Northern Territory coastline. However, there is also evidence for a similar change of estuarine systems in more arid (Ord and Fitzroy Rivers, Western Australia) and more humid (Baram River, Sarawak) climates (Fig. 1). In the former case the plains are covered by saline mudflats, in the latter by peat swamps.

Morphodynamics of the South Alligator Tidal River and Plains

The South Alligator River and its major tributaries rise on the sandstone Arnhemland plateau and their lower reaches traverse gently undulating lateritic plains covered by open forest or woodland of *Eucalyptus tetrodonta* and *E. miniata*. Spring tidal range in van Diemen Gulf is 5-6 m and tidal influence extends 105 km upstream because of the low gradient of the plains. The area receives 1300-1400 mm annual precipitation (1340 mm at Oenpelli), most of which falls in the wet season, November to May. During the wet season most of the lower river is freshwater, though tidally reversing. During the dry season, tidal flows are rapid and salt water penetrates progressively upstream until in the late dry there is often no fluviatile flow and the tidal reach is well mixed and saline throughout.

The stratigraphy of the deltaic-estuarine plain of the South Alligator River has been described in detail, based on more than 100 drillholes, pollen analysis and radiocarbon dating by Woodroffe et al. (1986). Much of the subsurface is composed of bluish-gray estuarine clays, with fibrous or woody organic fragments. Pollen analysis has confirmed that most of these were deposited beneath mangrove forests (Chappell and Grindrod 1985). These mangrove muds occur both at the base of drillholes, where they are transgressive recording marine incursion into a prior valley, and in an upper layer, 1-5 m below the plains surface. The majority of radiocarbon dates on this upper mangrove mud fall in a range 6800-5300 years B.P., indicating widespread mangroves

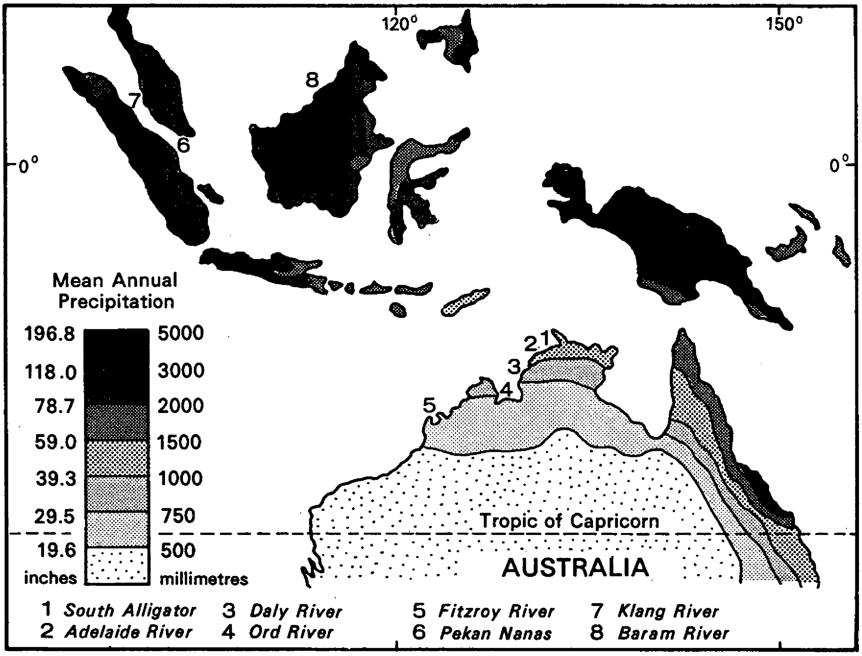

Figure 1: Mean annual precipitation in northern Australia and Southeast Asia, and location of rivers described.

at that time, termed the 'big swamp' by Woodroffe et al. (1985). The ages show no discernible spatial trend (see Figure 3 of Chappell 1988). The axis of the valley contains younger sediments, both laminated sands and muds deposited on channel margins, and channel fill clays deposited in paleochannels, associated with the migration of the river. These, and floodplain clays deposited from wet season over-bank floods, have been deposited since 6000 years B.P.

Estuarine infill within the South Alligator system has occurred in 4 phases (Woodroffe et al. 1986).

i) Transgressive phase (8000-6800 years B.P.). Marine incursion into, and mangrove forest establishment within, a prior valley occurred about 8000-7800 years B.P. when sea level was 10-12 m below present. Mangrove forest expanded with landward encroachment on terrestrial forest and woodland as sea level rose. The inferred distribution of mangrove about 7000 years B.P. during the transgressive phase in the South Alligator system is shown in Figure 2 (based on Woodroffe et al. 1986, Fig. 70).

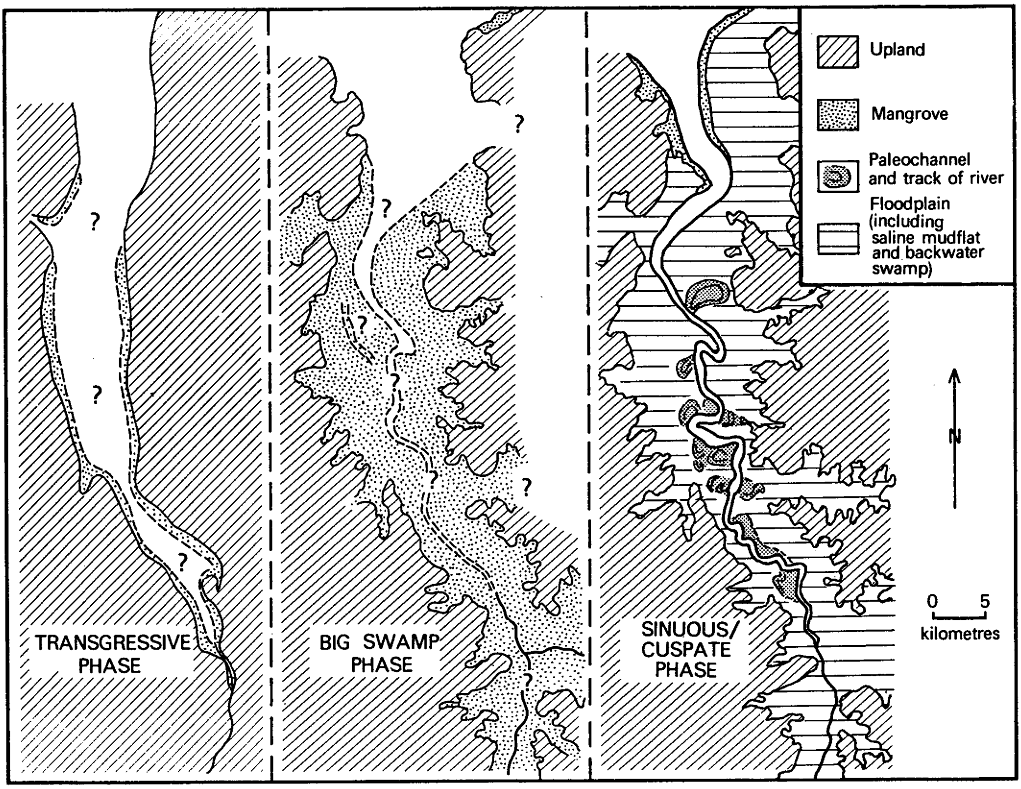

Figure 2: Transgressive, big swamp and sinuous/cuspate phases in the development of the South Alligator tidal river and plains.

ii) Big swamp phase (6800-5300 years B.P.). Widespread mangrove forest occurred as sea level decelerated and stabilised. Mangrove muds underlie most of the freshwater clays of the floodplain (except at the mouth of the river where some progradation of the estuarine funnel has occurred, Woodroffe _et al_. 1986). River bank erosion at several locations has exposed numerous _in situ_ mangrove stumps, with associated sub-fossil molluscan and crustacean fauna, also of big swamp age. The proven and inferred distribution of mangrove forests during the big swamp phase is shown in Figure 2 (based on Woodroffe _et al_. 1986, Fig. 71).

iii) Sinuous phase (approx. 5300-2000 years B.P.). This phase is one during which the river increased its sinuosity. The channel migrated across the plains and several meander cutoffs occurred, as recorded by laminated channel and paleochannel sediments within the track of the river. Freshwater floodplain clays also accumulated during this phase after the disappearance of mangrove forest.

iv) Cuspate phase (after 2500 years B.P.). This is the most recent phase and is denoted by a change of channel meander form from sinuous to cuspate (marked by sharp inner bends or meander spurs). This form has been adopted only in part of the South Alligator River and is discussed in more detail by Chappell (1987) and Vertessey and Chappell (in prep.).

The sinuous and cuspate phases relate to changes in channel morphology, and will not be differentiated in the broad discussion of mangrove and wetland habitat change that follows. The distribution and extent of mangrove and floodplain appear to have remained fairly similar throughout sinuous and cuspate phases and are shown in Figure 2. The track within which the river has migrated is also shown on this figure. The river has devoured its floodplain, migrating, where it has been active, at an average rate of 1 m yr^{-1}. It has eroded away big swamp deposits from about 20 per cent of the mid plains area. *In situ* big swamp mangrove stumps are only exposed in erosional river banks outside this meander track.

Mangrove and Wetland Habitats of the South Alligator River

The present mangrove forests of the South Alligator River are not extensive. On the coastal plain there is a zoned mangrove forest about 200 m wide, comprising a seaward open forest of *Sonneratia alba* and *Camptostemon schultzii*, an intermediate zone of *Rhizophora stylosa*, and a landward zone of *Avicennia marina*. A similar zonation occurs in the estuarine funnel, though the seaward zone is compressed and there is an additional upper intertidal zone, dominated by *Ceriops tagal* var. *australis* found between the *Rhizophora* and *Avicennia* zones. Erosion, particularly on the western bank, has exposed landward mangrove zones to wave attack. Along the meandering river the best developed forests are on meander point bars and along creeks draining paleochannels. *Camptostemon* and *Rhizophora* occur along creeks, *Ceriops* and *Bruguiera exaristata* occupy intermediate locations and *Avicennia*, *Excoecaria agallocha* and *Lumnitzera racemosa* occur at the landward margin of the forest. At the tidal limit *Sonneratia lanceolata* and *Avicennia* fringe the channel (see Davie 1985 for a more detailed account of present mangrove distribution).

The present distribution of mangroves represents a fraction of the area that was covered during the big swamp phase (Fig. 2). Composition of the big swamp forest has been determined from pollen analysis, though not all genera can be differentiated to specific level (Chappell and

Grindrod 1985; Hope et al. 1985; Russell-Smith 1985; Woodroffe et al. 1985, 1986). Assemblages of species appear to have been fairly uniform throughout the big swamp forest, and species had more widespread distributions through the system. Rhizophoraceous species occurred 6000 years ago at sites that are now at the tidal limit and where only Sonneratia lanceolata and Avicennia marina grow.

Pollen diagrams record succession and then elimination of mangrove forests from the plains (Fig. 3). The mangrove forest 6800 years B.P. was Rhizophoraceous, with Rhizophora slowly gaining dominance over Bruguiera/Ceriops. Sonneratia shows a minor peak (at about 3 m below plains surface in SAH40, a mid plains location) which may coincide with attainment of present sea level. Thereafter continued sedimentation was accompanied by successional change from Sonneratia through Rhizophoraceous forest again to stands of Avicennia. The final stage was replacement of mangrove by plains vegetation of grasses and sedges (Poaceae and Cyperaceae).

The upper level of mangrove pollen, occurring within the zone of pronounced oxidation, marks the transition from estuarine to freshwater clays. Where it has been identified by pollen analysis and where accurate survey data are available it appears to be a near-horizontal surface (Woodroffe et al. 1986, Fig. 80; Chappell 1987, Fig. 7). The present slightly convex cross-valley floodplain topography has developed over this near-horizontal surface. The typical morphology from river to upland margin consists of mangrove, saline mudflat, Upper Floodplain, Lower Floodplain and Backwater Swamps (Table 1). The broad Upper Floodplain is beyond the tides which are accommodated in the channel and carries a robust sedge cover. Further from the river Lower Floodplain occurs, with mixed sedges, grasses and herbs, forming ill-drained depressions, 20-30 cm lower than the Upper Floodplain. The lowest-lying areas are backwater swamps which form in reentrants within the uplands. These can be a metre or more below high spring tide levels in the river, but are not inundated by saline water because they are impounded by the higher floodplain adjacent to the river.

The cross-valley convexity of the floodplain surface, over a near-horizontal upper surface to the big swamp mangrove, representing the surface to the plains at around 5000 years B.P., indicates more rapid sedimentation from overbank flows close to the river. A similar form is characteristic of many alluvial floodplains (Lewin 1978). The presence of shell middens several of which are 2000-3000 years old, some being more than 4000 years old, overlying freshwater clays, but only shallowly-buried (20-30 cm) indicate that initially freshwater clays were deposited rapidly (Woodroffe et al.

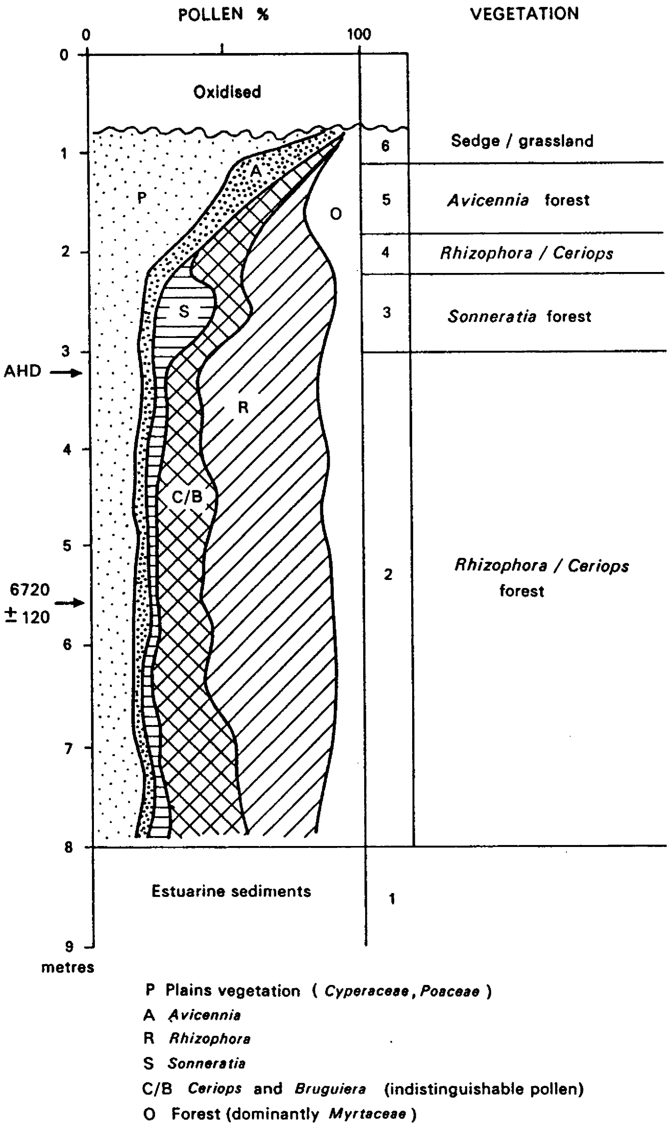

Figure 3: Pollen diagram from SAH40 mid plains, South Alligator River (after Chappell and Grindrod 1985).

1986; Chappell 1988). The Melaleuca swamps (upper backwater swamp) and perennial freshwater lagoons with floating aquatic vegetation (lower backwater swamp) owe their existence to the impounding of wet season freshwater runoff behind the wedge of floodplain clay which separates them from saline waters in the river. It appears that the floodplain adopted its convex form several thousand years ago, prior to formation of anthropogenic shell middens. It can be inferred that the productive backwater swamp wetlands have also been in existence for several thousand years.

Table 1
Equivalence of land/morphological units and vegetational communities on the South Alligator floodplains (based on Woodroffe *et al*. 1986, adapted from Taylor and Dunlop 1985).

Morphological unit (based on Woodroffe *et al*. 1986)	CSIRO land system (Williams *et al*. 1969; Galloway *et al*. 1976)	Vegetation (after Story 1969, 1976)	Vegetation community (after Taylor and Dunlop 1985)	Magela Creek equivalent (after Williams 1979)
Mangrove	Littoral	Mangrove scrub	-	-
Saline mudflat (upper intertidal and salt mudflat)	Littoral	Samphire	-	-
Upper Floodplain	Cyperus	Sedgeland	*Fimbristylis* sedgeland	-
Lower Floodplain	Copeman	Herbaceous swamp	*Oryza* swamp *Eleocharis* swamp	Mixed herbfield Annual swamp
Upper backwater swamp	Effington, Pinwinkle	Paperbark forest	*Melaleuca* swamp	Forest
Lower backwater swamp	Copeman	-	-	Freshwater lagoon

Note: Units do not correspond exactly, either in definition or when mapped.

Vegetation patterning in the wetland habitats of the floodplains is complex but is closely related to elevation, and thus also to frequency and duration of inundation. Taylor and Dunlop (1985) have classified the vegetation into several communities; from river to uplands these comprise *Fimbristylis* sedgeland, *Oryza* swamp, *Eleocharis* swamp, *Melaleuca* swamp, lawn and marginal woodland. Dominant species in these communities are listed in Table 2 (following Taylor and Dunlop 1985).

The general morphological zonation described above (related to other land and vegetation classifications in Table 1) has a gradual longitudinal gradient, being in the upstream segment about 1 m higher (in absolute terms) than at the coast. Net sedimentation over the last 5000 years has been greater at the upstream of the tidal reach where the big swamp mangrove may be buried by 1-1.5 m of floodplain clay, than at the coast where it is generally only shallowly-buried. The floodplain surface has a gradient similar to that of wet season floodwaters. In the upstream segment there are discontinuous levées.

Year to year variation in species composition on the floodplains is to be expected, particularly with a high percentage of annual life-forms in the wetland communities (Taylor and Dunlop 1985). Longer term changes will have occurred as a function of morphological change of the river channel itself. However, many of the wetland communities of the floodplain of the South Alligator River system are likely to have been in existence for the last 4000 years. At present pollen analysis does not allow sufficient differentiation of the wetland species composing the communities, and very few organic remains escape oxidation, to enable refinement of the history of development and succession of the wetland communities. Hope *et al*. (1985) on the basis of a radiocarbon date of 1400 years B.P. in floodplain clays, suggest proliferation of freshwater wetland environments in the last 1500 years at the southern end of the South Alligator deltaic-estuarine plain (Jones 1985). It appears likely that similar wetlands have been present on some parts of the plain for at least twice that length of time.

Mangrove and wetland habitats in the South Alligator River system have altered during the three stages shown in Figure 2; a pre-6000 year transgressive phase of expanding mangrove forests; a 6000-year big swamp phase of widespread mangrove forests; and a post-6000 year sinuous/cuspate phase during which freshwater wetlands have covered the floodplains and have changed little in extent. The morphology of segments of river channel on the Daly and Adelaide River, in comparison with those on the South Alligator, suggests that these rivers might be at different stages in a similar evolutionary sequence (Chappell and

Table 2
Species composition of main vegetation communities on South Alligator floodplains.

Fimbristylis sedgeland	*Oryza* swamp	*Eleocharis* swamp	*Melaleuca* swamp
Aeschynomene indica	*Blyxa* sp.	*Eleocharis dulcis*	*Blyxa* sp.
Bacopa floribunda	*Cyperus procerus*	*Eleocharis sphacelata*	*Centipeda minima*
Clerodendrum inerme	*Eleocharis dulcis*	*Ludwigia adscendens*	*Ceratopteris thalictroides*
Fimbristylis tristachya	*Eleocharis* sp. aff. *brassii*	*Myrtella cordata*	*Commelina lanceolata*
Fuirena ciliaris	*Ludwigia adscendens*	*Najas tenuifolia*	*Cyperus aquatilis*
Hygrophilia salicifolia	*Maidenia rubra*	*Nymphaea violacea*	*Hedyotis* sp.
Ipomoea aquatica	*Oryza meridionalis*	*Utricularia muelleri*	*Hygrophilia salicifolia*
Ipomoea coptica	*Phyllanthus* sp. aff. *urinaria*		*Isoetes coromandelina* ssp. *macrotuberculata*
Ischaemum arundinaceum			*Limnophila indica*
Ischaemum rugosum			*Limnophila fragrans*
Ludwigia octovalvis			*Ludwigia hyssopifolia*
Ludwigia perennis			*Marsilea mutica*
Malachra fasciata			*Melaleuca cajuputi*
Melochia corchorifolia			*Melaleuca leucadendra*
Merremia gemella			*Melaleuca viridiflora*
Monochorea cyanea			*Najas tenuifolia*
Paspalum scrobiculatum			*Nelsonia brunellodes*
Phyllanthus urinaria			*Nymphaea violacea*
Sesbania cannabina			*Nymphoides hydrocharoides*
			Paspalum scrobiculatum
			Pseudoraphis spinescens
			Utricularia limosa

Note: Data from Taylor and Dunlop (1985): only those species registering 1 or above on the Braun-Blanquet system of mean foliar abundance in plots examined by Taylor and Dunlop (1985) are listed.

Woodroffe 1985). Preliminary stratigraphic and radiometric results confirm the synchrony of transgressive and big swamp phases between these systems, being essentially controlled by the regional pattern of sea-level rise. However, rates of change in the post-6000 year phases have not been uniform between systems because of different rates of sediment supply, and relationships between fluviatile and tidal flow (see discussion by Chappell 1988). The channels exhibit different rates of migration. The Daly River channel migrates at 25 m yr^{-1} and has reworked much of its floodplain, so that big swamp mangrove mud is not widespread close to the channel and stumps are not exposed in the river bank. The Adelaide River has a much slower rate of migration, <0.1 m yr^{-1}, its plains are underlain by mangrove mud, but it does not have eroding banks and mangrove stumps are not exposed. The present vegetation patterns on some other estuarine floodplains in the Northern Territory show broad similarities to those of the South Alligator system (i.e. Adelaide River, Bowman and Wilson 1986) but as yet radiometric evidence is not available to determine the history of development of these freshwater plains.

The South Alligator model can be applied to some of the other macrotidal river systems of the Northern Territory; the early phases were synchronous, the later were not. Below, the model's application to areas outside the Northern Territory is examined.

Changing Mangrove Habitats in the Semi-arid Ord and Fitzroy Rivers

Sedimentologic and stratigraphic studies of the Ord River have been undertaken by Thom, Coleman and Wright (Wright *et al*. 1973, 1975; Thom *et al*. 1975; Coleman and Wright 1978) and of the Fitzroy River by Jennings (Jennings and Coventry 1973; Jennings 1975) and Semeniuk (Semeniuk 1980a, 1980b, 1981, 1982). Several similarities to the South Alligator River system are indicated, suggesting that the evolutionary model developed there might have application in this semi-arid region.

The Ord River, on the eastern edge of the Kimberley Plateau, drains into Cambridge Gulf, a structural embayment in Precambrian sandstone. The gulf is macrotidal with a spring range of 5.01 m at the mouth and 6.63 m at Wyndham. The region receives about 700 mm of annual precipitation, of which 85 per cent falls between December and March; annual pan evaporation at Wyndham is around 2350 mm. River flow was pronouncedly seasonal varying from 0.07 to 730 m^3s^{-1}, but since damming of the river freshwater flow is now almost constant (Burbridge and Messel 1979).

The Fitzroy River is in a similar setting to the west of the Kimberley Plateau, flowing into King Sound. Annual precipitation is 620 mm at Derby, most falling December to March, and annual pan evaporation is around 2400 mm. The estuary is surrounded by dunes which have not been active in the last 7000 years (Jennings 1975; Wyrwoll _et al_. 1986). Spring tidal range at Derby in King Sound is around 11 m; river discharge is negligible for 8 months of the year, but peak wet season discharges can exceed 4000 m^3s^{-1}.

The vegetation communities on the deltaic-estuarine plain of each river system are similar (Table 3). Mangrove forests are restricted to a sporadic littoral fringe. Behind these are narrow swards of samphire, and then extensive unvegetated saline mudflats. The rear of the plain adjacent to the upland margins has supratidal flats with a 'high marsh' composed of halophytes. Fluvial sediments, flanking the river, have a levèe vegetation of tall frontage forest in which _Eucalyptus papuana_ and _Adansonia gregorii_ are prominent. The distribution of these habitats is mapped in Figures 4 and 5.

The stratigraphy of the plains of the Ord River is not well known, but can be inferred from augering through similar plains beside the King River near Wyndham (Thom _et al_. 1975). These plains are underlain by bluish-gray estuarine clay with organic fragments. The sediments are superficially similar to mangrove mud found in the South Alligator estuary. A particularly organic-rich woody layer 3-4 m below the plains, containing molluscan and crustacean fragments, has been radiocarbon-dated 6800-6200 years B.P. (Thom _et al_. 1975) and is sedimentologically and chronologically equivalent to the big swamp mangrove mud of the South Alligator. A date of 4830 ± 210 years B.P. at shallower depth and to the north of Wyndham (Fig. 4) supports persistence of mangrove until this time.

Similar big swamp sediments can be inferred to underlie (or to have underlain) the plains of the Ord River. Wright _et al_. (1972) have reported exposure of _in situ_ carbonate-replaced mangrove stumps, 2 m above present high tide, and beneath 3 m of alluvium, near the present tidal limit. The similarity of the exposure to big swamp stump sites on the banks of the South Alligator River, combined with 6000-year dates on the organic horizon beneath the King River plains, suggest that this is also of big swamp age. The Ord River is bordered by many paleochannels indicating active channel migration and has evidently reworked much of its floodplain. This would mean that few areas of unreworked floodplain border the river and explains why there are few big swamp stump exposures along the river banks.

Table 3

Vegetation types on the plains of the Ord and Fitzroy Rivers, Western Australia

	ORD RIVER		FITZROY RIVER	
	CSIRO land system (after Stewart *et al.* 1970)	Dominant species (after Perry 1970; Thom *et al.* 1975)	CSIRO land system (after Speck *et al.* 1964)	Dominant species (after Speck and Lazarides 1964; Jennings 1975; Semenuik 1980a, 1980b)
Mangrove	Carpentaria	*Aegialitis annulata* *Aegiceras corniculatum* *Avicennia marina* *Ceriops tagal* *Excoecaria agallocha* *Rhizophora stylosa* *Xylocarpus australasicus*	Carpentaria	*Aegiceras annulata* *Aegialitis corniculatum* *Avicennia marina* *Bruguiera exaristata* *Camptostemon schultzii* *Ceriops tagal* *Excoecaria agallocha* *Osbornia octodonta* *Rhizophora stylosa* *Xylocarpus australasicus*
Samphire	Carpentaria	*Arthrocnemum halecnemoides* *Batis argillicola* *Salsola kali* *Sesuvium portulacastrum* *Sporobolus virginicus* *Suaeda* sp.	Carpentaria	*Arthrocnemum halecnemoides* *Sesuvium* sp. *Sporobolus virginicus*
Saline mudflat	Carpentaria	unvegetated	Carpentaria	occasional *Arthrocnemum halecnemoides* *Tecticornia verrucosa*
Supratidal (high marsh)	Carpentaria	*Arthrocnemum* sp. *Gomphrena conica* *Neptunia* sp. *Panicum paludosum* *Salsola kali* *Sporobolus actinocladus*	Carpentaria	*Chrysopogon* spp. *Fimbristylis* spp. *Sesbania cannabina* *Sporobolus virginicus* *Suaeda* sp. *Xerochlea* sp.
Fluvial deposits	Ivanhoe	*Adansonia gregorii* *Aristida latifolia* *Eucalyptus papuana* *Eucalyptus terminalis* *Sorghum stipoideum*	Djada Alexander	*Adansonia gregorii* *Bauhinia cunninghamii* *Eucalyptus papuana* *Terminalia platyphylla*

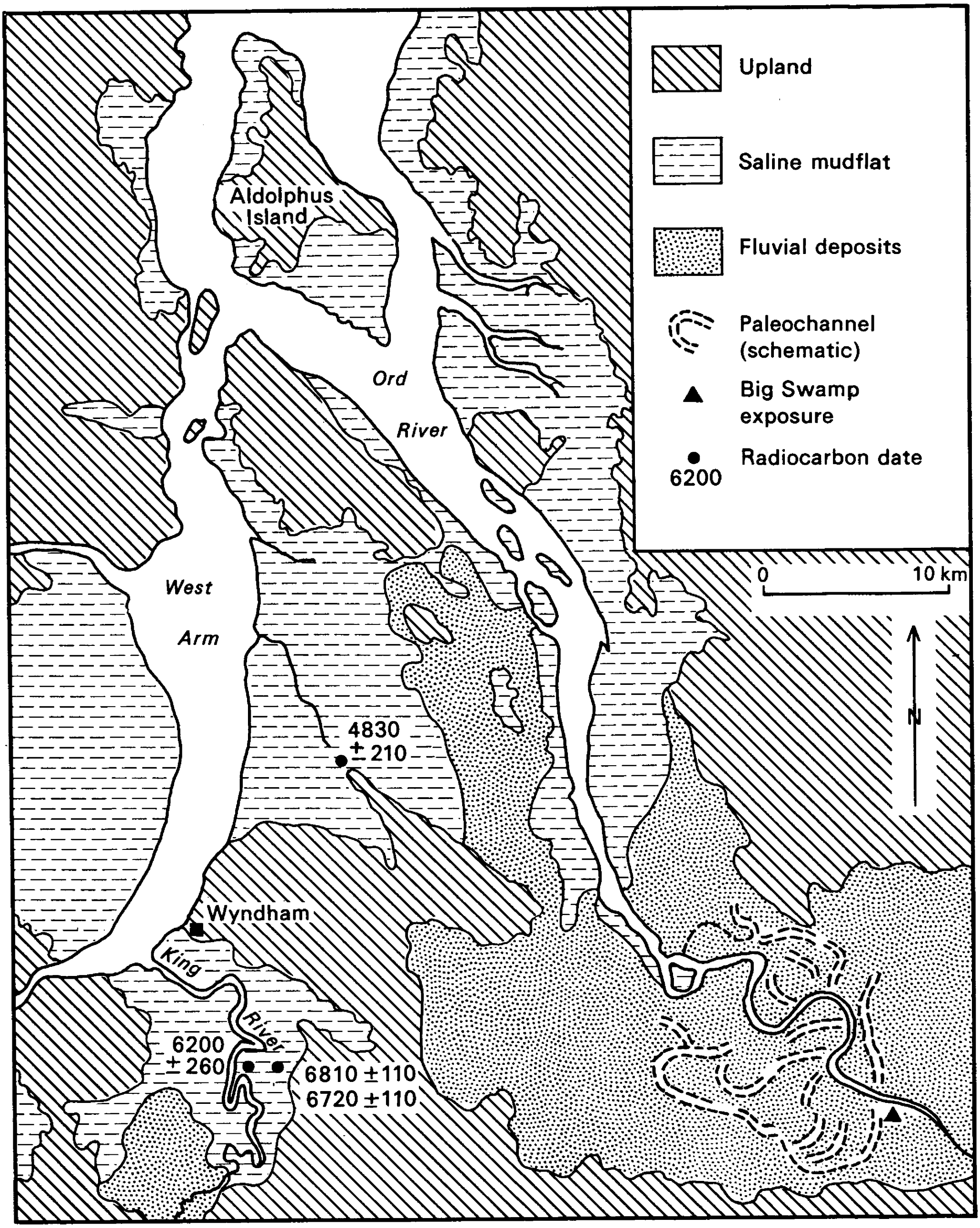

Figure 4: Ord River, Western Australia, and location of evidence of big swamp phase (based on Thom <u>et al</u>. 1975).

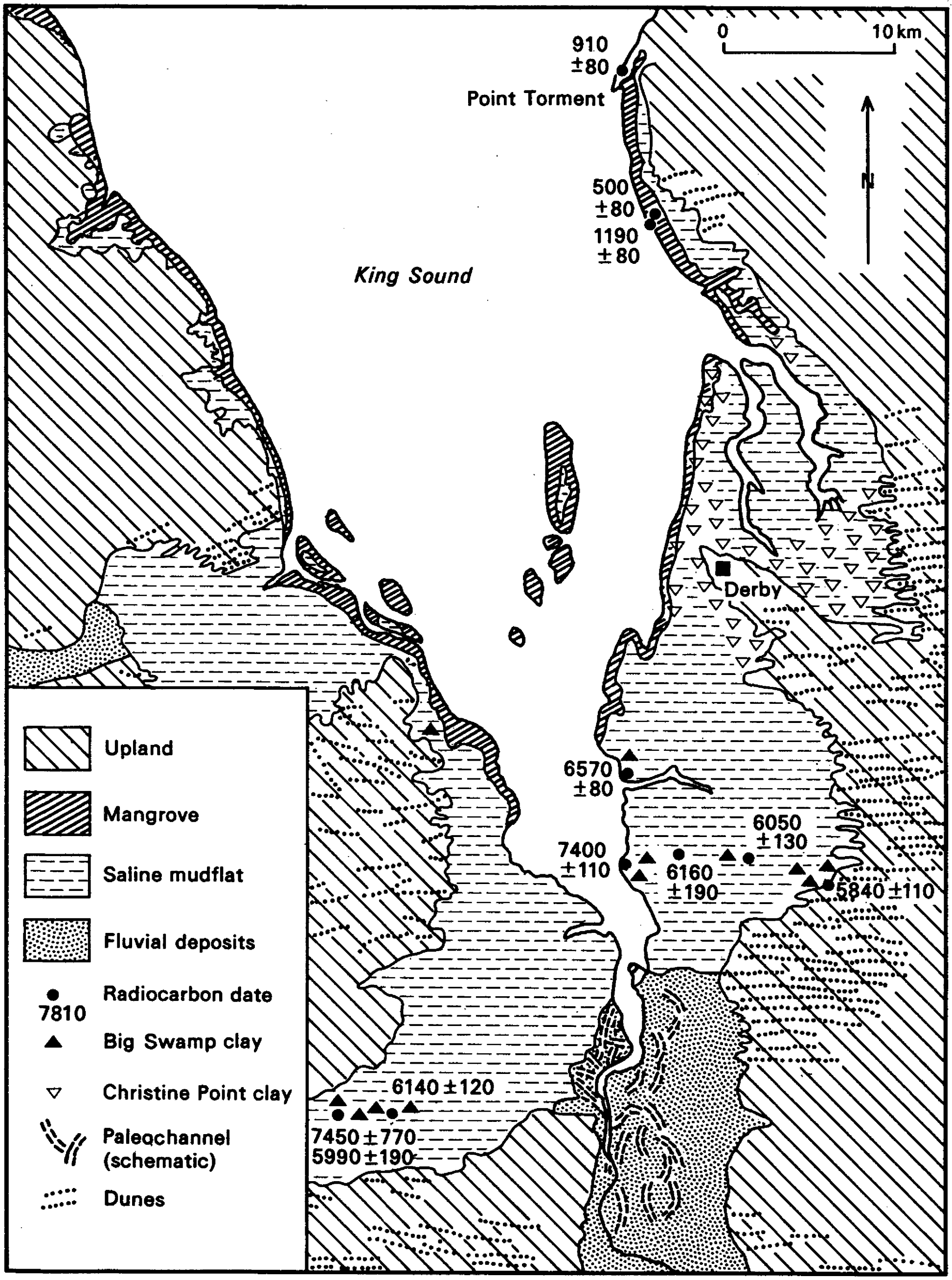

Figure 5: Fitzroy River and King Sound, Western Australia, and location of evidence of big swamp phase (based on Jennings 1975), with distribution of Christine Point Clay (after Semeniuk 1980a).

Thom has proposed a model of plains development in the Cambridge Gulf region with gradual disappearance of mangrove forests except from the littoral fringe, and establishment of broad saline mudflats (Thom et al. 1975). This model is compatible with the big swamp/sinuous/cuspate phases of the South Alligator, except that the restricted inundation of the Ord floodplains, and the hypersalinity resulting from high evaporation does not lead to freshwater floodplain development over the surface as in the wetter Northern Territory.

On the Fitzroy River widespread stratigraphic observations indicate that estuarine clays infill a valley system, transgressing prior dunes. Bluish-gray clays with abundant wood, identified as mangrove (Avicennia and Rhizophoraceae), outcropping as in situ stumps where banks have been eroded, are reported widely by Jennings (see Fig. 5), and two radiocarbon dates of around 7400 years B.P., one of 6600 years B.P., and five in the range 6200-5800 years B.P. have been reported from these deposits (Fig. 5, Jennings 1975). These are equivalent to big swamp mangrove muds.

Further accounts of the eastern shore of King Sound are given by Semeniuk (1980a) who recognises the following units around Derby: i) basal Mowanjum sand; ii) Airport Creek Formation of semilithified sand and mud; iii) Double Nob Formation, a black nodular paleosol; iv) Christine Point Clay, containing in situ mangrove stumps; v) Doctors Creek Formation, a shoaling tidal flat sequence; and vi) Point Torment Sand, recent coastal sands.

The Point Torment Sand consists of gravelly cheniers described by Jennings and Coventry (1973) migrating over mangrove sediments which have been radiocarbon-dated 1200-500 years B.P.. Christine Point Clay, distribution of which is shown in Figure 5, has been truncated and eroded prior to deposition of the younger, Doctors Creek Formation. Semeniuk (1980a) equates Doctors Creek Formation, within which there are mangrove remains, with the 'big swamp' mangrove muds dated by Jennings (1975). He then assigns Christine Point Clay a Pleistocene age.

Semeniuk describes Christine Point Clay as an eroded wedge of gray clay with abundant in situ mangrove stumps, burrows filled with calcareous/dolomitic concretions and crustacean fragments, covering >100 km^2 and more than 7.5 m thick. The description is very similar to big swamp mangrove mud. His reasons for equating the younger Doctors Creek Formation with the mangrove deposits on which Jennings reported ages were that: i) the erosional surface of the Christine Point Clay suggested a regression after its deposition; ii) the large mangrove stumps (up to 1.2 m diameter) exceeded the diameter of those presently found in the region (although Jennings has drawn attention to the fact that 6000-year mangroves reached diameters of up to 1 m); and iii) considerable time was required for diagenetic changes to shells and crustacea.

If the Christine Point Clay is actually of big swamp age, which is suggested by its similarity to South Alligator big swamp, as well as to the 6000-year deposits described by Jennings, then mangrove forests 6000 years ago were very extensive throughout King Sound and Fitzroy River (see Fig. 5). The younger Doctors Creek Formation is then equivalent to post-6000 year progradational deposits (such as those found in the estuarine funnel and coastal plain of the South Alligator River system). The formation appears laterally continuous with mangrove muds, beneath the Point Torment Sand, on which ages of 500-1200 years B.P. have been determined (Jennings 1975).

In the Fitzroy estuary and King Sound mangrove forests appear to have been more extensive (at least on the eastern margin) than the present plains. They have undergone long-term erosion (Jennings 1975; Semeniuk 1980b, 1981), with only localised recent progradation of the coast. As in the Ord River the mangrove forests have disappeared as sediments have built up beyond the highest tidal level, and extensive saline mudflats have developed.

Thus in both systems it is inferred that a transgressive phase occurred broadly synchronous with that in the South Alligator. This was followed by a similar big swamp phase. The post-big swamp phases have not been characterised by extensive floodplain development, but fluvial sediments have been deposited flanking the river which has actively migrated, presumably reworking some of the big swamp deposits.

Changing Mangrove and Wetland Habitats in the Perhumid Baram River

The Baram River is one of the bigger rivers draining northern Borneo. Its catchment is highly dissected and much is covered with mixed Dipterocarp forest. Its lower reaches flow between dissected lowlands of Tertiary shales and Pleistocene terraces (Liechti *et al*. 1960; Wilford 1961). The floodplain of the Baram River has infilled a prior valley, except for some Holocene progradation at the mouth, north of Miri (Fig. 6).

Northern Sarawak is characterised by heavy rainfall (mean annual precipitation around 3000 mm) uniform temperature and high relative humidity. Precipitation falls throughout the year, but particularly in intense thunderstorms during the southeast monsoon, April - August, and

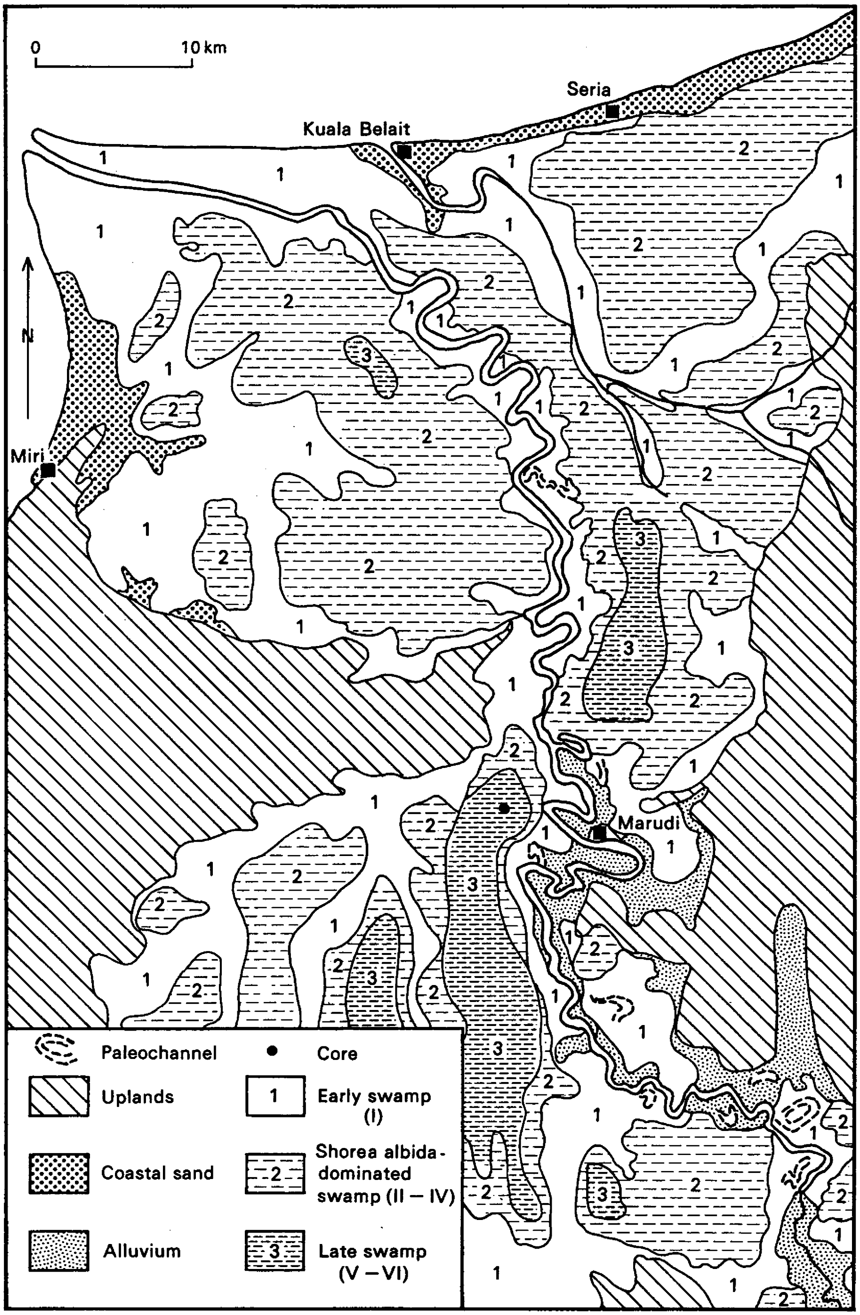

Figure 6: Baram River, Sarawak, distribution of peat swamps in early swamp, *Shorea albida*-dominated swamp, and late swamp stages (see text) and location of core (after Anderson and Muller 1975).

more uniformly during the northeast monsoon, October - February. Maximum tidal range is around 2 m at Miri, with mixed diurnal and semi-diurnal tides. Despite the mesotidal range with ephemeral bars formed at the mouth of the river, tidal influence is felt a long way up the river because of the low gradient of the plains.

Mangrove forests are not extensive at the mouth of the present Baram River, but the brackish water palm Nypa fruticans extends up the river, and is replaced by Saccharum sp. further upstream. The floodplains of the Baram River are almost entirely covered by tropical rain forest termed peat swamp, underlain by ombrogenous 'domed' peats (Whitmore 1975). Peat swamps extend >115 km up the river and cover more than 2,200 km^2 (Anderson 1964). Locally levées separate the river from the peat swamp, and alluvial forest ('empran') covers the narrow (<300 m wide) alluvial tracts flanking the river in mid-plains around Marudi. The peat swamp shows a zonation pattern in which six phasic communities can be recognised and has been mapped in detail by Anderson (Anderson 1961, 1964; Anderson and Muller 1975). These form a swamp catena from freshwater swamps with a muck substrate (<75 per cent loss on ignition) at the margin of the peat dome, to stunted rain forest in the interior. Details of the six phasic communities are given in Table 4 (after Anderson 1961, 1964; Anderson and Muller 1975), but for discussion are simplified into three stages; early swamp (comprising phasic community I, dominated by Gonystylus bancanus and Dactylocladus stenostachys); Shorea albida-dominated (phasic communities II, III and IV, in which S. albida is the dominant canopy tree, 30-45 m tall) and, late swamp (phasic communities V and VI, a transitional Tristania-Parastemon-Palaquium association, followed by a relatively stunted, 12 m tall, swamp of Combretocarpus rotundatus and Dactylocladus stenostachys). Only early swamp is inundated by floodwaters, but the water table is close to the surface in the peat swamp interior.

Much of the coastal peat swamps of Sarawak, including those at the mouth of the Baram, are dominated by Shorea albida. Late swamp is found covering the mid-plains of the Baram (Fig. 6). The structure and development of peat swamps has been described by Anderson (1964) and Hewitt (1967) and pollen analysis of a core taken from an area west of Marudi presently covered by late swamp communities (location shown in Fig. 6) has been described by Anderson and Muller (1975). Their diagram of arboreal pollen, greatly simplified, is shown in Figure 7. A basal clay 11.5-13 m below the surface containing mangrove pollen (Rhizophora-type, Avicennia-type, Sonneratia caseolaris and Nypa fruticans, as well as a riverbank plant, Oncosperma), is interpreted as mangrove clay which formed the substrate over which peat has accumulated. The peat contains abundant

Table 4

Composition of phasic communities I-VI, in the peat swamps of northern Sarawak (after Anderson 1961; Anderson and Muller 1975)

	Phasic community	Dominant canopy trees	Lower storeys and ground cover	Maximum canopy height
I	*Gonystylus*-*Dactylocladus*-*Neoscortechinia* association	*Gonystylus bancanus* *Dactylocladus stenostachys* *Copaifera palustris*	*Neoscortechinia kingii* *Alangium havilandii* *Thoracostachyum bancanum*	40-45m
II	*Shorea albida*-*Gonystylus*-*Stemonurus* assocation	*Shorea albida*	*Stemonurus secundiflorus*	>40m
III	*Shorea albida* consociation	*Shorea albida*	*Gonystylus bancanus* *Dyera lowii* *Combretocarpus rotundatus* *Tetractomia parviflora* *Pandanus andersonii*	48-58m
IV	*Shorea albida*-*Litsea*-*Parastemon* association	*Shorea albida* *Litsea crassifolia* *Combretocarpus rotundatus* *Calophyllum obliquinervum*	*Parastemon spicatum* *Tristania obovata*	30-36m
V	*Tristania*-*Parastemon*-*Palaquium* association	*Tristania obovata* *Parastemon spicatum* *Palaquium cochleariifolium* *Combretocarpus rotundatus* *Dactylocladus stenostachys*	*Pandanus sigmoideus* *Thoracostachyum bancanum*	<21m
VI	*Combretocarpus*-*Dactylocladus* association	*Combretocarpus rotundatus* *Dactylocladus stenostachys*	*Litsea crassifolia* *Ilex cymosa* *Garcinia cuneifolia* *Pandanus sigmoideus* *Thoracostachyum bancanum*	<12m

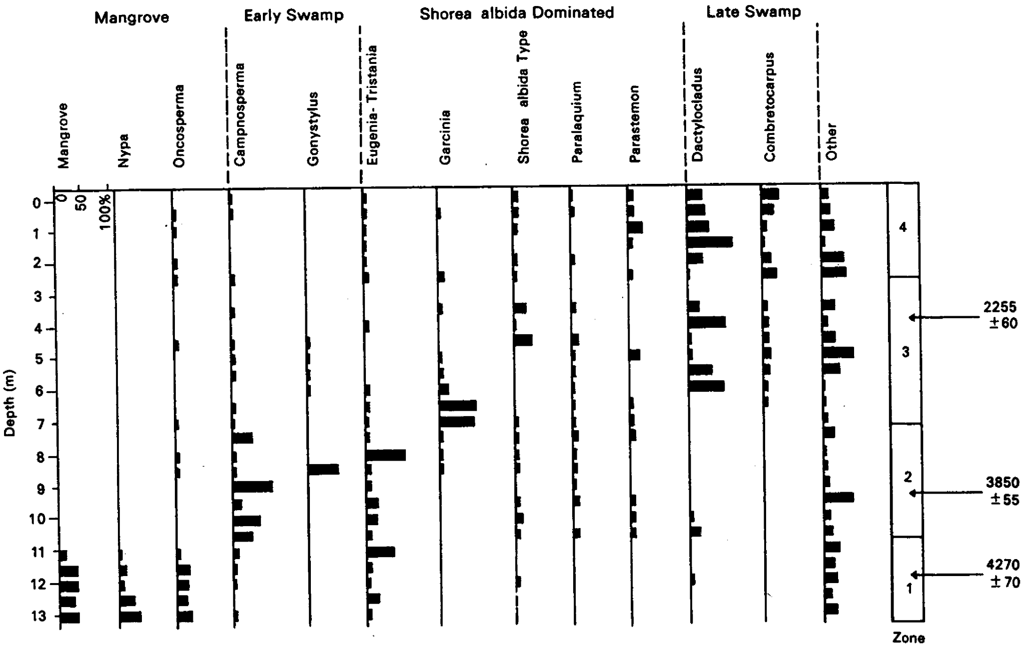

Figure 7: Pollen diagram (arboreal pollen) from peat swamp near Marudi (greatly simplified from Anderson and Muller 1975).

wood; it is highly humified at the base, becoming more sloppy with greater root content nearer the surface. Pollen indicates a vertical succession equivalent to the horizontal zonation from early swamp (in which Gonystylus, Dactylocladus and Campnosperma are recorded), to Shorea albida-dominated swamp (in which S. albida-type pollen is present though not particularly abundant), to late swamp (in the upper 2 m, with increased Combretocarpus and renewed Dactylocladus pollen).

Peat swamps have reached the latest stages of development over a wide area in the middle reaches of the Baram. With distance from the sea the swamps show greater convexity, greater depth of peat, and greater absolute height. In this respect they resemble the freshwater floodplains of the South Alligator River system.

Radiocarbon dates on the core (shown on the pollen diagram in Fig, 7) indicate that mangrove occurred at this location on the Baram River at 4270 ± 70 years B.P., but was replaced soon after by peat swamp. The reason for the disappearance of mangrove and the accumulation of peat in this and other peat swamps has been the subject of debate. Wyatt-Smith (1959) considered that freshwater was ponded behind coastal spits and hence swamp development related to spit development; Hewitt (1967) believed that the water was impounded by the accumulation of alluvium and formation of levées; and Anderson and Muller (1975) considered that impeded drainage resulted from saturation of mangrove clays and that it reflected sea-level history. Each of these authors interpreted the infill of valleys and overtopping of coastal deposits by peat swamps as a progradational sequence. However, it is also possible to infer a pattern of estuarine infill similar to that in northern Australia. There may have been widespread mangrove forests throughout the estuary persisting until at least 4200 years B.P. The coastal plain certainly appears to have prograded, as has occurred at the mouth of the South Alligator River. However, it would require more detailed radiometric dating over a wider geographical area to determine whether infill of the prior valley had been progradational or whether it involved a stage equivalent to the big swamp.

Peat swamp occurs in much of lowland Southeast Asia. There is some evidence from other swamps for similar patterns of change and similar chronology to those on the Baram River. The Klang River in western Peninsula Malaysia has peat swamps on its alluvial plain. These have developed over mangrove sediments (Webber 1954) and Coleman et al. (1970) report a basal date on peat of 4540 ± 110 years B.P.. Similarly Haseldonckx (1977) records build up of peat over mangrove mud, with disappearance of mangroves soon after 4900 years B.P. at Pekan Nanas in southern Peninsula Malaysia (Fig. 1). These dates are from too wide an area to confirm the big swamp hypothesis, but they do suggest some synchrony of development not unlike, but a little more recent, than, the big swamp phase in northern Australia.

Discussion

In each of the examples examined there are widespread mid-Holocene mangrove muds. These have been dated to around 6000 years B.P. in the South Alligator, Ord and Fitzroy Rivers (Woodroffe et al. 1985) and also in the Daly River (Chappell 1988). A similar age is likely for mangrove stumps from the East Alligator River and mangrove mud beneath plains of the Adelaide River. The synchrony results from stabilisation of sea level at that time.

Radiocarbon dating of mangrove remains, which are intertidal, can be used to reconstruct sea-level curves. A detailed sea-level curve has been determined for the South Alligator River region (Woodroffe et al. 1987), the data points for which are shown in Figure 8. Details of Holocene

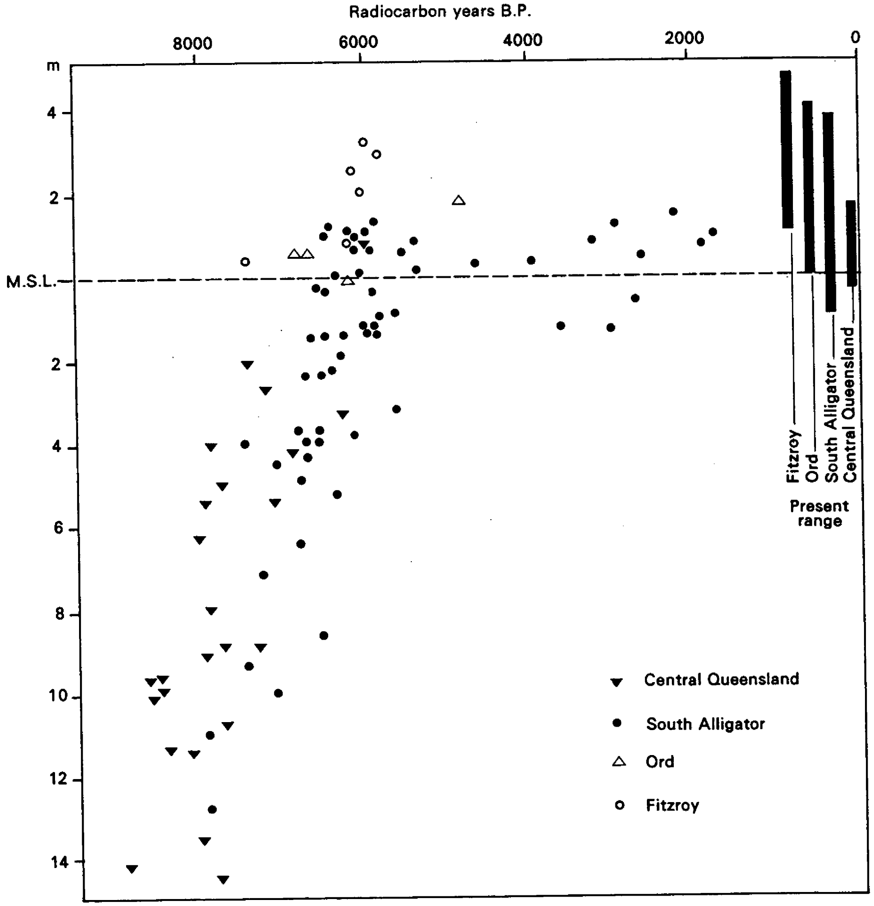

Figure 8: Sea-level data using mangrove wood, from northern Australia. South Alligator data after Woodroffe et al. (1987); Queensland data after Grindrod and Rhodes (1984); Ord data after Thom et al. (1975); and Fitzroy data after Jennings (1975).

sea-level history differ from one place to another in north Australia, largely as a result of hydro-isostatic deformation of the lithosphere (Chappell et al. 1982). In eastern Queensland there is convincing evidence for a sea level above present in the late Holocene (Chappell 1982; Chappell et al. 1983). There is, however, no evidence to support sea level having been above present in the Alligator Rivers region (Woodroffe et al. 1987; Chappell 1988).

In addition to differences in post-6000 year sea-level histories, the time at which present sea level was attained appears to differ between eastern central Queensland and northern Australia. Figure 8 also shows radiocarbon dates on mangrove mud, similar to that of the South Alligator River, from sites in central Queensland, particularly Hinchinbrook Island (after Grindrod and Rhodes 1984). The South Alligator results are significantly to the right of (i.e. younger than) the Queensland results and imply that sea level did not reach present level until 6000 years B.P. or later in the Alligator Rivers region (Woodroffe et al. 1987).

Also plotted on Figure 8 are radiocarbon dates reported from the Fitzroy estuary by Jennings (1975) and from the Ord River by Thom et al. (1975). The Fitzroy dates, and to a lesser extent the Ord dates, fall above those of the South Alligator during the period of stabilisation. In part this may be explained by the larger tidal range in the Fitzroy, and the broader present distribution of mangroves (Fig. 8). However, the earliest dates at which mangrove stumps are recorded within the present range of growth in the Fitzroy, 7400 years B.P., are considerably older (~1400 years) than in the South Alligator system and date from a time when sea level was 6-10 m lower than present in that area. The radiocarbon evidence points towards, but there are too few dates to confirm, a difference in relative sea-level history in details of attainment of present level between the Fitzroy and South Alligator Rivers.

Widespread mangrove forests also appear to have occurred preceding development of peat swamps in Sarawak, and perhaps other areas of Southeast Asia. While radiocarbon dating is sparse, there may also have been a pattern of rapid estuarine infill with an equivalent big swamp phase, at least in the Baram River around Marudi. If such big swamp occurred it appears to have been later, or have persisted longer, than in northern Australia. Though some peat swamps flank macrotidal rivers (i.e. Kiang River), those on the Baram are on a mesotidal river, and imply that it is estuaries with a low gradient rather than with a large tidal range, on which big swamp mangrove forests develop.

Figure 9 records radiocarbon dates on sea-level evidence from Southeast Asia. The dates are on a range of materials including coral, mangrove and shell, and come from sites in Malaysia, Indonesia and Viet Nam (after Fontaine and Delibrias 1974; Tjia 1977; Thommeret and Thommeret 1978; Geyh et al. 1979). Wilford (1961) has suggested that sea level reached present at around 5400 years B.P. in Sarawak, but there are too few data to confirm this. The dates in Figure 9 may not be representative of sea-level in northern Sarawak, particularly as they come from some distance away

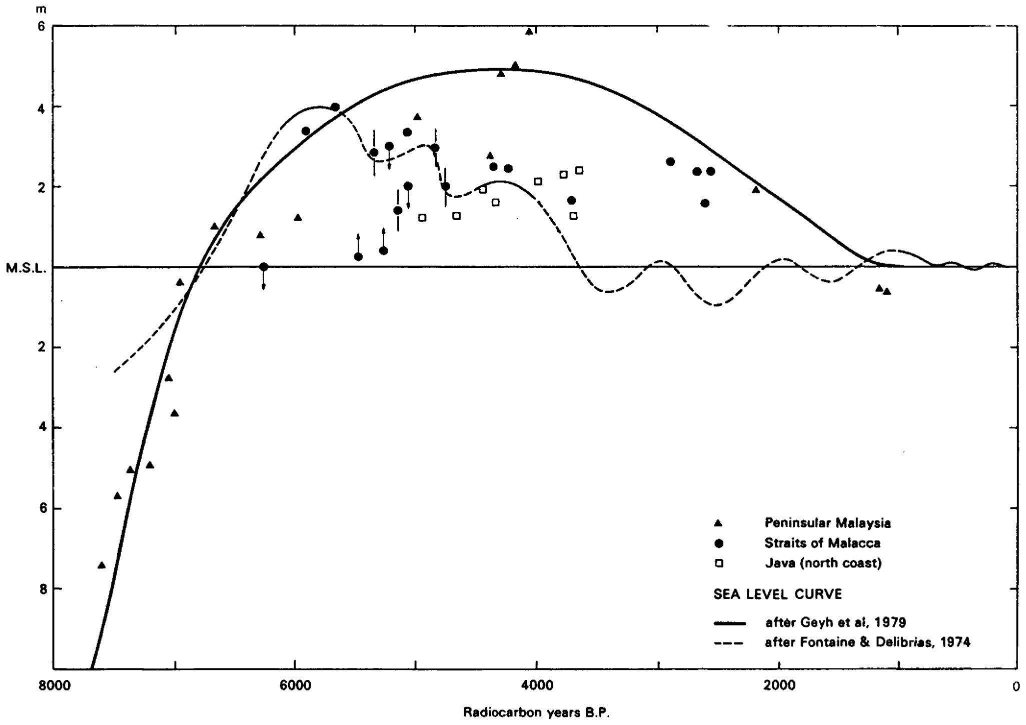

Figure 9: Sea-level data from Malaysia and Indonesia, compiled from information in Tjia (1977), Thommeret and Thommeret (1978) and Geyh _et al_. (1979). Material includes mangrove wood, coral and shell. Sea-level curves of Fontaine and Delibrias (1974) and Geyh _et al_. (1979) are shown.

and as significant geographical differences in sea-level pattern have been suggested above over shorter distances in Australia. Nevertheless there is considerable evidence, some of it from fossil mangrove material (i.e. Geyh _et al_. 1979) that sea level rose several metres above present in the mid-Holocene in the region. If sea level continued to rise until around 4200 years ago (Fig. 9) then big swamp in Southeast Asia might date from that time. Some peat swamps undoubtedly developed after coastal progradation, others appear to veneer muds deposited beneath widespread mangrove forests dating from the time that sea level reached its highest in the Holocene. While in northern Australia mangrove disappearance resulted from continued sedimentation under stable sea-level conditions, in parts of Southeast

Asia this effect may have been accentuated by a negative movement of sea level.

The post big swamp phases in northern Australia and Southeast Asia have been characterised by floodplain development. In semi-arid Western Australia little or no vertical accretion appears to have occurred over mangrove mud (except upstream fluvial deposits) but extensive near-horizontal saline mudflats have become established. In the wet-dry tropical Northern Territory, freshwater clays have accumulated forming slightly convex floodplains covered with a seasonal vegetation of annual grasses and sedges. In perhumid Sarawak ombrogenous peat swamps have developed with domed surfaces beneath perennial rainforest trees; several metres of largely autochthonous peat has developed and the vegetation has gone through seral changes (Fig. 10).

The vertical accretion floodplains, whether dominated by sedgeland or by peat swamp, show several similarities. They have gradual longitudinal gradients indicating greater accretion and burial of mangrove muds upstream. On the South Alligator plains radiocarbon dating indicates decelerating accretion, only slight burial of middens 2000-4000 years old has occurred. In the peat swamps of the Baram River, decelerating peat accumulation under the swamp communities is indicated.

Floodplains on large rivers are reworked by lateral migration of the river across them. Most rapid channel migration occurs on those rivers with a large sediment input, and on which catchment area to floodplain area ratio is high (Chappell and Woodroffe 1985; Chappell 1988). New floodplain accretes relatively rapidly over the younger channel margin deposits, as shown by well developed Upper Floodplain over laminated channel sediments which are less than 2,000 years old on the South Alligator plains, and peat swamp developed over alluvial deposits resulting from river migration on the Baram River (Anderson 1964).

The morphodynamic model reported by Woodroffe _et al._ (1986) can be applied with important modifications to several other river systems both in northern Australia and Southeast Asia. Chappell (1988) has indicated how geomorphological processes appear to have operated at different rates on several rivers in the Northern Territory. Changes of distribution and extent of mangrove and wetland environments can also be accommodated in the model, with application to semi-arid northwestern Australia where floodplains comprise largely unvegetated saline mudflats and perhumid Southeast Asia where ombrogenous peat swamps supporting forest develop.

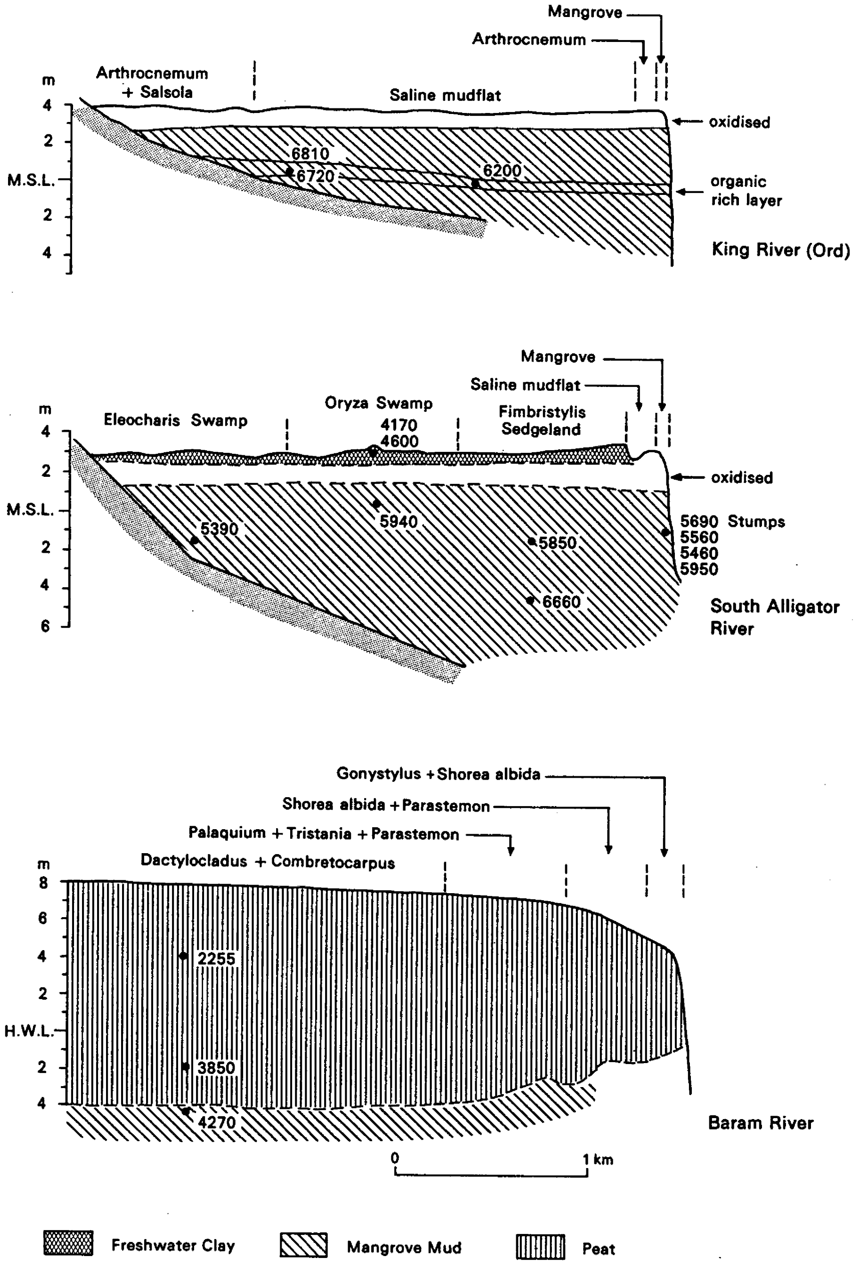

Figure 10: Characteristic cross-section of estuarine sediments in semi-arid, wet-dry tropics and per-humid tropics: vegetation zonation, stratigraphy and radiocarbon dates. King (Ord) River based on Thom et al. (1975); South Alligator River based on transect 6a of Woodroffe et al. (1986) and Baram River based on Marudi area after Anderson and Muller (1975).

Conclusion

The distribution and extent of mangrove and wetland habitats has changed during the last 8000 years. A three phase model of evolution and estuarine infill of the South Alligator tidal river and plains has application to other incised estuarine systems in the northern Australian and Southeast Asian region. It comprises an initial transgressive phase during which sea level rose and inundated prior valleys. There was then a big swamp phase characterised by widespread mangrove swamps. Later phases are termed sinuous and cuspate in the South Alligator River in relation to channel morphology.

The transgressive and big swamp phases were relatively sychronous in northern and northwestern Australia, being controlled by the pattern of sea-level change. They appear to have occurred a little later in Southeast Asia because sea level continued to rise until around 4200 years B.P.

The rate at which big swamp mangrove disappeared from the estuarine floodplain and the system progressed through later phases differed between systems and reflects sedimentation rate. In semi-arid Western Australia (Ord and Fitzroy rivers) mangrove forests were replaced by extensive saline mudflats. In wet-dry tropical Northern Territory (South Alligator River) freshwater floodplain clays accrete beneath seasonally-inundated grass and sedgeland. In perhumid Southeast Asia (Baram River) ombrogenous peats accumulate beneath peat swamp forests.

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GEOMORPHOLOGIC DYNAMICS AND EVOLUTION OF TIDAL RIVER AND FLOODPLAIN SYSTEMS IN NORTHERN AUSTRALIA

John Chappell

Delta floodplains and other coastal lowlands are amongst the world's most productive and populous land types. While the lowland floodplains of Northern Territory are not populous, they are a resource of considerable potential. As well they harbour wetlands which are highly valued in their own right. The question of what will happen to these lands if sea level rises should be considered. Recent estimates are that a rise somewhere between 0.5 m and 3 m will occur in the next 100 years (Hoffman *et al*. 1983; NRC 1983; PRB 1985), associated with 'greenhouse effect' global warming. This is likely to become much more than an academic matter. In the Northern Territory context, for example, I believe that 1 m rise of sea level in 100 years or so would turn the South Alligator plains and wetland to mangrove, samphire, and salt flat from the coast through to a zone about 20 km south of the Arnhem Highway, and that other parts of the Kakadu National Park would be similarly affected. We should understand this matter now so that appropriate monitoring can begin and the costs of remedial action be considered, before any such change is upon us.

The response of coastal lowlands and floodplains to a given sea level rise should not be gauged simply by tracing out the relevant contour on a map. Different systems respond differently, as shown by the variety of coastal and deltaic changes which occurred during and after the major post-glacial sea level rise, 16,000 to about 6,000 years ago. In some cases, valleys were drowned and became harbours, as at Darwin, while in others the processes of sedimentation maintained virtually constant wetland or mangrove swamp environments during the later phases of sea level rise. Three important factors are the rate of rising sea level, the rate of sediment supply, and the geometry of the lowland system. Interaction between these factors can be understood by investigating the history of any chosen system over the last 8,000 years or so. While this is a much longer time scale than that of the greenhouse effect, it provides essential information for estimating the probable future.

This paper is focussed on two cases in Northern Territory: the lower Daly and South Alligator river and plains system. The effects of past sea level change and of internal dynamics of the rivers are separated, and the response to any future sea level change is forecast.

Models of Floodplain Response to Sea Level Change

Lowland floodplains receive sediment from their river catchments. Carried overbank during floods, the concentration of sediment tends to decrease away from the channel as progressively finer particles settle from suspension. An idealised steady-state may be imagined where the floodplain gradually builds up while the coast advances seawards through longshore transport of sediment discharged by the river. Figure 1a illustrates this, with sea level held constant. In this model, the frequency of overbank flooding remains statistically constant, and shallow marine and coastal deposits are progressively overridden by floodplain sediments.

If sea level is falling the coastline moves seawards more rapidly by migration down the offshore slope as well as by continued sedimentation. As the offshore gradient is generally greater than that of the floodplain, the river may lower its bed accompanied by a decrease in overbank flooding. The rate at which the floodplain builds up will decline (Figure 1b). When sea level falls and remains low for a substantial time, as in glacial periods, the entrenched river may destroy much of its former floodplain through erosional meandering.

What happens when sea level rises depends on the sediment budget. Sediment input may be sufficient to maintain seaward progradation in the face of sea level rise, at a lower rate than the steady-state case (Figure 1c), or it may be insufficient in which case the sea invades the land and the frequency of overbank flooding increases (Figure 1d). The extent of marine invasion in this latter case also depends on floodplain gradient, and the extent to which drowned floodplain becomes tidal flat, saltmarsh, or mangrove depends on tidal range and sediment transport in the coastal zone. Where drowning is substantial, marine sediment from offshore sources may cover some of the former floodplain, extending the intertidal zone to a greater width than exists in the steady-state case (Figure 1e).

These simple models provide a guide to interpreting the record of geomorphic changes of tidal rivers in Northern Territory, studied in the 'Tidal Rivers and Mangroves' program of the North Australia Research Unit. However, the simple steady-state concept which underlies Figure 1 is not strictly applicable in cases where dynamic changes of river channels influence the upstream tidal behaviour, which may have effects that can be confused with those of sea level change. Dynamic effects in the South Alligator and Daly rivers are examined following an account of changes related to sea level over the last 8,000 years.

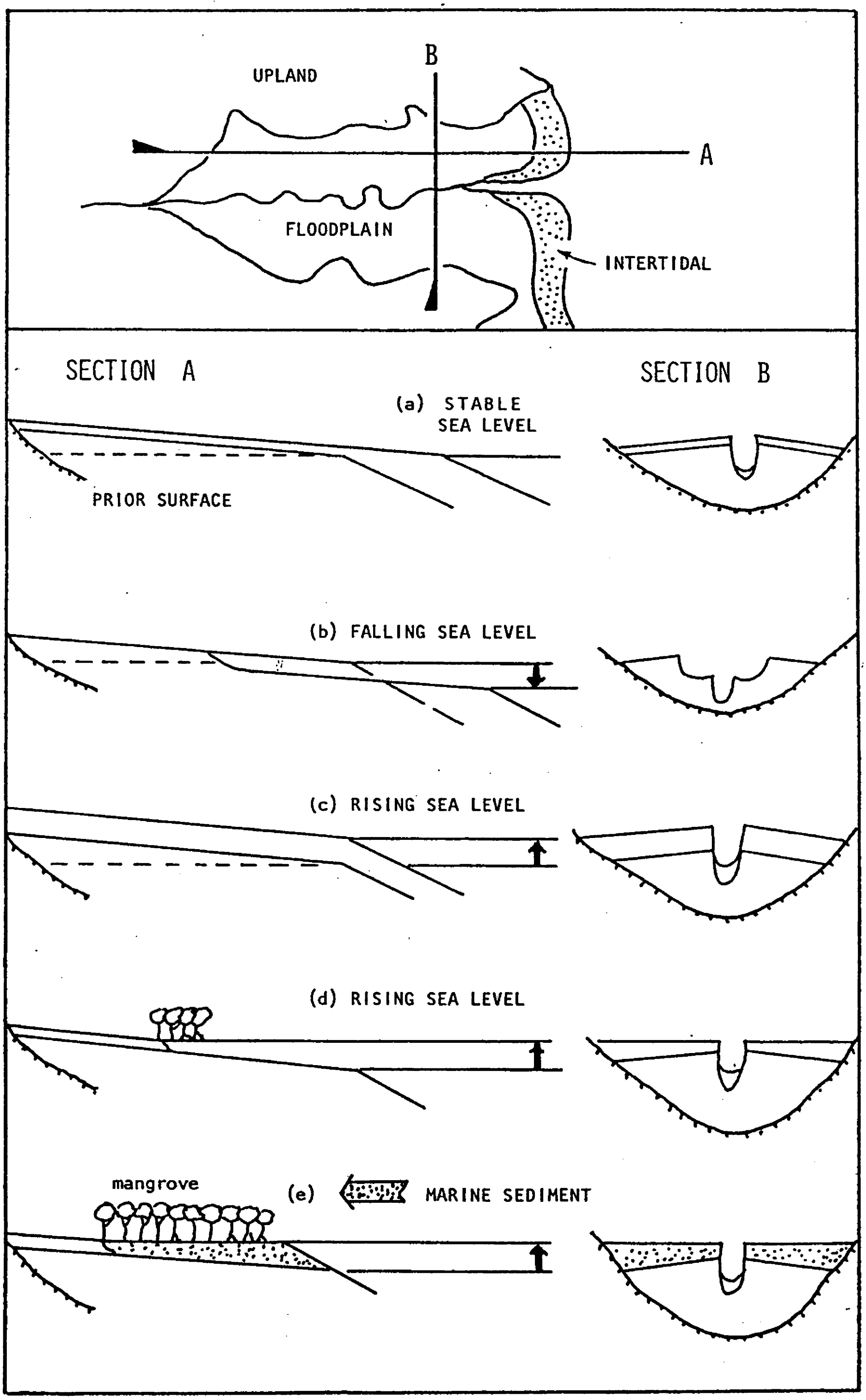

Figure 1: Models of river aggradation and coastal progradation under different sea level changes and sediment budgets. Longitudinal section (A) shown at left: transverse section (B) at right.

8000-year Histories of Lower Daly and South Alligator Rivers

The South Alligator and Daly rivers are tidal for the lower 100 km or so of their courses, with spring tidal ranges at their mouths around 6 m. As with other Northern Territory tidal rivers, both flow through broad sedge/grass floodplains set within low wooded uplands, and have mangrove fringed coastal plains at their mouths. The floodplain sediments range to 15 m thick (more than this near the coast, in the case of the Daly), and generally rest on a weathered substrate. Geomorphic mapping, stratigraphic drilling, and radiocarbon dating provide a picture of the evolution of these systems.

A convenient reference point for discussing the history of these tidal rivers is 6,000 radiocarbon years before present (B.P.). Studies elsewhere in Australia show that sea level relative to our coastline was rising before 6,000 years B.P., and that variation since then has been small (Thom and Roy 1985; Chappell _et al_. 1983). Patterns of sedimentation and tidal river development fall into two broad groups, corresponding with the pre-6,000 years rising sea level and the post-6,000 years stable sea level periods. Maps of the Daly and South Alligator tidal river systems, in Figures 2 and 3, highlight the widespread occurrence 6,000 years ago of mangroves throughout much of what is now sedge/grass floodplain. Development of extensive mangrove separates the pre-6,000 and post-6,000 years sea level periods. The stratigraphic section in Figure 2 shows that mangrove muds occur from 1 to 2 m below present floodplain clays. Using samples from drillholes taken throughout the South Alligator plains and from outcrops on the river banks, Woodroffe _et al_. (1985; 1986) showed that the upper few metres of these mangrove muds fall between 6,700 and 5,300 years B.P., with no discernable spatial trends. This is the basis for the distribution of 6,000 years B.P. mangrove deposits shown in Figure 2. Similar drillhole and outcrop results were used to prepare the Daly River map in Figure 3. The other palaeoenvironments shown in Figures 2 and 3 were also determined from radiocarbon-dated drillhole and riverbank samples.

Sedimentary textures and structures were combined with microfossil analysis for palaeoenvironmental determination from drillhole data, and these were linked to samples from modern depositional environments. Woodroffe _et al_. (1986) distinguish between morphostratigraphic units, which are sedimentary bodies having the surface expression of discrete geomorphic features, and stratigraphic units which are identified only on sedimentologic criteria and fossil content. This useful distinction emphasises that subsurface palaeoenvironments are known less precisely than those which still have some surface expression. Table 1 lists both

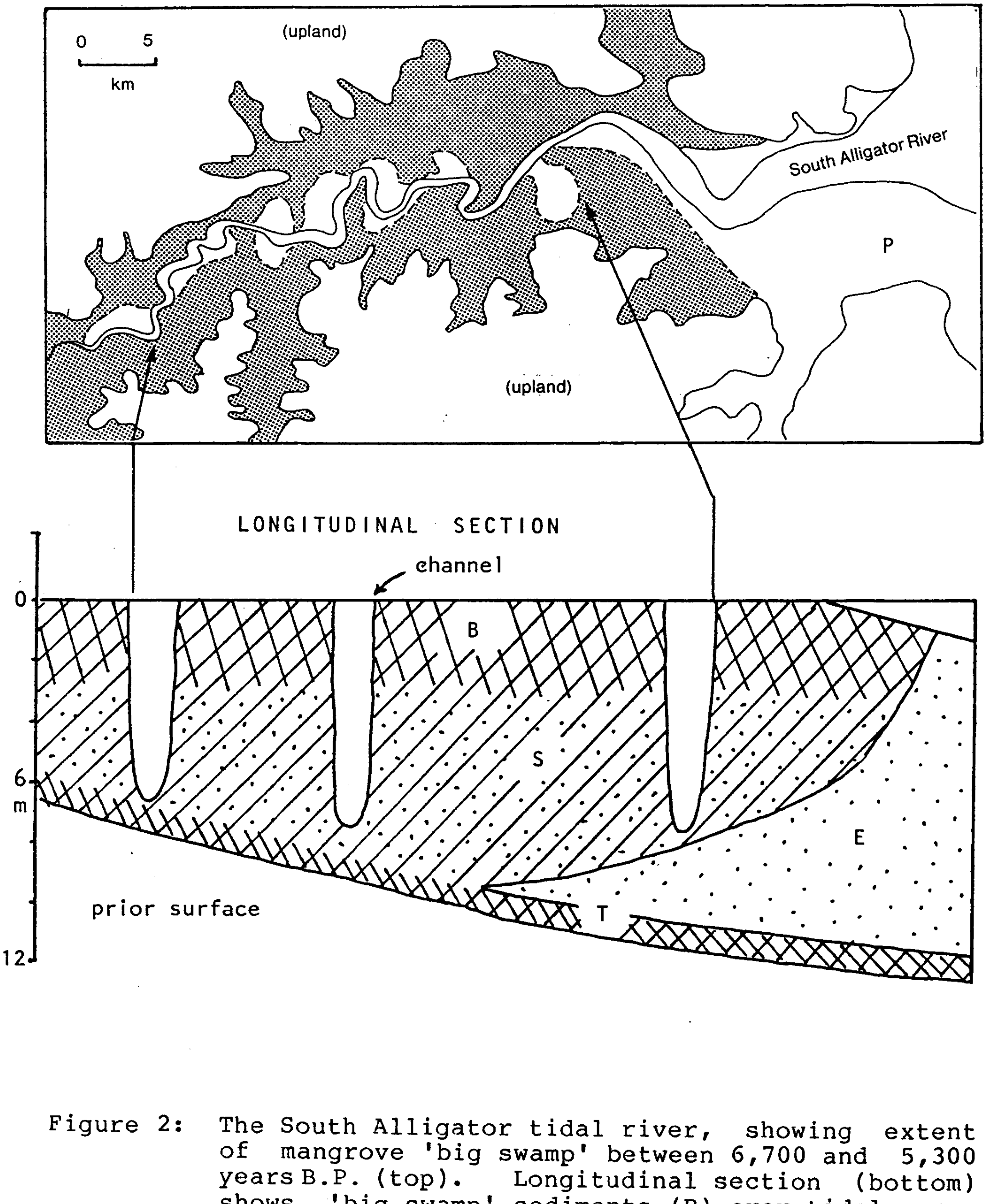

Figure 2: The South Alligator tidal river, showing extent of mangrove 'big swamp' between 6,700 and 5,300 years B.P. (top). Longitudinal section (bottom) shows 'big swamp' sediments (B) over tidal swamp and channel deposits (S), grading seawards into estuarine sediments (E). Transgressive mangrove muds (T) occur at the base.

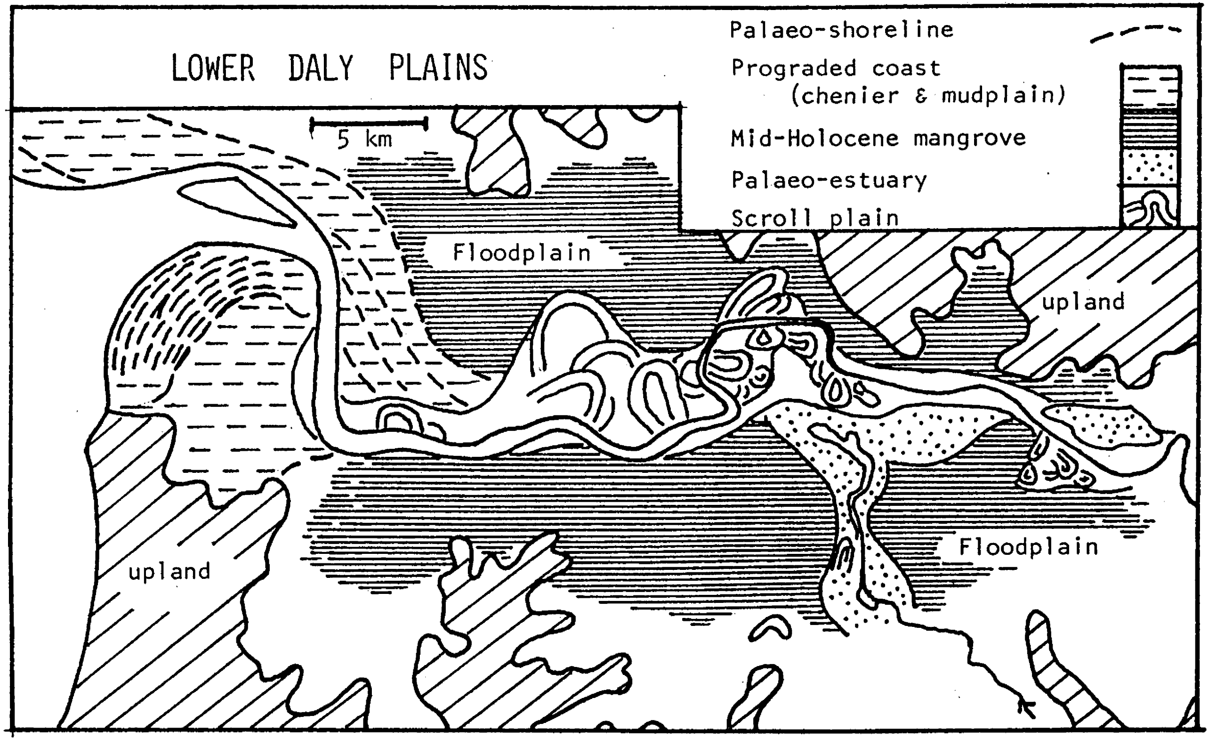

Figure 3: The Daly tidal river, showing the extent of the mangrove 'big swamp' of 6,500 to 5,500 years B.P., and other younger deposits which form the plains.

Table 1

Main characteristics of stratigraphic and morphostratigraphic units

	Texture	Other features	Surface form, or environment
Morphostratigraphic unit			
Deltaic/estuarine plain	clay	dark gray, cracking	floodplain
Fluvial plain	clay; sandy clay	brown & yellow soils	floodplain
Levee*	fine sand & silt	often laminated	low, elongate, meandering ridge beside channel
Chenier	sand/shell fragments	diverse mollusc fauna	low elongate ridge on coastal plain
Stratigraphic unit			
Marine sediment	sand & mud	shells & shell hash	nearshore
Estuarine sediments*	mud & sand	sometimes shelly	sub- & intertidal, estuarine
Undifferentiated sediments*	mud & sand, sometimes weakly organic	featureless, or burrowed	estuarine & tidal river (assumed)
Mangrove mud	organic mud	blue-gray, often contains wood	intertidal mangrove
Laminated channel sediments*	mud/fine sand	laminated	channel margin & shoal
Basal sediments	sand/clay/gravel	pallid/red-gray mottled/lateritic	prior valley floor side slopes

Notes: Those units marked * tend to be more sandy in the Daly River than in the South Alligator. (Modified from Woodroffe *et al*. 1986).

types of units identified in the South Alligator area by Woodroffe et al. (1986). Similar units are identified in the Daly system, with the difference that certain units there are more sandy. Comments in parentheses in Table 1 indicate unit characteristics in the Daly, where they differ from their counterparts in the South Alligator. A unit representing alluvial plain deposits beyond the range of the tidal river has been added to the original table.

The history before 6,000 years B.P. is interpreted from stratigraphic sections based on drillholes, similar to those shown in Figures 2 and 3. In summary, this is as follows. Rising sea level associated with northern continental deglaciation, at the end of the last ice age, began to invade prior valleys around the north Australian coast when levels were about 15 to 30 metres below present. This occurred between about 8,000 and 10,000 years ago. Where the sea encroached, intertidal deposits - most mangrove sediments - cover the former weathered land surface and are overlain by marine or estuarine sands and muds. These transgressive mangrove deposits are labelled T in Figure 2. Sedimentation kept pace with rising sea level near the margins of the deepening estuaries and intertidal deposits accumulated vertically under stable shorelines (labelled S in Figure 2). When sea level had risen to within a few metres of its present position, mangroves spread widely throughout the estuaries to achieve the distributions shown in Figures 2 and 3. Woodroffe et al. (1985; 1986) refer to this as the 'big swamp' phase, centred on 6,000 years B.P.. These deposits are labelled B in the stratigraphic sections.

The history since sea level stabilised 6,000 years ago commences with change from mangrove 'big swamp' to formation of sedge and grass floodplains. The timing of this change is not known exactly, but radiocarbon dates from shell middens which sit on the blacksoil clays of the South Alligator floodplain indicate that at least in some areas the change had occurred by 4,000 years B.P. (Woodroffe et al. 1986). The oldest beach ridges of sand or shell behind the coastal plains are dated as 4,000 to 5,000 years B.P. (Figures 2 and 3), and it is inferred that the grass/sedgeland floodplains were established when these beaches were forming. The transition from mangrove and estuarine deposits to freshwater clays of the floodplains is readily identified from pollens preserved in the sediments (Chappell and Grindrod 1985; Woodroffe et al. 1986), and is generally a metre or so beneath the surface.

Radiocarbon dates from shoreline deposits and shallow mangrove sediments of the coastal plains indicate relatively rapid coastal progradation from 5,000 to about 2,000 years B.P. at the mouth of the South Alligator (deposits labelled P in Figure 2). Similar progradation at the mouth of the

Daly has continued up to the present day but may have slowed about 2,000 years B.P., with shelly sands forming a series of concentric cheniers to the south of the river mouth and muddy progradation dominating on the north side.

The tidal rivers have meandered either side of their present courses, since the floodplains formed. Cut-off meander loops and other palaeochannnel remnants, as well as drillhole evidence of post-6,000 years B.P. channel sands, indicate the zones of meander migration shown in Figures 2 and 3. Radiocarbon dates from sediments filling the palaeochannels indicate when they became inactive, and rates of present-day channel migration can be estimated by comparison of aerial photographs taken in different years. There is evidence that meanders have altered in form over the last few thousand years, in some of the northern tidal rivers, and that other parameters such as channel width and depth in relation to distance from rivermouth have also changed, causing the upstream tidal range to increase in some cases. There are differences between systems. For example, the lower Daly River channel migrates about 20 times as fast as the lower South Alligator and has been statistically constant in form, whereas the South Alligator has become progressively less sinuous, wider, and shallower in the last few thousand years. Such changes, which can significantly affect nearby floodplains and wetlands, should be examined in the light of sea level and sedimentation trends of the last 6,000 years. Hence, the matter of channel dynamics and change is discussed later.

Sediment supply to these tidal river systems appears to have changed over the last 8,000 years. The quantities accumulated in the tidal river basins can be estimated from the radiocarbon-dated drillhole records. Figure 4 illustrates the technique. The volume between successive surfaces in time is calculated by reconstructing each surface from drillhole data. The prior landsurface which was buried after sea level rose is estimated from drill logs and projection of valley side slopes. Longitudinal and lateral slopes of the present floodplain surface are known from profile surveys in the case of the South Alligator (Woodroffe et al. 1986), and are estimated from spot heights for the Daly. Intermediate surfaces are largely based on depths to mangrove deposits of known ages, and are uncertain to the extent that a particular deposit may have been anything between lower and upper intertidal. The volume occupied by the river channel in the past is assumed to be the same as that of today. Uncertainties in these procedures give rise to upper and lower estimates for the volumes deposited in each epoch, in each basin.

Results for the Daly and South Alligator systems are listed in Table 2, for successive 2,000-year epochs from 0,

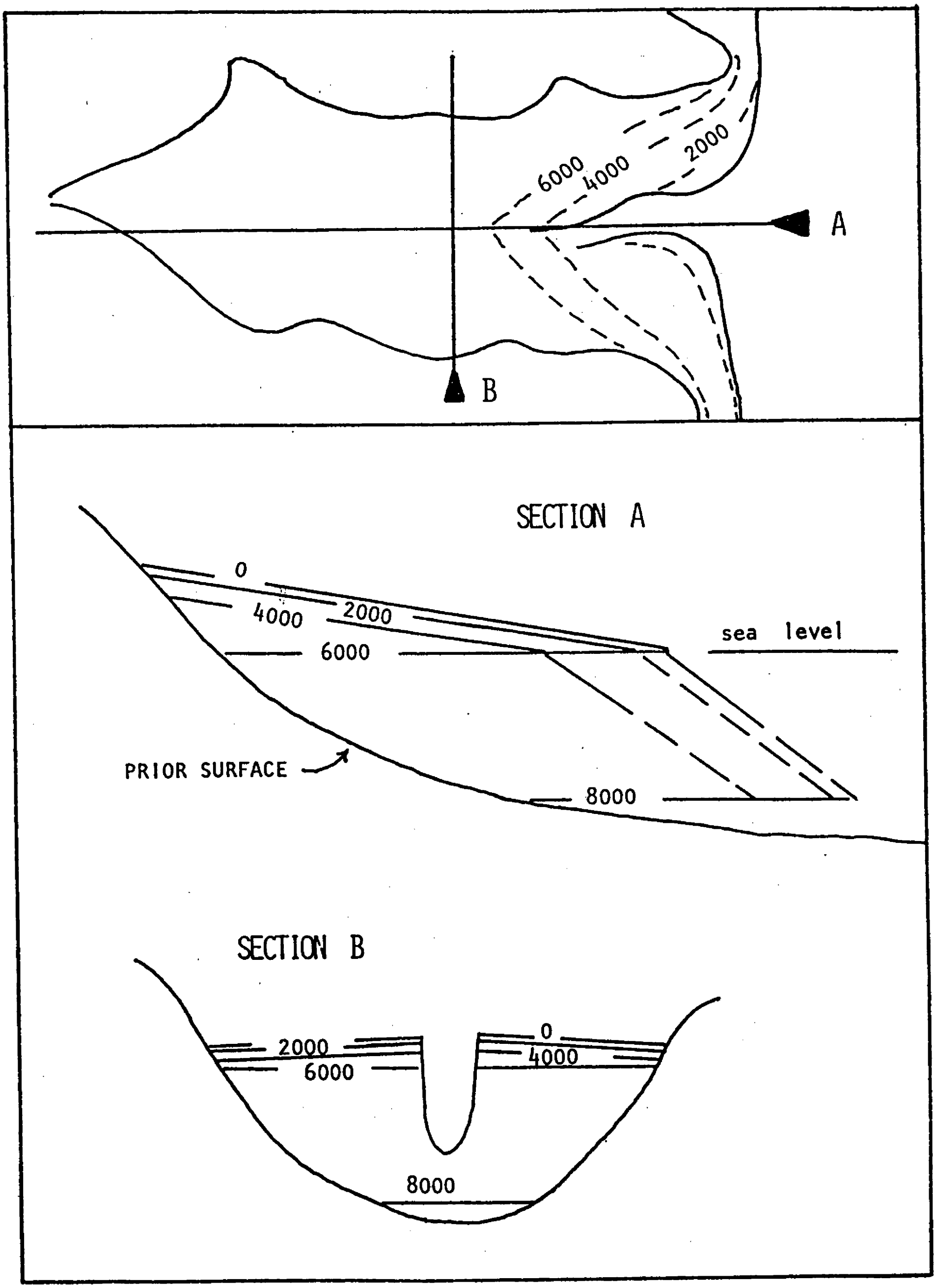

Figure 4: Basis for estimating sediment volume per unit time, from radiocarbon determination of prior surfaces within the deltaic/estuarine sediment body.

2,000, 4,000, and 6,000 years ago. Volumes associated with progradation of coastal plains are included in these totals. Sedimentation above the tidal limit is excluded, and estimates in the upper reaches of the tidal system are less certain for the Daly than for the South Alligator. The South Alligator data show a strong trend of sedimentation diminishing towards the present, and the Daly data show a weaker trend. The difference is linked to there having been proportionately less estuarine and coastal progradation over the last 6,000 years in the South Alligator than in the Daly. Vertical sedimentation rates are so much greater in the prograded estuarine and mangrove deposits than for overbanks floodplain clays, that estuarine sediments dominate the volumes listed in Table 2.

Table 2
Sedimentation in 2000-year intervals since 8000 years B.P.

Period	South Alligator		Daly	
(Years B.P.)	Mean thickness (m)	Volume (m^3)	Mean thickness (m)	Volume (m^3)
8000-6000	8	$3x10^9$	11	$4x10^9$
6000-4000	1	$5x10^8$	1	$2x10^9$
4000-2000	<.5	$4x10^8$	<.5*	10^9*
2000-0	<.1	10^8	<.2*	10^9*

Notes: Thicknesses marked * do not include intertidal and subtidal sediments added to coastal plains; volumes marked * include estimates of subtidal volume. Present day maximum vertical rates are estimated as 0.05 m/1,000 years for the South Alligator and 0.1 m/1,000 years for the Daly; actual rates over most of the floodplains are less than these figures.

These figures reflect gross sedimentation without accounting for provenance. Foraminifera and comminuted shell indicate that at least part of the sediment has a marine origin. The way in which this may have varied in the past is discussed in the next section.

Sea Level Versus Sedimentation in Last 8,000 Years

Vertical sequence of mangrove deposits indicate that sedimentation kept pace with sea level rise, 8,000 to about 6,500 years ago, in the middle Daly plains (Figure 3) and towards the margins of the South Alligator plains (Figure 2). Data from southeast Australia indicate that sea level rose by somewhere between 6 and 10 m in this time (Thom and Roy 1985), and results from New Guinea (Chappell and Polach 1976) are consistent with this. This rate of 4 to 7 m per 1,000 years is the same as the lower end of the range forecast for the next 100 years, related to the greenhouse effect. Whether future sedimentation will keep pace as it did before 6,500 years B.P. depends on whether the same sediment sources will be operative, as well as on present day geomorphology and transport processes.

Several factors indicate a substantial offshore sediment source during the pre-6,000 years B.P. period, and that this was more important relative to terrigenous sediment from the catchment in the South Alligator than it was in the Daly. Foraminifera in laminated estuarine and channel sands deposited before 6,000 years B.P., more than 50 km from the present South Alligator coast, show that at least part of the sediment is marine (P. Wang, pers. comm.). Basal transgressive mangrove and big swamp deposits are dominated by Rhizophoraceous taxa throughout the areas mapped in Figures 2 and 3, with no indication of feathering out inland into extensive fresher-water swamp deposits such as occur in the fluvially-dominated systems in Papua New Guinea. This distribution of mangrove resembles that which exists today in broad swamps with negligible terrigenous sediment input, such as at Hinchinbrook Island described by Grindrod and Rhodes (1984). The widespread development of mangrove, as sea level stabilised, is consistent with tidal redistribution of marine sediment, whereas the swamp would be expected to move progressively seawards in a system dominated by terrigenous input. Finally, the quantities of mangrove and estuarine sediment deposited in the South Alligator and Daly before 6,000 years B.P. are similar, despite that the Daly catchment (49,000 sq. km) is 5 times larger than the South Alligator (9,000 sq. km). As there is no reason to believe that sediment yields in the Daly catchment are smaller per unit area than for the South Alligator, the pre-6,000 years Daly volume would be expected to be substantially larger than that of the South Alligator, if terrigenous sediment was the dominant input. Summarising, the large volumes of pre-6,000 years sediment are thought to be due to a marine input. Whether or not the terrigenous inputs have diminished through time cannot be decided from data to hand.

Transition from mangrove 'big swamps' to sedge/grass floodplains is the first major change of the last 6,000 years. A phase of accelerated coastal progradation since 5,000 to about 2,000 years B.P. is the second feature of this period. Both invite explanation in terms of minor fall of sea level. Widespread change from mangrove to floodplain, indicated by radiocarbon dating to have occurred roughly 5,000 years ago, would follow if sea level began falling somewhat previously. Following the argument of Figure 1b, coastal progradation is likely to be most rapid when the rate of sea level fall is fastest. Only small changes, of the order of a metre or so, need be involved in very low gradient systems such as these.

There is some conflict between local evidence for post-6,000 years sea level change and that from other sites in northern Australia. Chappell _et al_. (1983) detail evidence from inner shelf islands of the northern Great Barrier Reef which shows a smooth fall of sea level by 1 m since 6,000 years B.P.. The same authors summarise evidence showing more than 2 m smooth fall relative to the southern Gulf of Carpentaria in the same period, and account for this regional variation in terms of hydro-isostatic crustal flexure. One would expect the Northern Territory coast centred on Darwin to show a similar fall, with the effect tending towards the upper end of the 1 to 2 m range in the shallow van Diemen Gulf-Alligator Rivers area.

Contrary to expectation, results from the South Alligator River reported by Woodroffe _et al_. (1986; 1987) suggest no such fall of sea level in the last 6,000 years. Age-height data on mangrove sediments reported by these authors are shown in Figure 5, superimposed on northeast Queensland and Gulf of Carpentaria curves from Chappell _et al_. (1983). Although the large tidal range of Northern Territory introduces uncertainty about the interpretation of mean sea level from mangrove sediments, South Alligator data cannot be said to conform with the Queensland curves without special pleading. Woodroffe _et al_. (1986; 1987) argue that progressive sediment compaction should not be invoked to explain the disagreement with north Queensland results, because many of the observations are from basal sediments. From a study of a chenier plain at Point Stuart, west of the Alligator Rivers, Clarke _et al_. (1979) also find no evidence for falling sea level in the last 4,500 years. It is concluded that other explanations be sought for coastal and floodplain changes in the Alligator Daly region, in this period.

The possibility remains that decreased coastal progradation at South Alligator and Daly River mouths in the last 2,000 years is due to minor sea level rise (using the argument of Figure 1d). It is hard to detect any such rise. Progradation at Point Stuart continued until at least 1,000 years ago (Clarke _et al_. 1979). Progradation of zoned mangroves has occurred in the lower West Alligator River in the last 600 years (Chappell, unpublished stratigraphic data). There is no evidence of salt invasion of swales, formed during the last 2,800 years, on the chenier plain south of the Daly River mouth. It may be claimed that recent salinisation further upstream in the South Alligator and other regions is evidence of rising sea level. However, it is shown below that where this phenomenon has been investigated it is caused by changing channel morphology, and sea level rise need not be invoked.

Summarising, no evidence for sea level change in this region in the last 6,000 years has been produced so far.

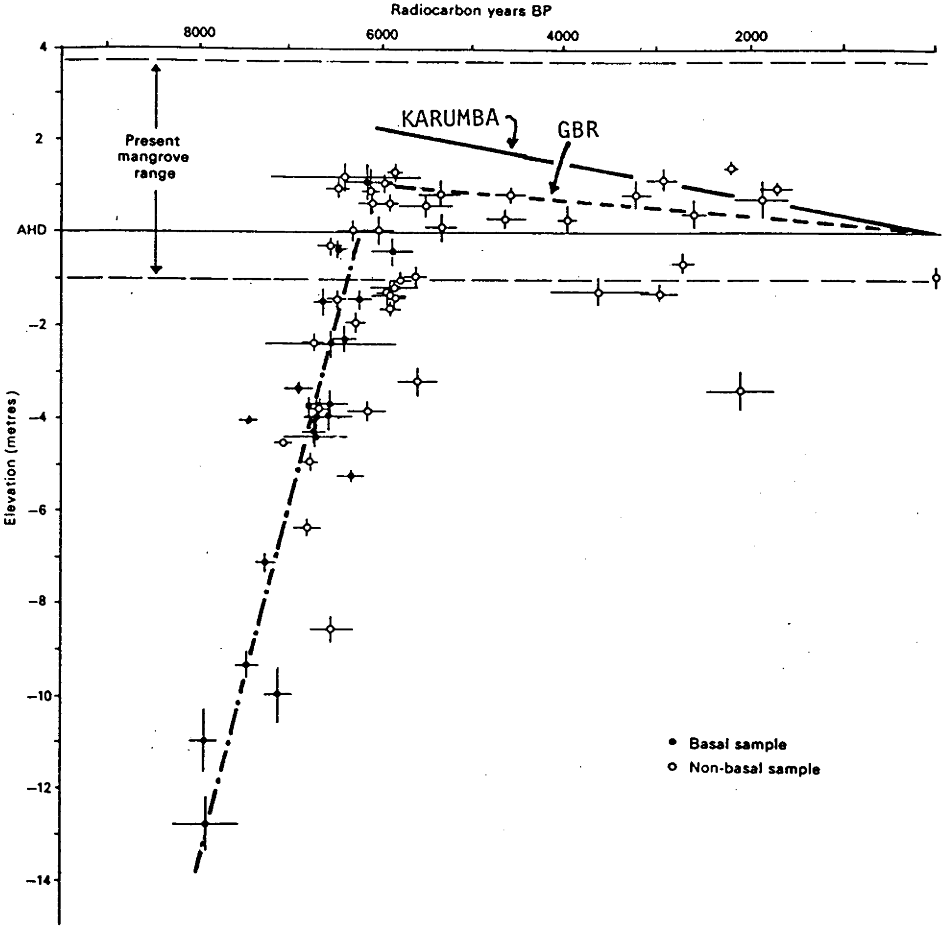

Figure 5: Sea level change interpreted by Woodroffe et al. (1987) from age/height data of dated mangrove deposits beneath the South Alligator plains (data points shown), compared with sea level curves given by Chappell et al. (1983) for Karumba and the inner Great Barrier Reef.

The following explanation of the geomorphic changes in this period is preferred. When sea level stabilised, about 6,000 years ago, sedimentation in the mangrove 'big swamp' progressively built the substrate higher, causing the succession from Rhizophoraceous to Avicennia forest described by Chappell and Grindrod (1985) and Woodroffe et al. (1985; 1986). As the swamp surface approached high spring tide levels, tidal redistribution of marine sediment, important throughout these systems during the previous period of rising sea level, was restricted to the coastal parts of the estuaries. Ensuing coastal progradation was accompanied by wet season flooding and fluvial sedimentation on the former high-tide mangrove flat, much as shown in the steady-state model of Figure 1a. Sedimentation on the plains thereafter was of terrigenous sediment only, which had been the minor component in the pre-6,000 years sediment budgets. Coastal progradation rates have decreased in some areas, such as the South Alligator mouth and south of Daly River, because progradation itself has moved the coastline increasingly into areas of higher wave energy and greater longshore drift.

Changes of Channel Morphology and Effects on Tidal Levels

The balance between floodplain sedimentation and maintenance of sedge/grass cover, against corrosion by saltwater invasion from the through-flowing tidal river, is delicate where floodplain gradients are small and tidal range is large. The hazard of salt invasion is greater where the floodplain slopes gently downhill away from the river, which is the case here. Any change of the river channel which increases the elevation of springtide high water level (SHWL) also increases the likelihood of salt invasion, if the tidal river itself is saline. This is the case in Northern Territory rivers, where sea water moves progressively upstream during the dry season, to an extent which is regulated by dry season fresh water base flow and tidal turbulence (Chappell and Ward 1985). In the South Alligator, for example, sea water salinities extend about 80 km upstream in the late dry season (Woodroffe _et_ _al_. 1986).

The elevation of SHWL upstream will increase if a tidal river becomes shorter through meander cutoff, and shallower through shoal formation. Both these changes have occurred in the South Alligator River in the last few thousand years, and probably occurred in the East Alligator in the same period. There is direct evidence for an associated increase of SHWL upstream in the South Alligator. Figure 6 shows the vertical distribution of mangroves along the river, from the coast to the tidal limit, and also shows the height of the upper mangrove zone in six stratigraphic profiles along the river dated around 5,000 to 6,000 years B.P.. Data from one profile dated 2,000 years B.P. behind the coastal mangrove also is shown (core 29). The diagram suggests that the mangrove/grassland transition has risen by about 0.5 m more at upstream sites than it has at the coast. This seems to be due to the following changes of the South Alligator channel over the last few thousand years.

Former channels can be reconstructed from their infilled remnants on floodplains. Figure 7 compares the present channel of the South Alligator with the reconstruction for 2,000 to 4,000 years B.P., from 25 to 75 km inland. The

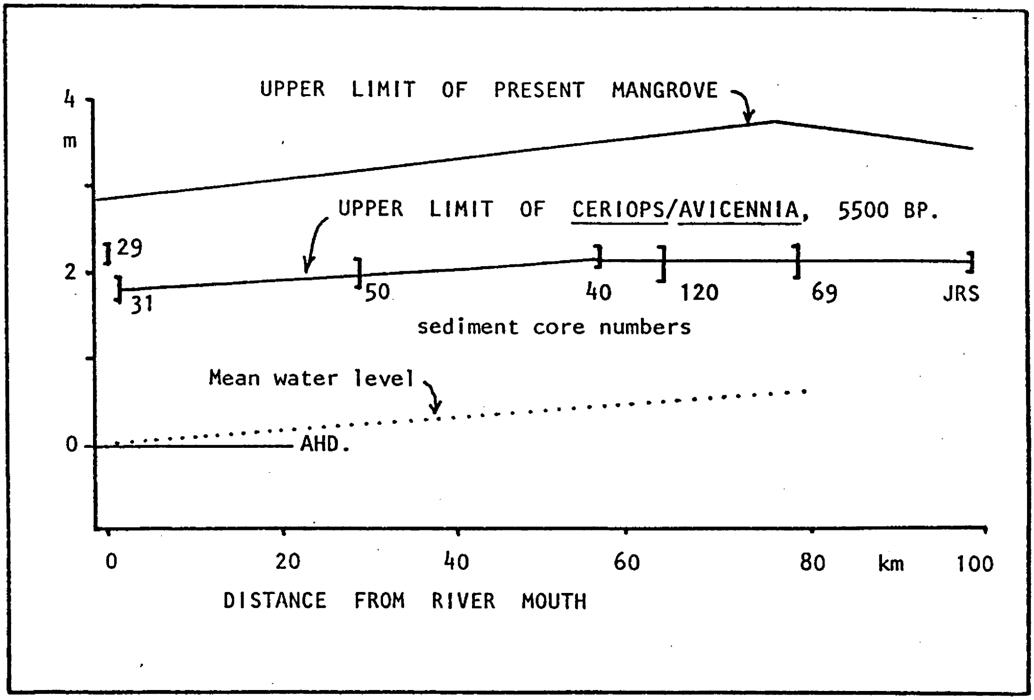

Figure 6: Longitudinal profiles of present upper limit of mangrove growth along the South Alligator River (from Woodroffe _et al_. 1986), and the uppermost mangrove zone (_Ceriops-Avicennia_) of 5,000 to 6,000 years B.P., determined from pollen analyses of cores (from Chappell and Grindrod 1985; Woodroffe _et al_. 1985, 1986, and unpublished data of J. Grindrod and J. Chappell).

reconstruction connects all visible palaeochannel remnants together, except in one area where meander cutoff clearly occurred twice (site B in Figure 7). Radiocarbon ages from channel-fill sediments and from the inner sides of meander loops indicate that the river was in this former course by 4,000 years ago. In some places, the former course was abandoned more recently than 2,000 years B.P.. The present river is shorter than this former channel due to meander cutoff without meander regrowth. Between 50 and 75 km upstream the channel is now a series of cuspate bends which are wider, shallower, and less sinuous than the meander loops which existed previously. A plot of width versus distance from the mouth for the present and palaeo rivers

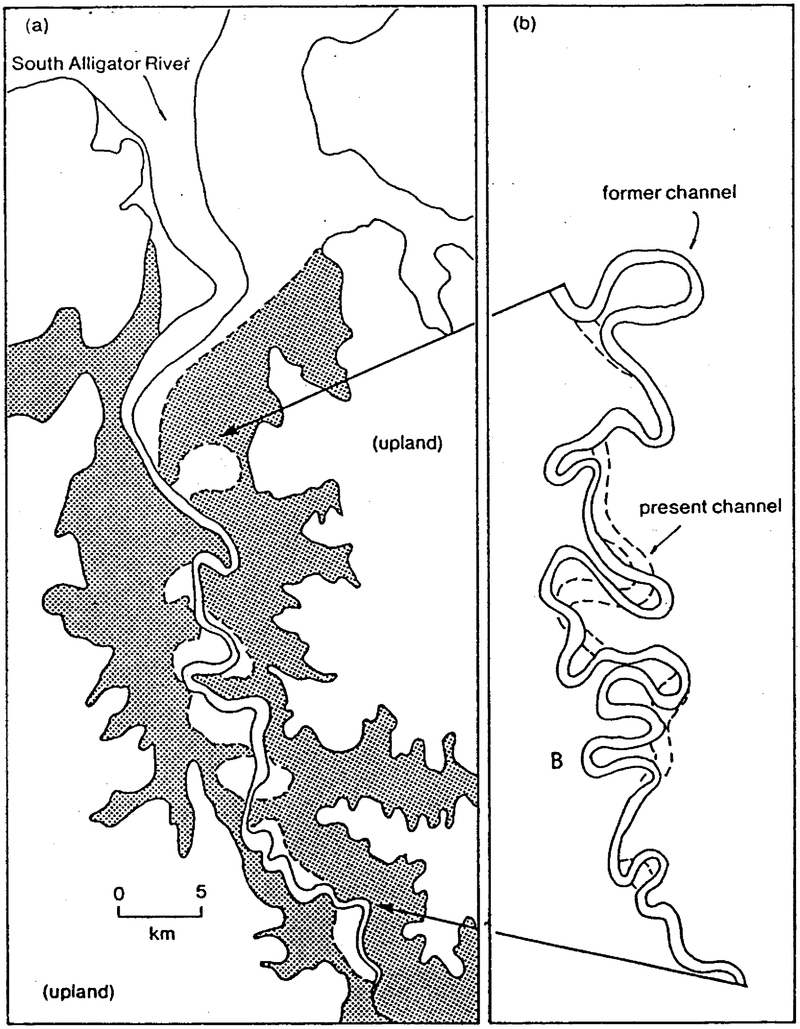

Figure 7: Comparison of the present South Alligator River with the channel of 2,000 to 4,000 years ago (from Woodroffe _et_ _al_. 1986).

shows this (Figure 8). Comparison with other rivers in the region suggests that the channel also became shallower when it changed from sinuous to cuspate forms. The former meanders of the South Alligator were similar in curvature and sinuosity to those of the present Adelaide River, which have an average depth of 11 m compared with 7 m at MWL for the present South Alligator cuspate bends. Depths of palaeochannel fill measured in the drillholes reported by

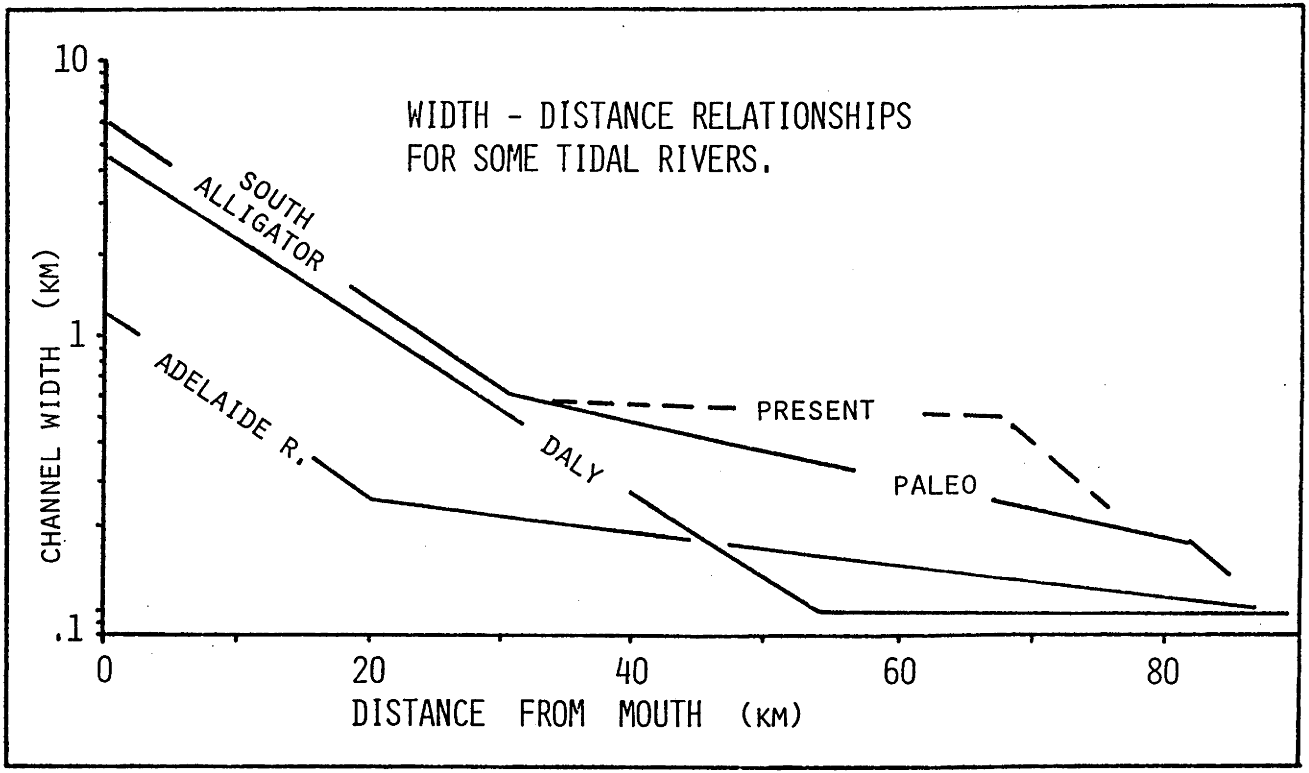

Figure 8: Width-distance relationships for the South Alligator, Daly, and Adelaide Rivers. The relationship for the palaeo-South Alligator River mapped in Figure 7 is also shown.

Woodroffe et al. (1986) also indicate that the palaeo river was deeper than the present cuspate bends. The shortening, shallowing, and widening which occurred are expected to increase SHWL by about 0.5 to 1 m in the upstream reaches of the South Alligator tidal river (Woodroffe et al. 1986), which is consistent with the comparison between past and present mangrove levels in Figure 6.

Not all rivers in the region have changed in the same way as the South Alligator. There is a spectrum ranging from the Adelaide River, which has a highly sinuous course and a very low rate of channel migration, through to the Daly River which has a highly mobile channel in which meanders cut off and reform continually. However, all probably flowed through sinuous meandering channels at the time their floodplains were forming, about 5,000 years ago, and subsequent changes depend largely on sizes of their catchments and of their floodplain and tidal river systems.

The original sinuous channels appear to have been inherited from the freshwater rivers which flowed down the prior valleys before sea level rose. For example, the sinuous Adelaide River channel is cut several metres into weathered bedrock underlying the Holocene deposits, and some of the sinuous bends in the South Alligator are similarly entrenched. Support for inheritance also comes from channel width/distance data. The rate at which a fluvial channel widens downstream depends essentially on the rate at which discharge due to runoff increases, while the width/distance relationship in a tidal river is exponential and depends essentially on tidal range and the properties of the bank materials.

Log-normal width-distance plots in Figure 8 reflect this difference. The regression slope for tidally-adapted estuarine funnels, which include the highly mobile lower Daly, is substantially steeper than for the sinuous reaches of the palaeo South Alligator and Adelaide rivers. The regression slope of the latter is consistent with runoff increase with distance from headwaters, and supports channel inheritance. The spectrum of tidal river types therefore is seen as ranging from those which flow in their inherited channels (Adelaide case), through those which have altered from an inherited sinuous channel to a cuspate tidal channel (South and East Alligators), to those where new cuspate bends, created by cutoff, rapidly migrate and reform sinuous loops (Daly case).

An increase of high tide levels in the last few thousand years is expected only in cases like the South Alligator which are intermediate in this spectrum. This is related to monsoonal flood discharges and therefore to catchment size. The tendency of a cuspate bend to persist

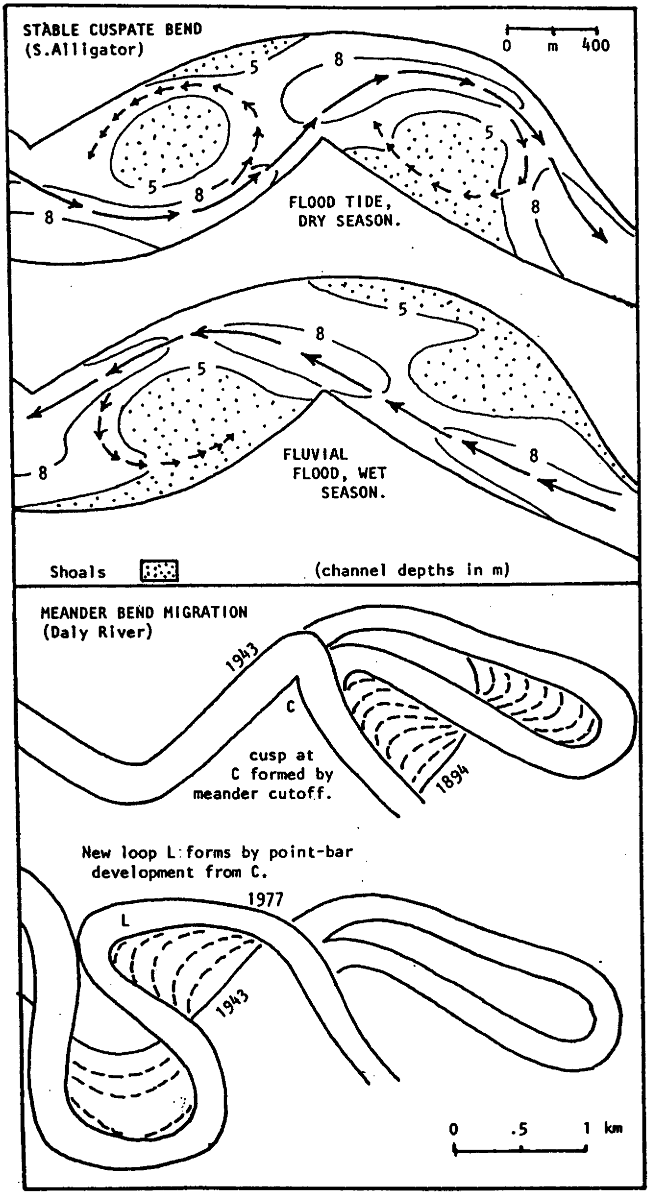

Figure 9: (a) Opposition of tidal and fresh-water flood flows in cuspate bends of the South Alligator River; dry season flow and sediment transport is dominated by flood tides, while wet season transport under monsoonal floods is in the opposite direction (from Vertessy and Chappell, unpublished data).
(b) Selected changes of the Daly River in the Moon Billabong area, about 40 km from the coast, since 1894 (from historical maps and aerial photographs).

or meander depends on the balance between upstream sediment transport by flood tides, and downstream transport by ebb tides and monsoonal floods. Field measurements show that these opposing trends are approximately balanced in the South Alligator cuspate bends, and a 40-year series of aerial photos confirms their stability. Figure 9a summarises the dynamics of flow and sedimentation in a South Alligator cuspate bend, while Figure 9b shows the progressive change from cuspate to sinuous form of a typical Daly River meander. The difference reflects dominance of fluvial over tidal flows in the Daly, which has monsoonal floods about 5 times greater than the South Alligator but has similar tidal discharges. Evolution of these tidal rivers over the last 6,000 years therefore depends on the relationship between fluvial flood and tidal flows in their meandering reaches. In those cases which change from sinuous to relatively stable cuspate meanders, tidal levels can increase upstream as the change occurs.

Conclusions

The changes which have occurred in tidal rivers of the Alligator-Daly region, over the last 8,000 years, are summarised in Figure 10. Changes of the last 5,000 years are relevant for predicting the future, and these vary from one system to another. In all cases, at least part of the tidal river channel of 5,000 years ago was inherited from the prior freshwater river of low sea level times. The way in which the channels have changed since depends on interaction between sediment input, and fluvial and tidal flows.

When sediment input is small the rate of meandering is slow and cutoff is rare. The original sinuous channel persists in this case (Figure 10a). When meandering is sufficiently rapid for cutoffs to occur within a few thousand years after sea level stabilised, newly-formed cuspate bends may persist if tidal sediment transport exceeds fluvial transport (Figure 10b). When sediment input is such that meandering is rapid, cuspate bends are an ephemeral form which grow into new meander loops (Figure 10c).

These patterns of change have occurred in different Northern Territory rivers over the last 5,000 to 6,000 years, with sea level stable. Sea level is expected to rise in future due to global 'greenhouse effect' warming, by something between 0.5 and 3 m in the next 100 years. Response of different river and floodplain systems will depend on the rate of fluvial sediment input. As this is a major factor affecting position in the spectrum outlined in Figure 10, response to rising sea level of different rivers is likely to vary in a parallel way. Those which flow in inherited channels passing through Holocene 'big swamp' and

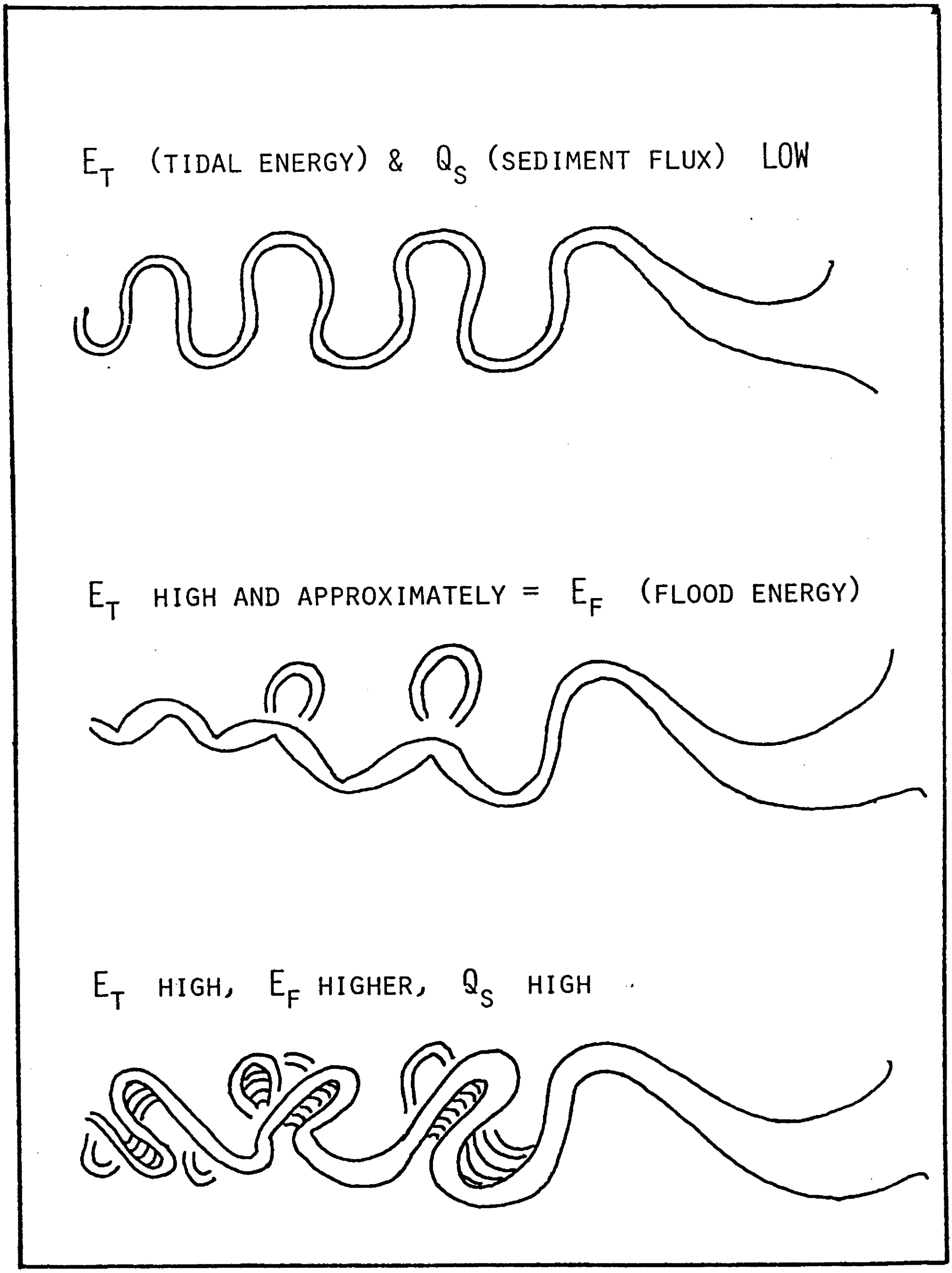

Figure 10: Evolution of Northern Territory tidal rivers, as a function of tidal energy (E_t), monsoonal flood energy (E_f), and sediment discharge (Q_s).

floodplain deposits lie at the low end of the spectrum (Figure 10a) and will be least able to build their floodplains to keep pace with rising sea level. Those which actively meander (Figure 10c) are the most able to keep pace.

The maximum rate of sea level rise which can be matched by floodplain aggradation can be estimated from the volumetric rate of sediment input divided by the area of the floodplain. This assumes that all sediment eventually finds its way onto the floodplain and that none is lost offshore from the river mouth. From the figures in Table 2 (which are partly based on past accumulation of floodplain sediments), an upper limit of 10 cm/100 years is calculated for Daly River. The result for the Alligator Rivers is only about 5 cm/100 years, and the Adelaide River almost certainly would be less. All are substantially less than the predicted rise over the next 100 years. The possibility of a large marine sediment input, such as occurred before 6,000 years B.P. is discounted, unless sea level were to rise sufficiently to place the plains beneath low tide level - a rise of 7 m or so. If it is unacceptable that the tidal river plains will become mangrove and samphire, then planning for their future management and for containment of rising seas should begin now.

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PRODUCTIVITY AND NUTRIENT DYNAMICS OF SEASONALLY INUNDATED FLOODPLAINS IN THE NORTHERN TERRITORY

Max Finlayson

The Northern Territory (NT) lies between latitudes 11°S and 26°S and has a climate that ranges from that of the seasonal Wet-Dry monsoon-influenced north to that of the relatively arid inland areas to the south, where rainfall is infrequent and irregular. These extremes in climate result in different wetland systems. The arid interior contains episodic saline lakes and intermittently flooded swamps, whilst in the Top End (that part of the Territory north of 15°S) coastal seasonally flooded swamps and floodplains are common, along with permanent waterholes (often called billabongs) and a fringe of salt-flats and mangroves (Paijmans _et al_. 1985). General ecological characteristics of these wetlands have been reviewed by Finlayson _et al_. (1988a) and Finlayson and Von Oertzen (forthcoming).

The tropical northern area of the NT (hereafter referred to as the Top End) has highly-seasonal summer rainfall with large rivers that deposit suspended material on the wide coastal plains. The coastal plains or lowlands have numerous floodplains, waterholes and swamps along the major rivers. The swamps can be extensive and are generally referred to as 'floodplains' although, geomorphically, they may be more precisely called backwater plains. The freshwater floodplains upstream of the tidal limits of the rivers have been formed by fluvially transported sediments deposited by distributary systems which drain upland regions. The morphology of the floodplains is diverse, and includes low-lying swamps, active channels and permanent lagoons.

Permanent lakes and seasonal lakes are rare in the NT and occur only along the northern coast (Paijmans _et al_. 1985). Fogg Dam is a permanent man-made lake near Humpty Doo that was built to retain water for the ill-fated rice development scheme in the 1950s. Permanent swamps occur along the northern coast, usually in association with seasonally-inundated floodplains. The Arafura Swamp on the Glyde and Goyder Rivers is a large (about 2,900 sq km), but poorly known permanent swamp in Arnhem Land. The floodplains vary in size with the more notable in this respect being those of the Adelaide, Alligator, Mary, Finniss, Reynolds and Daly rivers.

Some of the floodplains of the Alligator Rivers Region are now included within the boundaries of Kakadu National

Park (Stages I and II) and have been the subject of considerable biological investigation. The South Alligator floodplain has been studied by CSIRO Division of Wildlife and Rangelands Research, and the floodplain of the Magela Creek (a tributary of the East Alligator River) by the Alligator Rivers Region Research Institute. Much of the information presented in the following discussion of the seasonally inundated freshwater floodplains comes from the Alligator Rivers Region (see review by Finlayson _et al_. 1988a). A description of the aquatic vegetation and vertebrate fauna is presented as a prelude to discussing the levels of production on the floodplains. For many of the species on the floodplains though, such information is not available. Similarly there is very little information on the nutrient dynamics of these systems.

Climate and Hydrology

The climate of tropical Australia has been described by Ramage (1971) and Lee and Neal (1984). In the Top End there are two seasons. The Wet season commences late in the year (November-December) and lasts for 3-4 months, both the onset and duration varying from year to year. Low atomospheric pressure occurs at this time over northern Australia, and the resulting inflow of warm moist air from the surrounding tropical ocean leads to a hot rainy season. Associated with the monsoon are several significant features of the Wet season, namely thunderstorms, tropical cyclones and barometric depressions with their associated heavy falls of rain. Cyclones develop at sea during the Wet season causing destructive winds, torrential rain, flooding when these cross the coast and sometimes tidal 'storm-surges'. As the cyclones move inland they form barometric depressions and are an important source of rain. The approach of the monsoon (termed the 'build-up') is heralded by thunderstorms with localised, but very heavy rain. In contrast, thunderstorms occurring in March-April do not produce prolonged rain and indicate the approach of the Dry season which is characterised by Dry south-east trade-winds.

The wettest months are typically December-March while June-August are virtually rainless, though the amount that does fall during the Dry is more variable than that falling during the Wet season (Taylor and Tulloch 1985).

Water flows in many of the creeks and rivers on a seasonal basis. Flow commences sometime after the first rains of the Wet season (once the ground becomes saturated) and lasts until after the end of the rains. In Magela Creek the flow pattern consists of a series of flood events superimposed on a 'base' flow. The generalised hydrological pattern (Figure 1) described for the Magela by Sanderson _et al_. (1983) probably applies to many of the coastal creeks

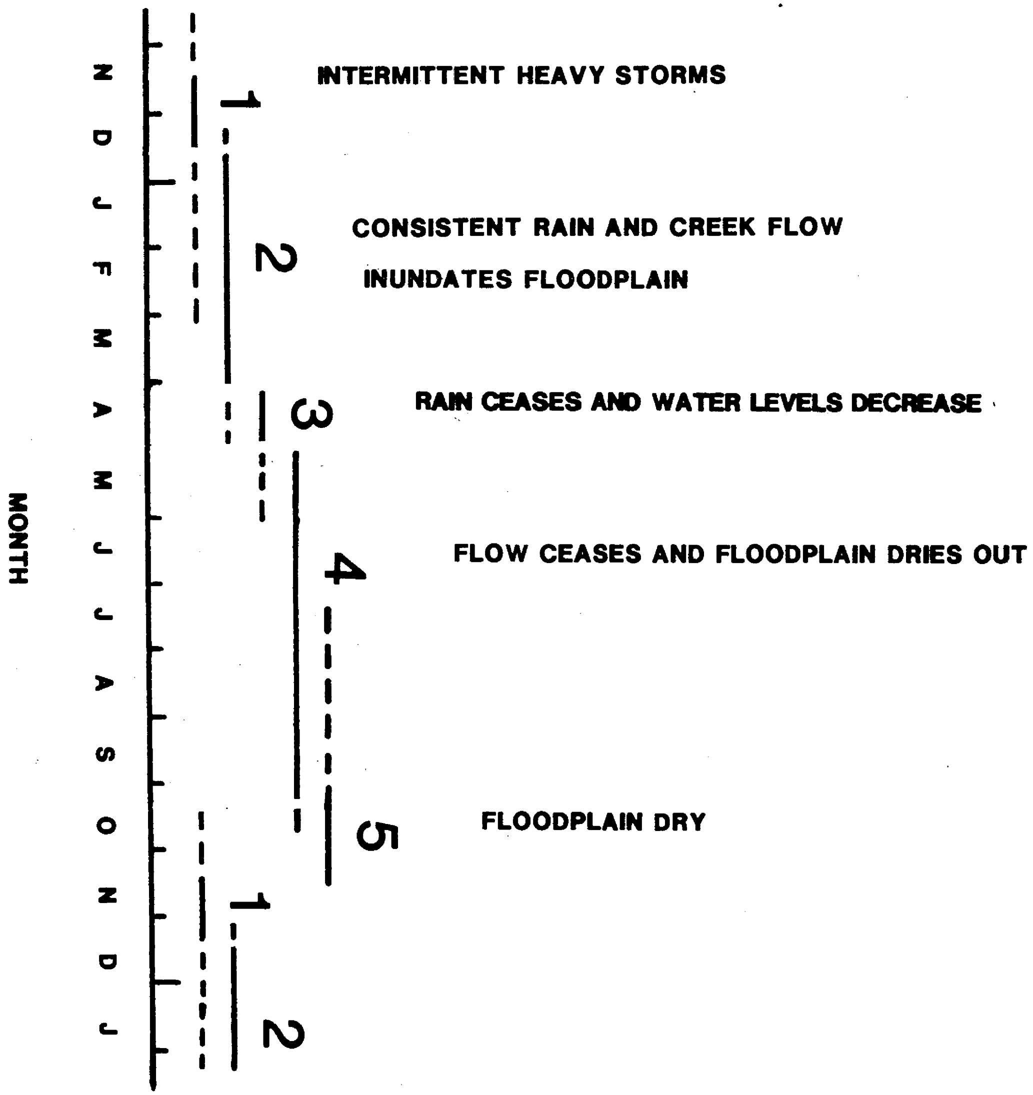

Figure 1: A schematic diagram of the seasonal cycle on the Magela Creek floodplain based on observations from 1979-85 (adapted from Sanderson *et al*. 1983). The cycle is broken into 5 components (numbered 1-5); the 'average' duration of each component (full line) and the variation (dashed line) as determined from the observations are presented.

and rivers. In brief, there is a period of intermittent storms that saturate the soil, followed by more consistent rains and wide-spread flooding. As rainfall increases continuous flow occurs in the braided channels and eventually into a narrow corridor region of channels and billabongs before spilling out onto the floodplains. At the end of the Wet season input of water to the streams finally ceases and evaporative losses increase. The outflow to the East Alligator continues for some weeks, leading eventually to the formation of a dry floodplain, except for the presence of isolated pockets of permanent water in billabongs and swamps. The drying-out phase can take many months. The creeks and channels also either dry out completely, or are reduced to a series of waterholes (billabongs).

Floodplain Vegetation

The distribution of the major plant species on the floodplains during the 1983/84 Wet season has been documented by Bayliss and Taylor and although not yet published several generalisations are evident. *Oryza meridionalis* grasslands and *Melaleuca* spp. woodlands are extensive and occur across most, if not all of the floodplains. The sedges *Eleocharis* spp. and *Fimbristylis* spp., the annual grass *Hygrochloa aquatica* and the water lilies *Nymphaea* spp. and *Nymphoides* spp. are also common. The grass *Pseudoraphis spinescens* is abundant on the Adelaide and Alligator Rivers floodplains, but not common outside these areas. The large emergent species *Phragmites karka* and *Typha domingensis* are described as uncommon on these floodplains, in contrast to their abundance on other floodplains. (*Phragmites karka* is, however, more widespread than suggested by Bayliss and Taylor; it occurs as fringing vegetation along both the South and East Alligator Rivers.) Hill and Webb (1982) attribute this change to grazing and trampling by feral buffalo. Disjunct distribution patterns are shown by the floating plant *Pistia stratiotes* and the emergent species *Typha domingensis*. The former, which may not be native to the NT, is common on the Finniss River and in the isolated Arafura Swamps. Isolated patches occur in swamps on many of the floodplains between Darwin and the East Alligator River. The latter species is virtually unknown in the Alligator Rivers and has not been recorded from the Arafura Swamps, but is common west of the Adelaide River.

A detailed analysis of aquatic plant distribution is available for the Magela Creek floodplain. Morley (1981) classified and mapped peak Wet season (April) herbaceous vegetation on one section of the floodplain and recognised 36 communities. The classification was not reproducible in subsequent Wet seasons (Sanderson *et al*. 1983). To overcome the problems of year-to-year changes Finlayson *et al*. (1988b) used peak Wet season vegetation data from several years to describe and map the following 10 broad plant communities on the floodplain:

(i) Melaleuca open forest and woodland (canopy cover 10-70 per cent);
(ii) Melaleuca open woodland (canopy cover <10 per cent;
(iii) Nelumbo-Hymenachne swamp;
(iv) Oryza grassland;
(v) Hymenachne grassland;
(vi) Pseudoraphis grassland;
(vii) Hymenachne-Eleocharis swamp;
(viii) Mixed grassland and sedgeland;
(ix) Eleocharis sedgeland;
(x) Open-water community.

Whilst not as rigorous as that proposed by Sanderson *et al.* (1983), this classification allows for seasonal and annual changes in vegetation associations and dominance. It is more extensive than the early and brief descriptions of Specht (1958) and Story (1976) and is more comprehensive than the map produced by Williams (1979).

An outstanding feature of the floodplain vegetation is the variation in its floristic composition and degree of foliar cover between the Wet and Dry seasons (Finlayson *et al.* 1986). Most species rely for their success on the existence of mechanisms that enable them to survive the Dry season when much of the water on the floodplains has evaporated. The growth strategies of perennial, geophytic perennial, true annual, and facultative annual species that enable the plants to survive are discussed by Finlayson *et al.* (1988b). Of the 125 plant species recorded from the Magela system six are restricted to permanent billabongs and permanent swamps. The remaining 119 species consists of 50 which occur in seasonally inundated areas (43 of which are water plants as defined by Cook *et al.* (1974)), 27 of which are common to both permanent waterbodies and seasonally inundated areas (24 of which are water plants) and 42 terrestrial herb and sedge species which occur on areas that dry out during the Dry season. The success of the majority of species depends on mechanisms that enable them to survive the extremes of inundation during the Wet season and exposure to the atmosphere during the Dry season.

Thirty-five perennial species occur on the Magela floodplain, including the emergent aquatic grasses *Pseudoraphis spinescens* and *Hymenachne acutigluma*, and the paperbark trees *Melaleuca* spp. Collectively these three grasses and the paperbark trees occupy about 16,000 ha, i.e. about 80 per cent of the floodplain. Five *Melaleuca* species occur on the floodplain with a major division between species occurring in seasonally inundated areas (e.g., *Melaleuca viridiflora*) and those occurring in areas subjected to prolonged waterlogging (e.g. Melaleuca leucadendra).

Thirteen perennial aquatic herbs occur in seasonally inundated areas during the Wet season. Three of these persist during the Dry season on dry areas of the floodplain whereas the other ten are restricted to permanent water bodies at this time. The former have a terrestrial growth form that enables them to survive the Dry season.

Geophytic perennials (species with underground perennating organs) are generally confined to seasonally inundated areas. The ten species in this group include four Eleocharis species and four Nymphaea species.

Fifty-seven species can be considered as true annuals; 15 of these are water plants and 42 are terrestrial herbs, grasses and sedges. The terrestrial species whilst being relatively diverse do not constitute a major portion of the total annual standing crop on the floodplain. Twenty-four facultative annuals occur on the floodplains, though some are perennial in the permanent billabongs and swamps. In seasonally inundated areas they depend on seed in the soil to survive the Dry season.

A characteristic feature of the vegetation of the floodplains is the floating 'grass mat'. Such mats occur on many systems, but are regarded by Hill and Webb (1982) as an endangered habitat due to extensive grazing of buffalo and cattle. The mats have pronounced zones of vegetation, and are usually formed on a base of Pistia stratiotes. Dominant species include Leersia hexandra, Cyperus platystylis, Hymenochaeta grossus, Cyclosorus interruptus, Typha sp. and Phragmites karka.

Productivity of Wetland Vegetation

In the following discussion, production is treated as an increase in plant weight per unit area over a period, whereas productivity is that increase expressed per unit time, i.e. the production rate (Westlake 1963). The only information on the productivity of the vegetation on the seasonally inundated floodplains is that collected for the Magela (Finlayson et al. 1985, 1988b).

Changes in the standing crop weight/unit area for the dominant aquatic grasses Pseudoraphis spinescens, Hymenachne acutigluma and Oryza meridionalis were determined from samples taken over an 18 month period. Standing crop (i.e. above-ground material only) rather than biomass values are reported due to difficulties associated in obtaining accurate below-ground samples during the Wet season. Standing crop weights were related to water levels (Figure

2). For example, *Oryza meridionalis*, an annual species, germinated following the first storms in October-November and then grew rapidly with a peak standing crop weight occurring in April. Flowering and seeding followed by senescence occurred over the next eight weeks as the site dried out. During the Dry season terrestrial herbs (e.g. *Coldenia procumbens* and *Phyla nodiflora*) dominate the areas occupied by *Oryza meridionalis* during the Wet season.

Oryza meridionalis had a maximum standing crop weight of 0.51±0.10 kg/sq m which, as there was no evidence of leaf mortality, grazing losses or further production, also represents the above-ground production. *Pseuedoraphis spinescens* had two growth periods: November-May with a production of 1.06±0.23 kg/sq m and July-January with 0.85±0.03 kg/sq m. It is likely that the second growth period is the initial part of a second growth cycle related to the 1984/85 wet-dry cycle. *Hymenachne acutigluma* similarly had two growth periods: November-January with 0.90±0.26 kg/sq m production and March-June with 1.19±0.12 kg/sq m. As these values are part of events that occurred within the 1983-84 wet-dry cycle the total annual standing crop production for *Hymenachne acutigluma* is 2.09±0.38 kg/sq m. This value, however, is likely to be an underestimate as it does not account for evident losses due to leaf and leaf sheath sloughing and grazing by insects.

Reviews of primary production by aquatic plants are available (e.g. Bradbury and Grace 1983). In general, emergent plants are more productive than submerged species (Westlake 1975; Bradbury and Grace 1983; Saxena 1986), though tropical and sub-tropical swamp plants are not necessarily more productive than temperate swamp plants (Howard-Williams and Gaudet 1985). As an example, *Typha orientalis* growing in inland temperate Australia has an annual above-ground productivity of 2.33 kg/sq m (Roberts and Ganf 1986) which is a relatively high value and within the range of 1.5-8.4 kg/sq m annual production for *Typha domingensis*, recorded, by Howard-Williams and Lenton (1975), in a shallow tropical lake in Malawi.

In addition to habitat characteristics the productivity of emergent shoots can be greatly affected by growth strategies such as the time of emergence, size and life-span of individual shoots. On the Magela floodplain plant growth-strategies are also influenced by the relative length of the period of inundation and/or flooding (Finlayson *et al*. 1988b).

The annual productivity of the grasses on the Magela floodplain reported here is within the range of 0.12-2.59 kg/sq m reported for a number of wetland plant species by Bradbury and Grace (1985). Whilst the values for the

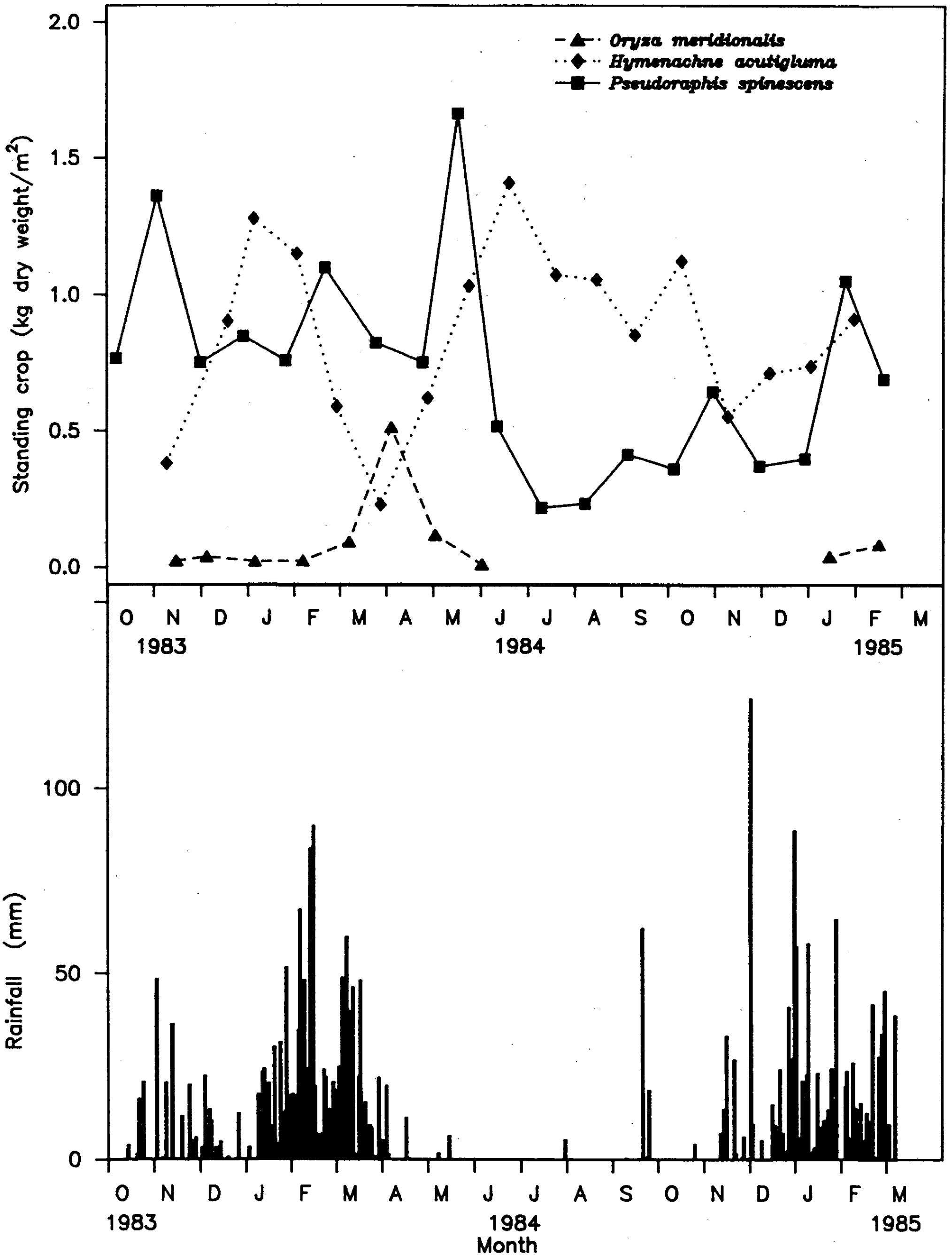

Figure 2: Aquatic grass standing crop weights and water depths at three sites on the Magela Creek floodplain

grasses from the Magela are not as high as those for large emergent species such as *Typha* spp. and *Phragmites australis* (Roberts and Ganf 1986; Hocking *et al.* 1983) they do indicate a relatively high level of annual production, especially *Hymenachne acutigluma* with 2.09 kg/sq m. As the three grasses *Pseudoraphis spinescens*, *Hymenachne acutigluma* and *Oryza meridionalis* cover 18 per cent (3,400 ha), 15 per cent (3,000 ha) and 13 per cent (2,500 ha) of the floodplain respectively (Finlayson *et al.* 1988b) the floodplain as a whole can be described as a highly productive ecosystem.

Productivity information for *Melaleuca* spp. woodland and forest on the Magela floodplain is not available, but some data on litterfall has been published (Finlayson *et al.* 1985). Litterfall in tropical forests has been shown to be linearly related to tree biomass and to site latitude, altitude and precipitation (Spain 1984). On the Magela litterfall appears to show a bimodal pattern (Figure 3) with peaks being recorded during the Wet season (January) and mid-Dry season (June-July). As both of these periods are associated with high wind speeds (monsoons and south-east trades respectively) it seems that wind has a marked influence on litterfall. There are also marked differences in the amount of litter at different sites, with annual values ranging from 8±1 to 15±2 t/ha, relatively high values compared to those from other forests (Spain 1984).

The weight of *Melaleuca* litter is dominated by leaves throughout the year, twigs being of secondary importance (Figure 4). Components such as flowers, fruit and floral bracts do not constitute a large proportion of the total litter. The increase in litter during the mid-Dry season is almost entirely because of increased leaf abundance in the litter. Decomposition of the leaf litter is not rapid (Finlayson *et al.* 1984), nor does it accumulate on the forest floor as it is physically moved by flowing water during the Wet season.

The nature, distribution and biomass, and hence productivity of the floodplain vegetation is being affected by the presence and increasing spread of a number of alien plant species. The most prevalent of these are *Mimosa pigra*, *Salvinia molesta* and *Brachiaria mutica*. The first two species have been declared noxious weeds under the Northern Territory Noxious Weed Act 1985, though the last, a commonly utilised pasture species, is not similarly classified. The extent of invasion of wetlands by *Brachiaria mutica* has not been assessed, although in the Alligator Rivers Region it successfully colonises areas that have been previously grazed by feral buffalo.

Mimosa pigra is an aggressive, prickly shrub from South and Central America that has been recorded in the NT since

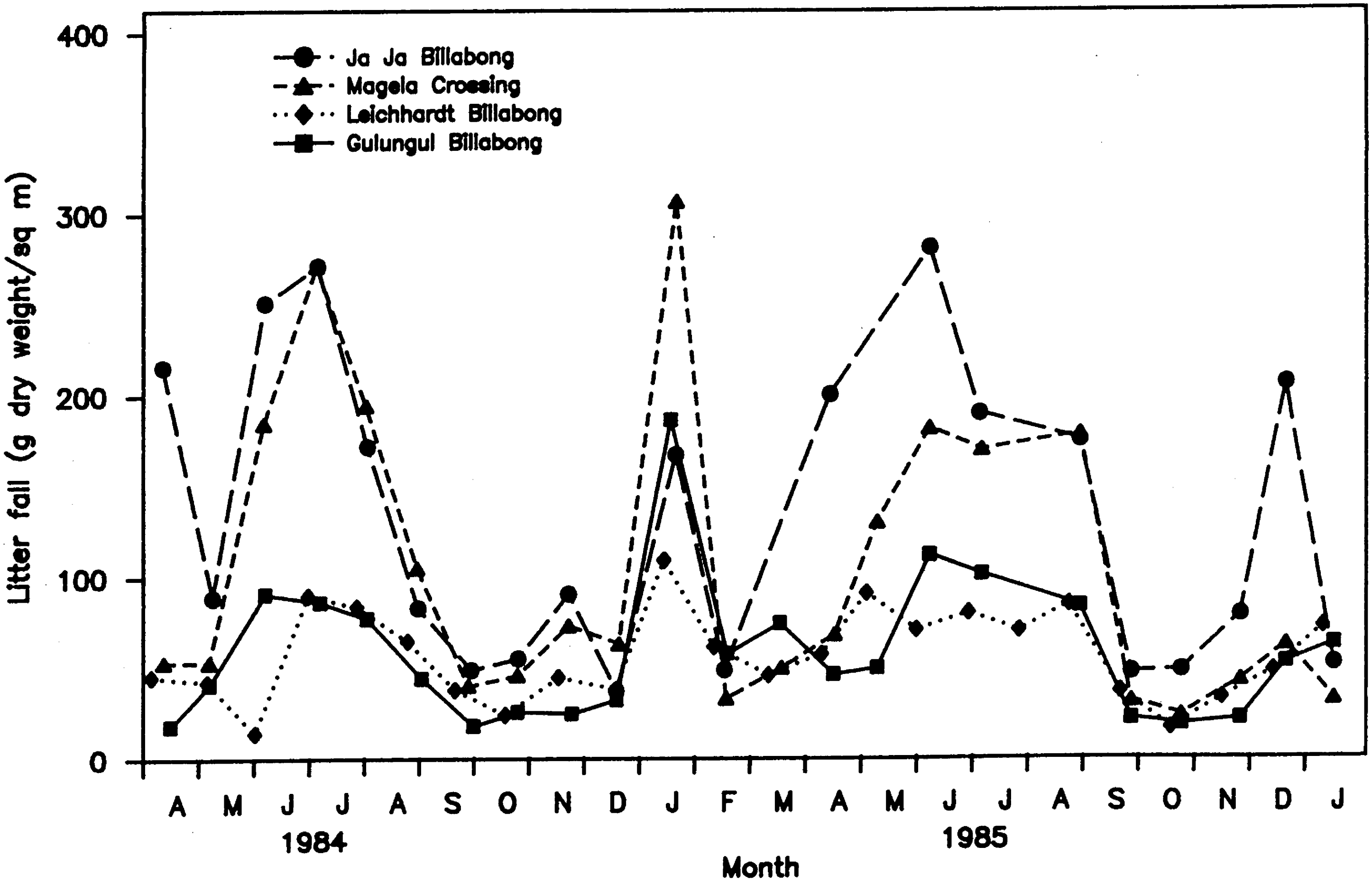

Figure 3: Seasonal litter fall in four *Melaleuca* spp. swamps on the Magela Creek floodplain

late last century. The plant is mainly concentrated along the Adelaide River, east of Darwin, where it covers an estimated 8,000 ha (Considine 1985). From there it has spread to sites in the Batchelor-Rum Jungle area, the lower Mary River, the Daly, Reynolds and Finniss Rivers, Kakadu National Park and a number of locations around the city of Darwin (M. Lonsdale pers. comm.). It has not been reported anywhere else in Australia. It generally occurs in monospecific stands and because of the density of its shade eliminates vegetation, reducing the area available as breeding sites for the normal fauna of the area. Essentially, this species can change the status of wetlands from grassland to scrubland. It has a high production rate, about 12,000 seeds/sq m/year, of small seeds that are easily dispersed (M. Lonsdale pers. comm.). The high seed output, persistence of seedlings and resprouting of mature plants results in rapid regeneration or establishment. It has an annual productivity rate of about 8 t/ha (M. Lonsdale pers. comm.).

Salvinia molesta is a free-floating fern of South American origin that was first recorded in Darwin in 1976 and subsequently at Nhulunbuy, followed by infestations on the Adelaide, Reynolds, Mary, Finniss and Howard Rivers, and on Mount Bundy Station (G. Flannigan pers. comm.). The most recent record is from Kakadu where infestations were found in the southern part of the Magela floodplain in September 1983 (Finlayson 1984a). The plant was distributed further in subsequent Wet seasons and now completely covers several billabongs during the Dry season. Infestations in some billabongs have been colonised by *Ludwigia adscendens*, *Leersia hexandra* and *Cyperus platystylis* to form extensive floating-mat communities. The productivity of *Salvinia molesta* in the NT wetlands has not been determined but in Mount Isa growth rates of 17-26 per cent/day (i.e. doubling times of 3-4 days) have been recorded (Finlayson 1984b). As with *Mimosa pigra* the effect of this species on the productivity of the native plants and animals has not been quantitatively assessed, though it is obvious that in some areas, at least, it is detrimental to the growth and development of the native vegetation.

Vertebrate Fauna Description and Productivity

The floodplains of the Top End hold a high number of vertebrate animals. These include freshwater and saltwater crocodiles (Webb *et al.* 1983a; Bayliss *et al.* 1986), other large reptiles such as the filesnake (Shine 1986) and freshwater turtles (J. Legler pers. comm.), freshwater fish (Bishop *et al.* 1986), introduced Asian water buffalo (Graham *et al.* 1982) and many species of water birds (Morton and Brennan, forthcoming). These numbers (Table 1), when taken in conjunction with the sizes of the animals, convey the

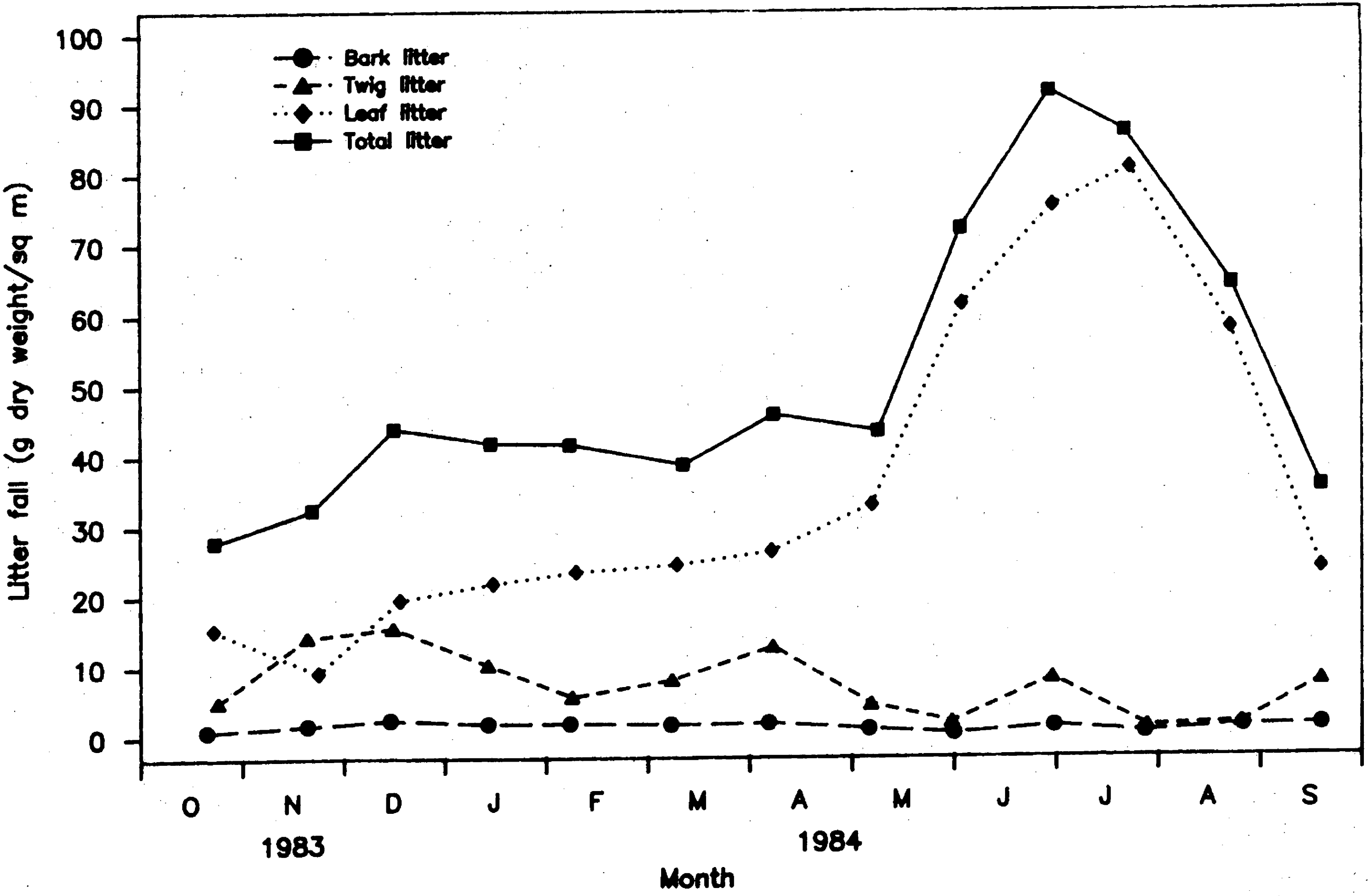

Figure 4: Seasonal changes in major components of litter fall in a <u>Melaleuca</u> spp. swamp on the Magela Creek floodplain

reality of a high standing biomass of animals. Information on biomass of vertebrate animals in the freshwater floodplains has been summarised by Finlayson *et al.* (1988a). The actual productivity of many vertebrate species on the floodplains has not been assessed and can only be inferred from population studies.

Large body-size in higher animals is typically correlated with long generation time (time to reach sexual maturity) and the capacity to withstand short-term minor environmental disturbance (Pianka 1983). Such animals exploit the freshwater wetlands by their high level of mobility and/or by their having mechanisms that allow them to withstand periods of little or no nutrient intake. The large aquatic reptiles withstand these periods by having low metabolic rates and slow growth rates, and/or food habits that lower their dependence on foods provided by the aquatic environment.

The Arafura file snake, *Acrochordus arafurae*, is perhaps the vertebrate animal on the floodplains that best demonstrates the extremes of slow growth and low metabolic rate. They reproduce less frequently than other snakes with only 7 per cent of adult-sized females found by Shine (1986) to be 'reproductive'. Similarly, in the same study only 5 per cent of the snakes contained prey items, suggesting that food requirements and hence the metabolic rate for this species is lower than most other reptiles (Seymour *et al.* 1981; Shine 1986).

Freshwater turtles depend heavily on vegetable foods of terrestrial origin. *Emydura australis* and *Elseya latisturnum* are omnivorous and opportunistic while *Elseya dentata* and *Carettochelys insculpta* subsist in the Dry season on a diet of leaves, flowers and fruit (J. Legler pers. comm.). Vegetable foods include *Melaleuca and Eucalyptus* leaves, flowers, fig fruits and *Pandanus* roots and fruits.

Crocodylus johnstoni (freshwater crocodile) eats less during the Dry season than during the Wet season, particularly when the temperature is lower (Webb *et al.* 1982). Captive freshwater crocodiles also have depressed food intake during the Dry season (with no decrease in water or substrate temperatures) (Webb *et al.* 1983b). It appears that reduction in feeding activity could have some physiological basis independent of environmental temperature (Webb *et al.* 1983b). A large part of the food of freshwater crocodiles comes, perhaps surprisingly, from the terrestrial environment. Approximately 40 per cent (estimated using a variety of techniques) of their food is of terrestrial origin (Webb *et al.* 1982). Adult *Crocodylis porosus* (saltwater crocodile) also consume foods of terrestrial origin. Prey items include birds, wallabies and other crocodiles as well as other reptiles. Smaller Crocodylus porosus are opportunistic feeders and mainly eat invertebrates (Taylor 1979).

Some freshwater fish also have food habits that lower their dependence on foods provided by the aquatic environment. Surface feeding species such as Melanotaenia splendida inornata and Melanotaenia nigrans (chequered and black-striped rainbow fish) as well as such highly-specialised species as Toxotes chatareus and Toxotes lorentzi (the archer and primitive archer fish) are dependent on food from terrestrial sources.

Of the larger fish species, Lates calcarifer (barramundi) has great mobility, breeding at the mouth of the river system and then either staying in the salt water or swimming upstream to the freshwater. The juveniles spend their early weeks in brackish coastal swamps with some migrating upstream to the freshwater floodplains.

Fish migration occurs during the Wet season. Recolonisation of the lowland sandy creeks and backflow billabongs in the early-Wet results in the most obvious seasonal changes in fish community structure. Movement occurs in both an upstream and downstream direction from Dry season refuge areas on the floodplains and upper escarpment areas.

The diversity of freshwater fish in the tropical floodplains is higher than in temperate areas of Australia (Bishop et al. 1986). About 50 species occur in the Alligator Rivers Region, though only a few, Pingalla nov. sp. (the black-anal finned grunter) and Pseudormugil tennellus (the Arnhem Land blue-eye), appear to be endemic.

The freshwater floodplains in the NT are the prime habitat for 68 bird species, the adjacent grass/sedgelands for 26 species and the Melaleuca-dominated fringing forests for 20 species, which together comprise 45 per cent of the Top End bird species (Morton and Brennan, forthcoming). The numerically dominant species on the floodplains are Anseranus semipalmata (magpie goose), Dendrocygna arcuata (wandering whistle-duck), Egreta intermedia (intermediate egret) and Plegadis Falcinellus (glossy ibis). There are also an additional 18 species of migratory birds from the Charadriidae and Scolopacidae families, though few are resident.

Broad scale, seasonal changes in distribution occur for wetland birds (e.g. Tadorna radjah (Radjah shelduck), Dendrocygna arcuata and Dendrocygna eytoni (the whistle ducks)) and the magpie goose Anseranus semipalmata. The seasonal patterns differ with species, but the mobility of

Table 1

Estimates of the abundance, size or weight of a variety of wetland animals in the Top End of the Northern Territory (from Finlayson et al. 1988a)

Species	Size/Weight	Abundance
1. CROCODILES		
Crocodylus johnstoni	to 3 m long	mean = 1.57 per pool (max. = 61)
Crocodylus porosus	to 7 m long	
Tidal River (Adelaide)		
Downstream		mean = 135 ± 5 (10 km)$^{-1}$
Upstream		mean = 54 ± 6 (10 km)$^{-1}$
Side Creeks		mean = 44 ± 2 (20 km)$^{-1}$
2. TURTLES		
Carettochelys insculpta	to 0.7m long(shell)	17 (100 m)$^{-1}$
Chelodina rugosa	to 0.4m long(shell)	9 (100 m)$^{-1}$
Elseya dentata	to 0.35mlong(shell)	38 (100 m)$^{-1}$
Elseya latisternum	to 0.2m long(shell)	8 (100 m)$^{-1}$
Emydura australis	to 0.3m long(shell)	10 (100 m)$^{-1}$
3. FILE SNAKE		
Acrochordus arafurae	to 2.5 m long	100 ha^{-1}, > 50 kg ha^{-1}
4. WATERFOWL		
Anseranus semipalmata	to 2.5 kg	279 km^{-2} (1984 dry season)
Dendrocygna arcuata and		88 km^{-2} (1984 dry season)
Dendrocygna eytoni		
5. BUFFALO		
(South Alligator River)		15 km^{-2}

these animals allows for exploitation of habitats inadequate for the support of a resident population or allows for the maintenance of higher population sizes than would otherwise be possible. Movement of species between floodplains has been documented for the Alligator Rivers Region (Morton *et al.* 1987). The results suggest that the waterbirds move between the wetlands in response to changes in the feeding and breeding habitats. The Magela, for example, has extensive areas that remain wet for lengthy periods throughout the Dry season. The number of birds on these areas in the late-Dry exceeds one million, reflecting migration from nearby dried out wetlands. However, during the transition from Dry to Wet the birds disperse from the Dry season refuge areas to more highly favoured feeding grounds such as the East Alligator floodplain. Unlike other floodplains or wetlands in the area, the East Alligator floodplain regularly contains high densities of birds during the Wet season. The extent of dispersion of waterbirds from the Dry season refuge areas is not known; the population on the Magela is about 200,000 during the Wet.

The diets of all granivorous bird species on the floodplains are linked to the phenological state of the floodplain plants. *Nettapus pulchellus* (green pygmy geese) feed on *Hygrochloa aquatica* during the mid-Wet and change to *Limnophila indica,* *Caldesia oligococca* and *Nymphoides* spp. later in the Wet season. In the early Dry *Nymphaea violacea* becomes a more important food source for this species while *Nymphaea macrosperma* and *Hydrilla verticillata* are important when the aquatic habitat has contracted further in the late-Dry. This piscivorous/insectivorous species have different habitat and foraging strategies that affects the types of prey likely to be encountered.

The wetlands of the Top End have been subject to disturbance from feral cattle, and particularly the water buffalo, *Bubalus bubalis*. Since buffalo were released during early attempts at settlement by Europeans (from 1827-49) they have increased in number to about 280,000 animals and range in distribution up to 100 km from the coast (Graham *et al.* 1982). Very little quantitative evidence is available on the threat they might or do constitute to the wetlands, though the Feral Animals Enquiry (Letts *et al.* 1979) compiled substantial circumstantial evidence on these threats. More recently Taylor and Friend (1984) and Friend and Taylor (1984) have related ground surface features attributable to buffalo activities to the vegetation structure and plant life, and to the abundance of small animal species on the floodplains.

The extent of buffalo impact on the major wetlands between the Daly and East Alligator Rivers has been surveyed by Fogarty (1982). He reported open plains heavily grazed and pug-marked, networks of tracks and swim channels, reduction in floating grass mats and vegetation cover (especially of reeds) around billabongs, bank erosion and slumping, and saltwater intrusion. These changes have resulted in a loss of natural vegetation, invasion of alien plants, increased areas of high salinity water and high turbidity, and destruction of crocodile-breeding areas. Fogarty (1982) presents specific detail for each wetland surveyed.

The destruction and loss of floating grass mats from the Finniss/Reynolds region has been documented by Hill and Webb (1982). The combined effect of intensive grazing and trampling has broken the connection between the mats and the bank, allowing them to be washed out onto the floodplains where they eventually fall apart. The same trampling and grazing has been held responsible for the demise of *Phragmites karka* over 3,000-4,000 ha of swamps in Kakadu National Park (Hill and Webb 1982).

Nutrient Dynamics

The dynamics of nutrient turnover and cycling on the seasonally inundated floodplains have not received a great deal of attention. However, the role of aquatic grasses and paperbark trees (*Melaleuca* spp.) in cycling nutrients (and trace metals) on the Magela floodplain is currently being investigated (Finlayson *et al*. 1984, 1985, 1988a), as part of an assessment of the consequences of water release from the Ranger uranium mine. There have not been any studies that have attempted to relate the energy and nutrient pathways of either the primary or secondary producers on the floodplains.

The water quality, including nutrient concentrations, of Magela Creek billabongs and creek water have been investigated; a summary of the results of these investigations is presented below. Magela Creek water, after the first flush of the Wet season, is neutral to acidic, very soft with low buffering capacity, and has low concentrations of ions (Brown *et al*. 1985; Morley *et al*. 1985; Walker and Tyler 1984). The velocity with which the 'front' of the Wet season flood advances across the plain influences the limnological characteristics of the billabongs. In general, a slow advance enables cooler, more acidic and more-highly oxygenated water to displace the warmer, less acidic and poorly-oxygenated water in the billabongs, whereas a high velocity causes 'sheet-type' flow over the billabong, initially trapping the existing water. Solutes generally increase in concentration during the Dry season, due to evaporation and ingress of mineralised groundwater (Brown *et al*. 1985).

The initial inflow of acidic water into the billabongs can result in extensive fish kills, such as that reported by Brown *et al*. (1983) in Ja Ja Billabong. Following a heavy localised storm and significant runoff to the billabong, in excess of 3,400 dead fish, mainly *Lates calcarifer, Arius leptaspis, Liza diadema* and *Tandanus ater*, were collected. The full extent of the kill was not determined as some fish were removed by predators (birds, crocodiles and monitor lizards). The fish mortality was attributed to the combined effects of low pH values and an increase in aluminium concentration due to natural phenomena, though direct evidence for this was not obtained. The fish kills tend to occur annually following the commencement of the Wet season when the first flushes of water occur across the floodplains. This water is acidic, pH 3-4, and contains high concentrations of labile aluminium, up to 84,000 μg Al/L (Noller and Cusbert 1985). If the flush is slow and the flush water remains in the billabongs for several hours fish kills can occur.

Billabongs on the Magela were extensively sampled from 1978 to 1981 by Walker and Tyler (1982). A summary of their data is presented in Table 2. During the Wet season the billabong water chemistry resembled that of the creek with conductivity less than 20 μS/cm, pH 6.4-7.0 and ionic dominances of $Na>Mg>Ca>K>$ and $HCO_3>Cl>SO_4$. During the Dry season the water quality was more site specific with conductivities in mid-July (1980) ranging from 17-110 μS/cm and pH from 5.8 to 7.1. The channel billabongs had conductivities of 17-37 μS/cm and equimolar proportions of Na and Mg, whereas backflow and floodplain billabongs had 38-110 μS/cm conductivities and $Na>>Mg$. Floodplain billabongs, unlike the backflow type, developed a SO_4 anionic dominance. The chemical composition of the floodplain billabongs changed later in the dry with conductivities ranging from 60-1,200 μS/cm and most billabongs becoming Cl dominated. The ionic dominances have been used to classify the billabongs (Table 2).

Mudginberri and Bowerbird Billabongs had equimolar amounts of Na and Mg and low conductivities of 15-30 μS/cm throughout the Wet and Dry seasons, and were chemically stable after the first flush of the Wet season. In contrast Georgetown, Coonjimba, Leichhardt and Buffalo Billabongs progressed towards seawater Na:Cl ratios during the Dry season and developed a Na and Cl ionic dominance. Wet season inflows reduced conductivities and restored the Na/HCO_3 ionic proportions. Corndorl, Ja Ja, Mine Valley, Jabiluka, Nankeen and Island Billabongs also tended towards a NaCl dominance but, in addition, had a large increase in SO_4, attributed to groundwater ingress. The Wet season floodwaters restored the Na and HCO_3 dominance and reduced conductivity.

Nitrogen and phosphorus concentrations during the Wet season were relatively low and similar between billabongs, with total phosphorus generally <40 µg/L, inorganic nitrogen <35 µg/L and total nitrogen <1050 µg/L.

Table 2

Classification of Magela Creek billabongs based on late Dry season characteristics (adapted from Finlayson et al. 1988b)

Type of Billabong	Ionic Character	General Characteristics	Total Phosphorus
Channel	Na/Mg HCO_3	Maintain ionic character of Wet. $K_{25} < 90$ µS/cm $5.8 < pH < 6.5$ Turbidity < 50 NTU	< 70 µg/L
Backflow	NaCl	Progression through Dry to NaCl dominance $35 < K_{25} < 630$ µS/cm $4.0 < pH < 6.0$ Turbidity in late Dry season > 100 NTU	< 400 µg/L
Floodplain	SO_4	SO_4 dominance with trend to NaCl dominance during Dry $60 < K_{25} < 1200$ µS/cm $3.5 < pH < 5.5$ Turbidity in late Dry season > 100 NTU	100-300 µg/L

Except for channel billabongs these values increased during the Dry season. The channel billabongs had relatively low nutrient concentrations that changed little with season. Floodplain billabongs were generally hyper-eutrophic by the late Dry. The Wet season floodwaters flushed and diluted these billabongs. Backflow billabong nitrogen and phosphorus concentrations remained more or less constant through the early dry and increased abruptly late in the dry with total phosphorus eventually exceeding that of the other billabongs.

From the nutrient-concentration scheme of Vollenweider (1968) for classifying the trophic status of waterbodies, the billabongs were regarded, on the basis of the total phosphorus levels, by Walker and Tyler (1982) as meso-eutrophic to hyper-eutrophic during the Wet, and all except the channel billabongs hyper-eutrophic during the Dry. McBride (pers. comm.), however, has pointed out that total phosphorus values recorded in Ja Ja Billabong by the Northern Territory Water Division over the same period did not exceed 45 µg/L, designating it as oligo-mesotrophic. On the basis of the inorganic nitrogen concentrations Walker and Tyler (1982) classified the billabongs as ultra-oligotrophic during the Wet, whilst during the Dry all except the channel billabongs were mesotrophic to hyper-trophic. After considering these data they suggested nitrogen was the likely limiting nutrient; an assessment that was later reversed when the phytoplankton levels were correlated to the nutrient levels in the water (Walker and Tyler 1984).

Hart et al. (1987) have calculated an input-output budget for the Magela Creek floodplain. Their data suggests that the floodplain is a net sink for the nutrients nitrogen and phosphorus entering from the catchment. The implications on the productivity of the floodplain vegetation of the floodplain accumulating rather than exporting nutrients have not been assessed.

Concluding Remarks

The above discussion has concentrated on describing the species composition and productivity of plants and vertebrate animals of the seasonally-inundated floodplains. The production levels are high and in view of the marked seasonal changes in water availability and population sizes the floodplain ecosystems are undoubtedly dynamic. There is, however, very little available information on the transfer and cycling of energy and nutrients between the different trophic levels.

In addition to the plants and vertebrate fauna discussed above, the floodplain ecosystems contain large and dynamic populations of invertebrate animals (Marchant 1982; Julli 1986) and algae (Thomas 1983; Ling and Tyler 1986). These organisms add to the diversity and productivity already discussed, but very little is known about their roles as primary producers or consumers, and in the cycling of energy and nutrients.

The cycling of nutrients by the floodplains vegetation is being investigated on the Magela (Finlayson et al. 1985). These studies, however, are related to the potential effect of mining on the floodplain ecosystem and are not directly concerned with the effects of alien plant invasion, feral animal invasion and eradication, phenomena (or threats) that have the potential to alter the productivity and basic biotic structure of the floodplain ecosystems (Finlayson et al. 1988a). As an example, the impact of the feral buffalo on the floodplains has been well documented (e.g. Fogarty 1982), but the consequences on the population structures and productivity of floodplain species of removing large numbers of these animals has not.

Threats to the biotic structure on the floodplains include the already mentioned alien plants and feral animals, plus the potential effects of future agricultural, tourist and mining developments. The distribution of funds being spent on these different potential threats has been pointed out by Finlayson et al. (1988a) when comparing the resources devoted to investigations into the environmental aspects of uranium mining in the Alligator Rivers Region and those into the threat posed to the biotic environment on the floodplains by alien plants. It is not suggested that the expenditure on investigations into the effect of uranium mining is unjustified, but rather, that funding of alien plant research is inadequate, especially as alien plants threaten all the freshwater wetlands in the Top End. Similar statements could be made about the long-term effects of other threats and changes on the production and nutrient turnover characteristics of the floodplain ecosystems.

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ORGANISATION OF MANGROVE FORESTS ALONG NATURAL SALINITY GRADIENTS IN THE NORTHERN TERRITORY: AN ECOPHYSIOLOGICAL PERSPECTIVE

Marilyn C. Ball

'Mangrove' is an ecological term referring to an association of woody trees and shrubs which form the dominant vegetation in tidal, saline wetlands along tropical and sub-tropical coasts. The species are often distributed in a banded zonation pattern normal to shore (e.g. Semeniuk 1985). These vegetation patterns generally are well correlated with the frequency and duration of tidal immersion (Watson 1928; Chapman 1944; Macnae 1968). Such correlations between vegetation and tidal characteristics tend to be site specific because the two factors are not directly related. Tidal characteristics exert their influence on vegetation through intermediate factors which either directly affect growth or are resources required for growth. Such factors include the salinity of surface and ground water and the degree of soil saturation.

Naturally, the salinity and water content of the mangrove soils fluctuate over various time scales. Interspecific differences in the extent to which species can adjust to the seasonal ranges in environmental conditions will play a major role in the success of a species in different habitats. Conditions are most extreme during late dry season when soil salinities are maximal and soil water contents are minimal. These are likely to be the conditions which are most limiting to species distributions and relative success in different swamp habitats.

A summary of the distribution and relative importance of major mangrove species in relation to the salinity and water content of the soil during late dry season along the Adelaide River is shown in Figure 1. For example, Bruguiera parviflora is one of the prominent species found in mangrove forests along tidal reaches of the Adelaide River. Water dispersed propagules become widely distributed in the forest system during the wet season and establish over a wider range of conditions than those which support later stages of development. Although mature individuals of B. parviflora also occur over a wide range of conditions, the relative importance of these trees to the forest structure varies along gradients of salinity and water content. The conditions in which B. parviflora is the dominant species in terms of both size and number of individuals are much more restricted than those which permit growth of the species to maturity. Other major species are also widely distributed

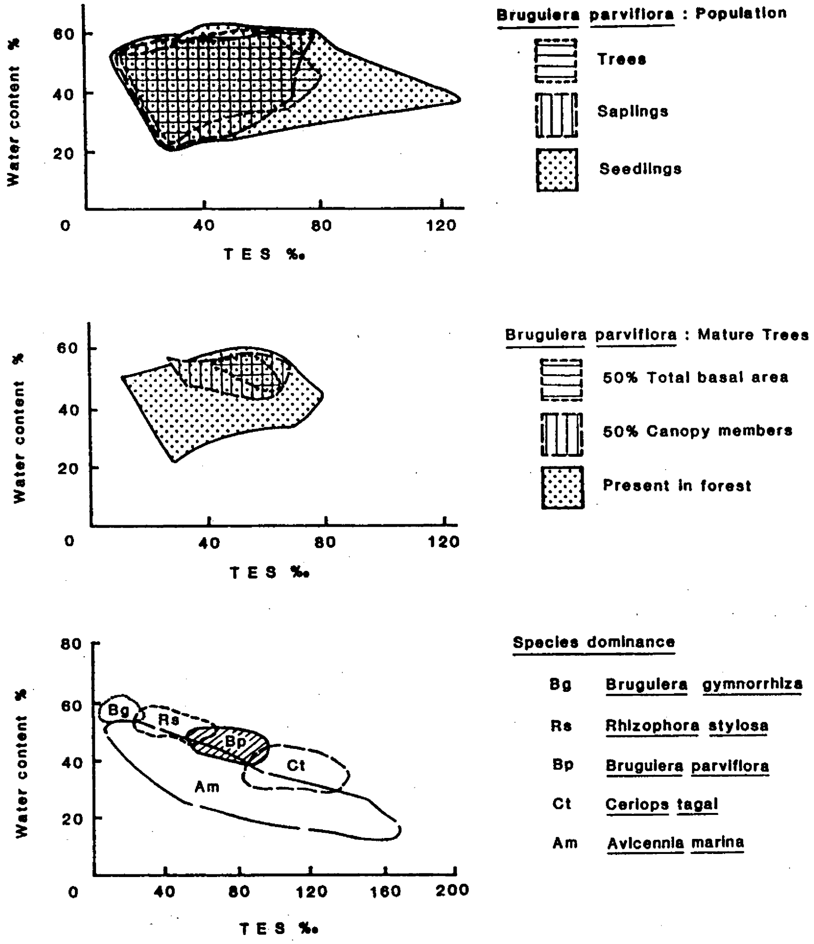

Figure 1: Distribution of *Bruguiera parviflora* in relation to the water content and total extractable salt (TES) of the soil during late dry season. Top panel depicts the distribution of three developmental stages (i.e. seedlings, saplings and mature trees) along gradients of water content and TES. The middle panel shows the stratification of the population of mature trees in terms of their relative importance to the forest along gradients of water content and TES. The population is classified as being present in the forest, being dominant in terms of density (i.e. accounting for at least 50 per cent of the canopy members) and being dominant in terms of size (i.e. accounting for at least 50 per cent of the total basal area). The bottom panel shows the conditions in which *B. parviflora* is the dominant species in terms of both density and size in relation to the distribution of dominance among other major species of the Adelaide River system.

throughout most of the mangrove system, but are dominant only in a narrow range of conditions which can be defined by the salinity and water content of the soil during late dry season. The implication of these findings is that interspecific competition is a major factor influencing the differential distribution of the species along environmental gradients, consistent with previous findings in southern Florida (Ball 1980).

Mangroves are halophytes, plants which naturally complete their life cycles under saline conditions (Flowers *et al.* 1986). Salinity in the mangrove environment is largely due to NaCl and varies in time and space from freshwater to hypersaline conditions. There are marked interspecific differences in salinity tolerance, as shown in a recent study of 16 mangrove species (Ball and Pidsley 1988). For example, growth of *Sonneratia lanceolata* is maximal in salinities ranging from freshwater to 5 per cent seawater, and declines to minimal values in 50 per cent seawater. Most mangrove species also grow in freshwater, but growth is stimulated by saline conditions, with the optimal salinities for growth ranging from 5 to 50 per cent seawater. Finally a few species appear to be obligate halophytes. In two species, *Ceriops decandra* and *Sonneratia alba*, extremely poor growth and time dependent decline in vigour indicate that the plants are not likely to grow to maturity under freshwater conditions. Propagules of two other species, *Bruguiera parviflora* and *Ceriops tagal* var. *australis*, failed to grow under freshwater conditions. The addition of as little as 5 per cent seawater to the culture solutions was sufficient to produce vigorous specimens of all four apparently obligate halophytes. The physiological bases of either growth stimulation or apparent requirements for saline conditions are unknown (Flowers *et al.* 1986).

In summary, mangroves typically grow maximally under relatively low salinity conditions, but differ in the range of salinities over which high growth rates are sustained (Figure 2). In general, the broader the range of salinity tolerance of a species, the slower is its growth rate under optimal salinity conditions (Ball 1988b; Ball and Pidsley 1988). It appears that increasing salinity tolerance is at the expense of the growth rate (Ball 1988b; Ball *et al.* 1988). The following discussion will consider the physiological bases of coping with salinity, and how these physiological attributes might contribute to the differential distribution of mangrove species along natural salinity gradients.

Mangroves, like most other salt-tolerant plants (see review Flowers *et al.* 1986), accumulate high concentrations of inorganic ions which apparently function in the osmoregulation of leaves and other tissues. The vacuole is the

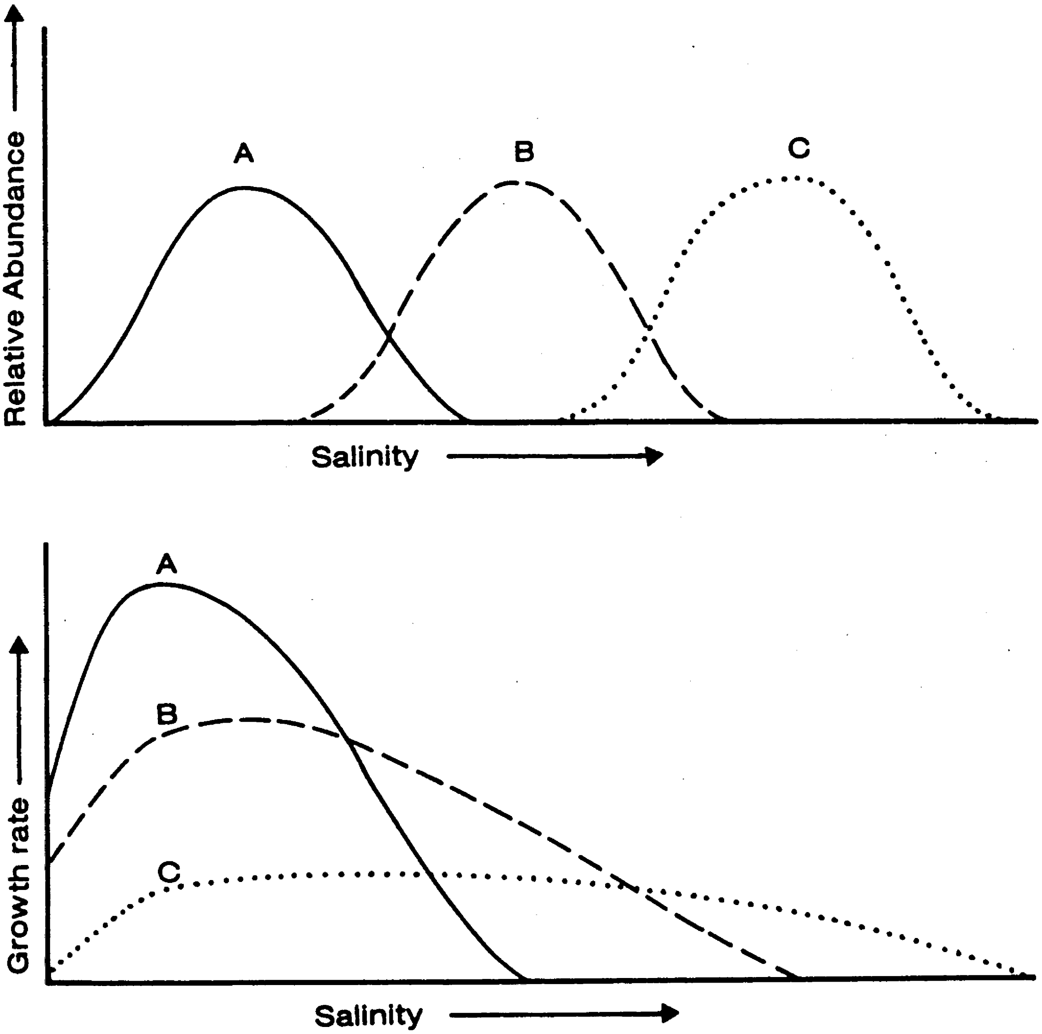

Figure 2: Schematic diagram of the ecological and physiological responses of three hypothetical mangrove species to variation in salinity. The top figure shows the distribution of three species (A, B, C) along a natural salinity gradient. Each species is dominant over a different range of salinities. The bottom figure shows the physiological responses of the same species to the salinity gradient. Species A is dominant in salinities optimal for its growth, whereas species B and C are dominant in salinities which are sub-optimal for their growth but which prevent or limit the growth of other species (after Ball 1988a).

major site of ion accumulation, with the concentrations of ions in other intracellular compartments apparently differing little from those in salt-sensitive species, except perhaps during salinity stress. Osmotic adjustment in the cytoplasm is apparently achieved by synthesis of compatible solutes, low molecular weight organic compounds which do not interfere with metabolism. In this manner, intracellular compartmentation of ions protects biochemical processes which are just as sensitive to high concentrations of NaCl _in vitro_ as those isolated from glycophytes.

While salinity tolerance requires a high degree of cellular competence in ion accumulation and compartmentation, it is also a whole plant phenomenon. The critical problem is that the uptake of ions by the roots must be balanced by the capacity of the shoot to accommodate the salt influx (Ball 1988a). Although the mangroves, like most other halophytes, accumulate inorganic ions for osmoregulation, these requirements are met by the uptake of only a fraction of the Na^+ and Cl^- ions contained in the external soil solution. Indeed, most (i.e. 90 to 99 per cent) of the external NaCl is excluded from entry into the transpiration stream, with species possessing salt secretion glands in the leaves being the least effective at salt exclusion (Scholander _et al._ 1962, 1966; Atkinson _et al._ 1967; Scholander 1968; Clough 1984).

The mechanism(s) of salt exclusion are unknown, but appear to entail considerable costs to the plant (Ball 1988b). For example, maintenance of a particular shoot evaporation rate, say 1 mmol m^{-2} s^{-1} in _Aegiceras corniculatum_ with increase in salinity from 50 to 500 mM NaCl was associated with an increase in the root mass/leaf area ratio from 38 to 79 g m^{-2} and a decrease in the rates of water uptake from 26.3 to 12.7 mol g^{-1} s^{-1}, respectively (Ball 1988b). _Avicennia marina_, a more salt tolerant species, took up water at half the rates of _A. corniculatum_ and hence the cost of water gain in the former species was twice that in the latter (Ball 1988b). These results are consistent with previous studies showing that the hydraulic conductances of roots of _Avicennia marina_, even those grown in freshwater, are as much as two orders of magnitude lower than those of salt sensitive plants, and decrease with an increase in salinity (Field 1984). It may be that restricting the rate of water uptake is involved in salt exclusion and maintenance of specificity for uptake of K^+ over Na^+. Thus, if the rates of water uptake were to decline with increasing salinity and/or with the effectiveness of ion exclusion, then a greater root mass might be required to supply a given quantity of water at a given tolerable salt concentration. Similarly, a greater root mass may be needed relative to leaf area with decreasing humidity in order to satisfy the increasing demand for water at the leaves as well as to maintain the effectiveness of salt exclusion at a given salinity (Ball 1988b). Such changes in carbon partitioning may influence growth rates as growth of new leaves has positive feedback on biomass production while growth of new roots has positive feedback on plant water status (Schulze *et al.* 1983). Whatever the reason, the carbon cost of water uptake increases with increasing salinity and is greater in the more salt tolerant species (Ball 1988b).

The uptake and distribution of ions in the shoot must be controlled so as to maintain turgor and protect sensitive metabolic sites from ion stress. The mechanism(s) by which mangroves achieve salt balances in the shoot are poorly known. A few species possess salt secretion glands in the leaves. In these species, some of the salt borne in the transpiration stream to the leaves is absorbed for osmoregulation of growing tissues, with the salt concentrations presumably maintained within physiologically acceptable levels by salt secretion (Atkinson *et al.* 1967). In contrast, the non-secreting species must balance the transport of ions to the shoot with the capacity of the shoot to store ions. In other words, growth must keep pace with the rates of ion uptake. Hence, the balance between carbon gain and the expenditure of water with its associated salt uptake may be critical to growth under saline conditions. This suggests that differences in salt exclusion coupled with differences in water use efficiency may play major roles in determining relative degrees of salt tolerance.

The importance of water use efficiency to the maintenance of favourable ion levels in shoots of *Aegiceras corniculatum* and *Avicennia marina* is shown in Table 1. Salt exclusion at the roots was similar in both species and increased from 90 to 97 per cent with increase in salinity from 50 to 500 mM NaCl (approximately 10 to 100 per cent seawater NaCl concentrations, respectively). Some of the salt was retained in the roots and the remainder was borne to the leaves in the transpiration stream. The xylem Cl^- concentrations increased with increasing salinity, but the flux of salt per unit leaf area was similar in both species. However, the transport of Cl^- to the shoot per unit of shoot growth was greater in *A. corniculatum* than in *A. marina* because the net water use efficiencies were lower in the former species. As both species accumulate similar concentrations of Cl^- per unit growth, the amount of salt secreted per mol water transpired (and hence also per mol carbon gained) increased more with increasing salinity in *A. corniculatum* than in *A. marina*. These data underscore the importance of water use efficiency to the salt balance even in species with the flexibility of expelling excess salt.

Table 1

Salt balance in shoots of Aegiceras corniculatum and Avicennia marina in relation to salinity (after Ball 1988)

Parameter	*A. corniculatum*			*A. marina*		
Growth salinity (mM NaCl)	50	250	500	50	250	500
Net water use efficiency (mg dw mol^{-1} water)	73.8	45.0	41.4	81.0	79.2	91.8
Net Cl^- uptake ($\mu mol\ Cl^-\ mol^{-1}$ water)						
Accumulation:						
Roots	15.6	25.1	19.2	44.0	35.1	112.9
Stems	20.8	7.7	2.2	10.5	17.0	28.3
Leaves	26.1	26.0	16.9	34.2	34.6	47.3
Total	62.5	58.8	38.3	88.7	86.7	188.5
Secretion	28.7	85.6	157.0	13.4	64.2	94.8
Total Uptake	91.2	144.4	195.3	102.1	150.9	283.3
Shoot salt balance						
Cl^- uptake to shoot per unit shoot growth (mmol g^{-1} dw)	1.2	3.5	8.5	1.1	2.3	3.0
Cl^- accumulation (% shoot uptake)	62.0	28.2	10.8	76.9	44.6	44.4
Cl^- secretion (% shoot uptake)	38.0	71.8	89.2	23.1	55.4	55.6

Gas exchange in leaves of mangroves is characterised by unusually conservative rates of water loss and water use efficiencies for C_3 species (Ball 1986). These water use characteristics are functions of the biochemical capacity of the mesophyll to fix carbon dioxide and the ease with which stomata allow carbon dioxide and water vapour to exchange between the leaf and air. As in other C_3 species, (Farquhar and Sharkey 1982), the relationship between stomatal conductance and photosynthetic capacity is such that the leaf expends an amount of water consistent with maintenance of the assimilation rates at or very near the photosynthetic capacity except under extreme conditions when such co-ordination may be lost (Ball 1981; Ball and Farquhar 1984a, 1984b). The amount of water spent in gaining carbon varies between species as well as between environmental conditions. However, it appears that the water use characteristics become increasingly conservative with increase in the salinity tolerance of both salt-secreting and non-secreting species (Ball and Farquhar 1984a; Ball 1988; Ball _et al._ 1988).

Conservative water use may be a consequence of the high carbon costs of water uptake, and may also contribute to the maintenance of favourable carbon/salt/water balances (Ball 1988b). However, restriction of the rates of water efflux also restricts the rates of CO influx, causing the leaf to operate at low internal CO concentrations, but with a high water use efficiency (Cowan 1977). Thus, conservative water use within the constraints of C photosynthetic metabolism is at the expense of the assimilation rate and hence also the growth rate (Cowan and Farquhar 1977).

Conservative water use has implications for the functioning of leaves under environmental conditions. Although salinity varies both temporally and spatially in a mangrove swamp, the soil salinity changes much more slowly at the roots than the microclimatic conditions which affect the diurnal expenditure of water in relation to carbon gain in the leaves. The evaporation rates depend on both the leaf conductance to water vapour and the vapour pressure gradient between the leaf and air (vpd). Diurnal variation in the latter is due mainly to variation in leaf temperature because the ambient vapour pressure changes little during the course of a day. The closer that leaf temperature stays to air temperature, the closer the evaporative demand of the leaf will reflect the saturation vapour deficit of the air. Leaves which operate with high evaporation rates can take advantage of the high irradiances required to maintain high photosynthetic rates with minimal increase in leaf temperature over air temperature. In contrast, leaves with more conservative expenditures of water must avoid high irradiances if leaf temperatures are to be maintained within physiologically acceptable ranges. Thus, maximising carbon gain relative to water loss involves a complex balance between stomatal behaviour in relation to photosynthesis and variation in leaf properties in relation to light interception and evaporative demand (Cowan and Farquhar 1977; Cowan 1982).

Photosynthesis in mangroves is maximal at leaf temperatures ranging from 25° to 30°C, and declines precipitously with increase in leaf temperature above 35°C (Moore *et al*. 1972, 1973; Andrews *et al*. 1984; Andrews and Muller 1985; Ball *et al*. 1988). Stomatal conductance changes in the same sense as photosynthetic capacity with variation in leaf temperature (Andrews and Muller 1985; Ball *et al*. 1988). However, the decline in stomatal conductance with increase in leaf temperature above levels optimal for photosynthesis, is not sufffficient to reduce the evaporation rate and it increases with temperature-induced increase in vpd (Ball *et al*. 1988). This causes the water cost of carbon gain to increase with increase in leaf temperature above optimal levels. However, the positive correlation between stomatal conductance and assimilation rate with variation in irradiance, temperature and vpd has been shown in simulations (Farquhar 1979) to be consistent with a strategy to minimise water loss relative to carbon gain even as water use efficiency varies (Cowan and Farquhar 1977).

There are interspecific differences in the slope of stomatal conductance as a function of the assimilation rate with variation in leaf temperature, irradiance and vpd (Table 2). The slope increases with increasing salinity tolerance of the species in the Rhizophoraceae. Thus, for a wide range of environmental factors affecting photosynthesis during the course of a day, the assimilation rate at a given stomatal conductance is greater (and hence water use is more conservative) the greater the salinity tolerance of the species (Ball *et al*. 1988).

As in other mangroves, the optimal leaf temperatures for photosynthesis in the Rhizophoraceae are very close to the average air temperatures in the tropical and subtropical environments in which the plants are grown (Andrews *et al*. 1984; Andrews and Muller 1985; Ball *et al*. 1988; Moore *et al*. 1972, 1973). However, the rates of water use in all of the species examined are not sufficient to prevent heating of the leaves above ambient air temperatures during periods of intense insolation. For example, when exposed canopy leaves of *Rhizophora apiculata* were constrained in a horizontal position, the leaf temperatures increased from 4° to 11°C above ambient air temperatures of approximately 30°C with increase in incident irradiation from 1430 to 2585 uE m^{-2} s^{-1}, respectively. In contrast, leaves left in their natural, almost vertical orientation avoid the maximum heat load during the middle of the day when irradiance and air temperatures are greatest. At midday, these leaves received only 20 percent of available sunlight and were approximately 10°C cooler than they would have been if fully exposed to the sun. Earlier and later in the day, the leaves received about 1000 uE m^{-2} s^{-1} and leaf temperatures were 30°C, conditions nearly optimal for photosynthesis (Ball et al. 1988). Thus the increase in leaf angle is a compromise between the requirements for illumination and for maintenance of favourable leaf temperatures with minimal evaporative cooling.

The maintenance of leaf temperatures close to air temperatures has two major consequences for leaf functioning (Andrews and Muller 1985; Ball et al. 1988). First, avoidance of high light intensities during the middle of the day, when the heat load on the leaf is greatest, could allow the leaves to sustain relatively constant, albeit low assimilation rates throughout the photoperiod. This would result in a greater net gain of carbon than would occur if the leaves were horizontal and subject to temperature-dependent inhibition of photosynthesis for extended periods during the day. Second, maintenance of favourable leaf temperatures is critical to maximising the total integrated gain of carbon for a minimum expenditure of water during a day.

As water use characteristics become increasingly conservative with increasing salinity tolerance, it follows that interspecific differences would be expected in the display and properties of leaves in relation to maintenance of favourable leaf temperatures with minimal evaporative cooling. Increasing leaf angle (i.e. the inclination to the horizontal) decreases the intensity of radiant heat loading. Leaf angle increased with increasing exposure to the sun among members of the Rhizophoraceae growing together in North Queensland (Ball et al. 1988). The angle was greater, and hence the proportion of projected leaf area on a horizontal surface was smaller, the greater the salinity tolerance of the species (Table 2). Apparently, the species which are more conservative in water use are those that tend most to avoid intense radiation (Ball et al. 1988).

Leaf size is another property influencing leaf temperature. Heat convection between a leaf and its environment depends on resistance to transfer imposed by a boundary layer, the characteristics of which are a function of leaf geometry and wind speed. Boundary layer conductance is enhanced by decrease in leaf size. This results in the temperature of the leaf being closer to ambient air temperature without disadvantaging the leaf in terms of light interception. In the Rhizophoraceae, leaf size decreases with increasing exposure (Ball et al. 1988) and is smallest in the most salt tolerant species (Table 2). Similarly, leaves of mangrove species which dominate hypersaline

Table 2

Variation in gas exchange characteristics and in the display and properties of fully exposed leaves in relation to salinity tolerance in the Rhizophoraceae. Species are listed in order of increasing salinity tolerance, with *B. gymnorrhiza* being the least salt tolerant. Values for A/g are slopes obtained by linear regression of the assimilation rate (μmol CO_2 m^{-2} s^{-1}) as a function of stomatal conductance to water vapour (mmol $m^{-2}s^{-1}$) with variation in irradiance, leaf temperature and leaf to air vapour pressure difference over a range naturally experienced by the leaves under tropical field conditions. All data from Ball et al. (1988) except * from Andrews and Muller (1985).

Species	A/g	Rosette area (cm^2)		Individual leaf area (cm^2)		Specific leaf weight	Succulence
	(μ mol/mmol)	Total	Projected	Total	Projected	(g dw m^{-2})	(g water m^{-2})
Bruguiera gymnorrhiza	0.072	635	356	58	32	133.1	262.5
Rhizophora apiculata	0.096	553	196	69	25	148.8	348.4
Rhizophora stylosa	0.101*	419	126	44	13	169.3	387.9
Ceriops tagal	0.113	102	39	8	3	189.2	463.2

environments along arid coasts of northern Australia (i.e. *Avicennia marina*, *Ceriops tagal* var. *australis*, *Excoecaria ovalis*, *Lumnitzera racemosa* and *Osbornia octodonta*), are much smaller than those of species dominating humid, low salinity wetlands (e.g. *Bruguiera gymnorrhiza* and *Rhizophora apiculata*). Thus, mangrove leaves are smallest under conditions in which, due to intense radiation and/or limitations to evaporative cooling, they sustain the greatest heat load (Ball *et al*. 1988).

Finally, a third leaf property influencing leaf temperature is that of heat capacity per unit area, which increases with increase in the dry weight and water content per unit area. These two factors (i.e. specific leaf weight and succulence) increase with salinity (Camilleri and Ribi 1983), exposure (Ball *et al*. 1988) and with increase in the salinity tolerance of the species in the Rhizophoraceae. The heat capacities of the leaves in Table 2 range from 1.1 to 2.2 X 10^3 J m^{-2} C^{-1} in *Bruguiera gymnorrhiza* and *Ceriops tagal* var. *australis*, respectively. Leaf temperatures of both species would increase during a lull in air movement because of reduction in boundary layer conductance, but the rate of temperature increase would be slower in the leaf with a greater heat capacity. For example, Ball *et al*. (1988) calculated that the period of a fluctuation in environment on a typical day in North Queensland such that the amplitude of fluctuation in leaf temperature is halved would be 1.8 minutes in *B. gymnorrhiza* and 3.6 minutes in *C. tagal*. Thus, although succulence may be primarily involved in the maintenance of favourable internal ion concentrations (Flowers *et al*. 1986), there is a tendency for mangrove leaves to be more succulent under conditions in which, due to intense irradiation and/or limitations to evaporative cooling, they are most vulnerable to rapid fluctuations in leaf temperature (Ball *et al*. 1988).

Maintenance of favourable leaf temperatures through variation in the display and physical properties of leaves is not without cost to the plant. First, increasing the angle of inclination reduces heat loading on a leaf, but is at the expense of the amount of light available to support photosynthesis. Second, decrease in leaf size enhances the heat transfer rates, but this requires greater investment in supportive and conductive tissue per unit of exposed leaf area than large leaves. Finally, increase in leaf succulence, or more correctly in heat capacity, buffers against rapid changes in temperature, but at the expense of leaf carbon which might otherwise be invested in expansion of leaf area. Thus, maintenance of favourable leaf temperatures with minimal evaporative cooling is at the expense of the assimilative capacity of the plant, with the expense increasing as water use becomes more conservative (Ball *et al*. 1988).

In summary, there are many attributes associated with salt tolerance, but two in particular have major implications for interspecific differences in physiognomy and growth. First, the carbon cost of water uptake increases with increasing salinity and is greater in the more salt tolerant species (Ball 1988b). This is manifest in the field by increase in the root/shoot ratio along gradients of increasing salinity. Second, water use becomes increasingly conservative with increasing salinity and with increase in the salinity tolerance of the species (Ball and Farquhar 1984a, 1984b; Ball _et al_. 1988; Ball 1988b). This is manifest in the field by the decreasing size of individual leaves and decreasing degree of canopy coverage along gradients of increasing salinity. Enhancement of these attributes is at the expense of the growth rate, such that species tolerant of broad ranges of salinity tend to grow more slowly even under optimal conditions (Figure 2).

Differences in water use characteristics in association with interspecific differences in salinity tolerance have implications for the organisation of mangrove forests along salinity gradients (Ball _et al_. 1988; Ball 1988b). Species tolerant of lower ranges of salinity, such as _Bruguiera gymnorrhiza_, operate with lower water use efficiencies and hence can maintain larger leaves with greater projected leaf areas than those with greater salt tolerance. Under low salinity conditions, stands of this species have dense canopies which allow little transmission of light to the forest floor. In contrast, species which are highly salt tolerant, such as _Ceriops tagal_ var. _australis_, operate with very high water use efficiencies and hence maintain small leaves with a low proportion of projected leaf area. This slow growing species characteristically forms stands with open canopies, which under low salinity conditions could not exclude the more rapidly growing, densely canopied species characteristic of low salinity environments. Although vigorous specimens of _C. tagal_ var. _australis_ can be found in low salinity environments, this species becomes limited mainly to the highly saline habitats in which competition from other species is reduced or absent. This may contribute to the characteristic segregation of mangrove species along salinity gradients.

It is apparent that interspecific differences in salinity tolerance have major affects on both the structure and composition of mangrove forests along natural salinity gradients. The results of these studies do not preclude the roles that other factors such as tidal sorting of propagules (Rabinowitz 1978) or predation of propagules (Smith 1987) might have on the segregation of species along salinity gradients. However, such factors are more likely to be of local significance, and of secondary importance to the physiological attributes of the species in determining vegetation patterns. It appears that the species from an available pool become distributed differentially along salinity gradients primarily because of interspecific interactions and differences in individual tolerance limits.

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APPENDICES

Appendix 1	The Alligator Rivers: A Mirror to a Continental Prehistory Rhys Jones
Appendix 2	Changes in Aboriginal Exploitation of Wetlands in Northern Australia Betty Meehan

APPENDIX 1

THE ALLIGATOR RIVERS: A MIRROR TO A CONTINENTAL PREHISTORY

Rhys Jones*

Sustained archaeological research in the floodplain valleys of the South and East Alligator Rivers over the past 40 years have resulted in the prehistory of this region being by far the best known within the Australian tropics. It is also one of the three or four most intensively studied areas in Australia. In previous surveys I have tried to give an outline of the prehistory of the Australian continent, taking a broad-scaled approach and illuminating this with data from widely distributed sites (e.g. Jones 1979, 1988 in press).

In this paper I would like to reverse the procedure, giving a detailed account from one locality and showing how these data illuminate some key factors in the interpretation of the prehistory of Australia. In this way I am echoing the approach of some modern French historians notably F. Braudel whose intensive studies on the histories of individual villages have been used to illuminate broad issues of French social history in the late Middle Ages.

The Alligator Rivers rise in dissected plateau uplands characterised by palaeozoic hard sandstones and conglomerates. The western edge of this plateau is characterised by a complex escarpment wall, some 300 m in height in places. In this escarpment are numerous enclosed gorges with narrow mouths such as Deaf Adder Gorge and Jim Jim Gorge on the South Alligator system and Tin Camp Creek on the East Alligator (Fig. 1). Conversely, standing out on the plains away from the main escarpment edges are several block-like outliers, fronted by vertical cliffs in places. The largest of these is the Nourlangie-Mt Brockman outlier and there are numerous smaller ones, e.g. the Djawumba Massif further to the north. Emerging out of the escarpments, the Alligator Rivers flow into flat wide valleys and empty into the Van Dieman Gulf situated about 12`10' South. These valleys and floodplains formed during the Post-glacial marine transgression which filled the previously downcut valleys related to full last Glacial low

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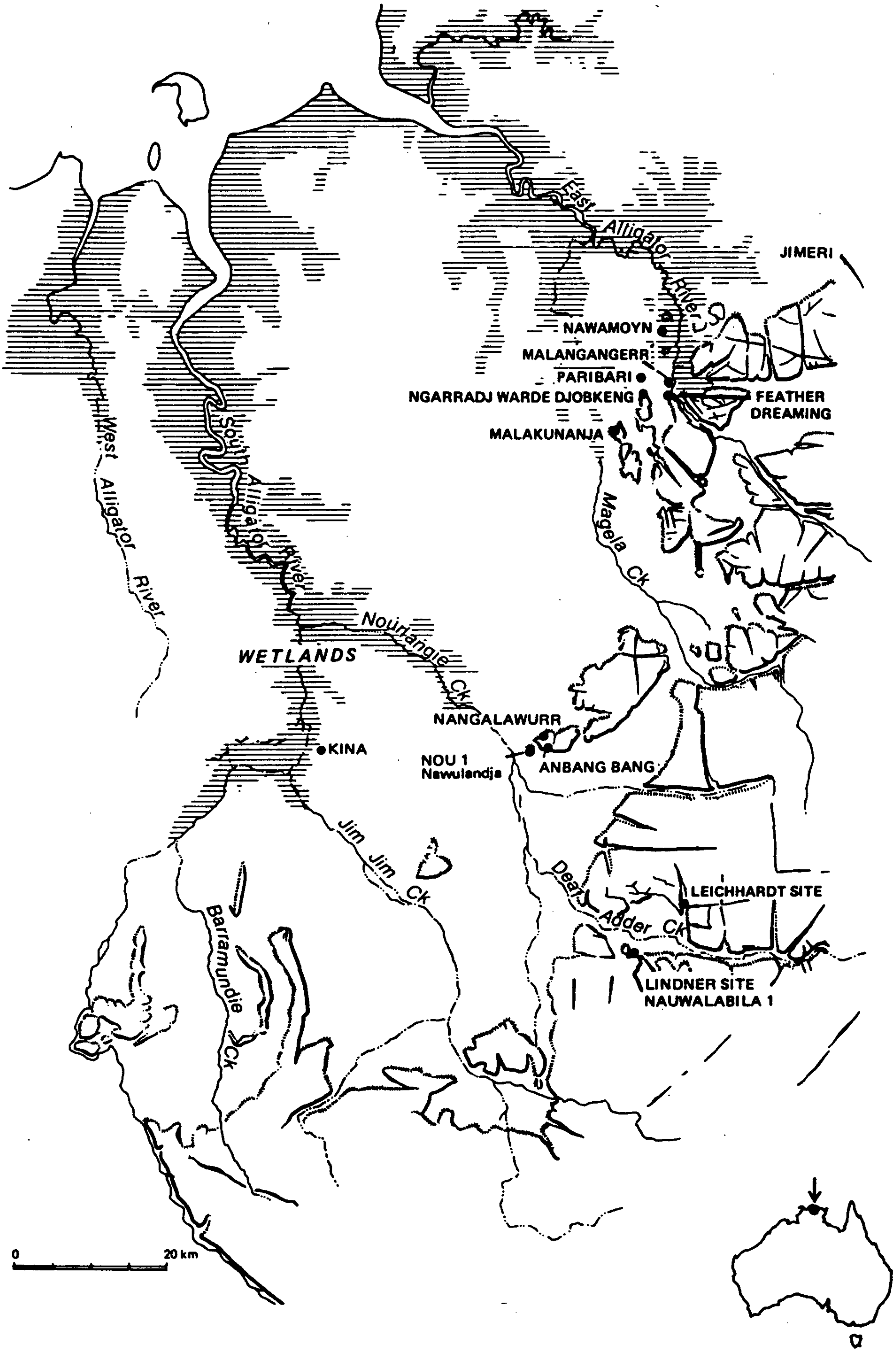
*Department of Prehistory, Research School of Pacific Studies, Australian National University, Canberra.



Excavated archaeological sites in the Kakadu region.

Figure 1

sea levels, which at 18,000 years BP were 150 m below present levels.

Recent geomorphological work (Hope et al. 1985; Woodroffe et al. 1985, 1986, 1987) has shown that as the sea reached its present level, it flooded the South Alligator River valley to a point some 70 km inland from its present mouth and in the period c.7000 to 5500 years BP, a major phase of mangrove growth filled most parts of this valley. Later prograding processes gave rise to the present floodplain. This has a complex structure of levees and parallel chenier coast-fringing sand dunes, behind which are seasonally inundated salt flats and in many places extensive freshwater lagoons. The wetlands of the two rivers are usually flooded during the wet season and support enormous seasonal populations of water birds and other aquatic life. They constitute one of the major tropical wetland systems in northern Australia.

The close physical proximity of these wetlands and the escarpment edge, with tracts of savanna woodland in between, gives the Alligator Rivers a range of ecological zones which supports a high diversity of plants and animals. For example, some 40 per cent of Australian endemic freshwater fish species are found in the South Alligator and Nourlangie system alone. Botanists have also shown a high diversity index of plant species, especially along the escarpment edges (Russell-Smith 1985). It was the appreciation of this biological diversity contained within a reasonably small area, that was one of the major reasons to declare it, firstly a National Park and later as a World Heritage region (Calaby n.d.). This same diversity of species, both plant and animal, made the region into one of the most densely occupied Aboriginal landscapes in Australia at the time of European contact.

Ludwig Leichhardt on his long journey from Moreton Bay to Port Essington in 1845 came onto the edge of the escarpment near the South Alligator River and he looked outwards across the plain in the late dry season, before descending into the wetlands and proceeding northwards. His journal gives a vivid account of the richness of this area from a hunting/gathering point of view, with abundant wetland plant foods and dense flocks of water birds. He commented upon the high Aboriginal density in the region, saying

> No part of the country we had passed was so well provided with game as this ... The cackling of geese, the quacking of ducks, the sonorous note of the native companion, and the noises of black and white cockatoos, and a great variety of other birds, gave to the country, both night and day, an extraordinary appearance of animation (1847, 497).

Archaeological research

Among the first archaeological surveys was that by Norman Tindale (1928) who described decorated rockshelter sites near Oenpelli. The first systematic excavation was done by McCarthy and Setzler in 1948 as part of the American-Australian Scientific Expedition to Arnhem Land. They excavated 12 small rockshelters on two outlier hills near Oenpelli - Inyaluk and Arguluk (McCarthy and Setzler 1960).

Despite important pioneering work during the 1920s and 1930s it can nevertheless be stated, that systematic prehistoric research, using modern methods was initiated in Australia and Papua New Guinea in the early 1960s. The last 25 years have seen a revolution in our knowledge of the prehistory of this continent and the islands of the western Pacific. The Alligator Rivers region was one of the locations for this pioneering effort and has remained a key area for archaeological research over the intervening period.

Golson and Mulvaney carried out an archaeological reconnaissance of the general area in 1963 as part of their assessment of the potential of sites in tropical Australia. They excavated sites in the Katherine River catchment immediately to the south of the Kakadu region. Golson also explored and identified some key locations for archaeological excavation on the East Alligator River near Cannon Hill. This investigation formed the basis for the PhD research of Carmel Schrire (formerly White) between 1964 and 1966. This major contribution (Schrire 1982) involved systematic excavations in rockshelter sites at small outliers on the East Alligator plain (Cannon Hill-Cahill's Crossing) and a second rockshelter series Jimeri 1 and 2, in the Tin Camp Creek plateau valley to the east (Fig. 1). Schrire established Pleistocene occupation at two of her plains sites, Malagangerr and Nawamoyn, which also established the basic stone artefact sequence for the region.

The late Pleistocene levels contained steep edge scrapers, flaked core-tools and a great surprise - edge-ground hatchets, which are discussed further below. In mid-Holocene times, the industries were transformed by the appearance of new tools - especially bifacial and unifacial stone points and small adzes or chisels, both tool types being hafted armatures for composite tools. For her latest phase Schrire postulated a fundamental difference between the plains sites as opposed to the plateau ones, which she interpreted as being due to seasonally different uses of the landscape (White and Peterson 1969).

As part of the Alligator Rivers Region Environmental Fact-Finding Study (ARREFFS), Kamminga and Allen (1973) carried out further explorations and pilot excavations of numerous rockshelter sites, including those to the south of the region in the valley of Nourlangie Creek, which drains into the South Alligator River. Near Schrire's original sites they established a Pleistocene antiquity at Malakanunja on the Djawumba outlier and also in the Lindner site at Deaf Adder gorge to the South.

Allen continued his researches in the region carrying out a major excavation at Ngarradj Warde Jobkeng some 10 km south of Malagangerr in the East Alligator valley where he was able to replicate Schrire's sequence and refine the chronology and associated palaeo-environmental changes in the Holocene period. At this time in the late 1970s, a deeper appreciation was being gained as to the major ecological changes that occurred in these valleys in late Holocene times, including the formation of freshwater wetlands with their high densities of potential food for hunter/gatherers. Bordering the edges of these wetlands were extensive open archaeological sites especially on the middle reaches of the South Alligator River floodplain, which were explored by D. Lindner and J. Kamminga in 1973 (Kamminga and Allen 1973).

A parallel strand of exploration concerned the rock art of the region, which is now firmly established as being one of the major rock art provinces in the world. Major studies were done by Edwards (1974), Brandl (1973) and particularly Chaloupka (1977, 1978, 1984) and exploration and work continues with a new generation of workers including Tacon (1985, 1986, 1987 in press), Lewis (1977, 1983, 1986), Gunn (1987) and others.

The Kakadu archaeological project 1979-85

In 1979 the Department of Prehistory at the Australian National University was invited by the Australian National Parks and Wildlife Service (ANPWS) to carry out a new programme of fundamental research in the newly declared Kakadu National Park and to advise it on issues of site management and interpretation. The fieldwork for this project, under my direction, was carried out in the dry season of 1981 with subsequent follow-up research and is published in Jones (1985).

Our aim was to carry out detailed research to the south of the area worked in by Schrire. We chose a transect along the Nourlangie Creek system from sites within the Deaf Adder gorge of the escarpment in the east; sites on the Nourlangie Rock outlier in the centre and sites bordering the South Alligator River-Nourlangie Creek confluence in the west (Fig. 1). We attempted to integrate the archaeological research with palaeoenvironmental work paying particular attention to processes of sand accumulation in the plateau valleys and the environmental changes in the South Alligator River valley floor from late Pleistocene to late Holocene times. We also deliberately chose some sites which had a wide range of faunal remains and we used techniques in the field to maximise evidence of past plant use - both macroscopic remains and microscopic, with pollen and phytoliths. These were integrated in contemporary studies of ethnobotanical plant-use and studies of plant distributions together with an assessment of the potential effect of humans on such floristic distributions particularly through the use of fire.

Antiquity

So far in the South and East Alligator River valleys, six sites have been excavated with basal dates in excess of 10,000 years (Jones and Negerevich 1985, 5-7). At Nawamoyn Schrire's basal date was 21,450±380 BP (ANU 51), and at nearby Malangangerr, she obtained two readings from a split sample; ANU 77A of 24,800±1600 and ANU 77B of 22,900±1000; the latter result being considered the most reliable by the laboratory. Another sample from the same lowest sand gave a value of 19,600±550 (GAK 628). These samples were finely communated particles from within the basal sand. It is likely that some part of this lowest unit containing artefacts may date from a period somewhat older than these results. Even so, direct radiocarbon evidence of antiquity

21,000-24,000 years still constitutes our oldest direct evidence for human occupation of the Australian tropical savanna. Both of these sites are rockshelters with defined taluses fronting onto small sandsheets outside.

In contrast to these, the Lindner site, Nauwalabila 1, offered a somewhat different geomorphic situation for the accumulation of deposit. This site was formed when a huge block of rock fell off the southern escarpment edge of Deaf Adder gorge (Fig. 1). Sand carried from this escarpment, probably by water processes, accumulated in the floor of this valley and built up around the rock. The floor of the shelter at present is almost flat and is continuous with the sand sheet which extends along this side of the valley over an area of several square kilometres. There is a slight slope downwards to the streambed, north of the site (Hope et al. 1985, 229-32). Thus if an occupation layer were to be found at a depth of say 1 m below the present at this site, then the entire valley floor was also lower by this amount at that time.

When I first visited this site in June 1972, I felt that investigation of its stratigraphy and chronology could give information not only on prehistoric human occupations but also how these related to the geomorphic formation of the valley floor sandsheets as a whole. A pilot investigation by J. Kamminga in 1973 revealed artefacts down to a depth of about 2.5 m with an associated radiocarbon date of 19,975±365 BP (SUA 237). We excavated adjacent to this pit and were able to reach the base of the sandsheet at a depth of about 2.8 m, all excavated units of which contained stone artefacts.

Beneath this sand was a consolidated rubble, 40 cm thick resting on large boulders. The rubble contained stone artefacts to its very base. Combining our own C14 dates with those obtained by Kamminga, a depth-age curve can be constructed which when extrapolated to the base of the sand, suggests a date for latter of about 30,000 years BP. The lowest charcoal from our excavations were tiny fragments at about 2.2 m depth, some 30-40 cm below Kamminga's 20,000 year old date. We have not attempted to date these, but could try to do so using the accelerator mass spectrometer method (AMS). A problem with samples this small is that the potentiality of their being contaminated or being out of original stratigraphic position, e.g. having fallen down a little crack in the deposit, is much greater than with a sample consisting of scores of individual charcoal fragments, where such errors tend to get evened out.

A new method which offers considerable potential is that of thermoluminescence (TL) dating on the sand grains themselves (Wintle et al. 1984). This would date the time which had elapsed since the sand grains were last exposed to solar radiation, i.e. when they lay open to the hot sun before being buried by successive layers of sand. The method has been successfully applied to date sandsheets in the Magela Creek area of the East Alligator valley where basal dates for sand have been obtained ranging from 30,000-35,000 years ago (East et al. 1987). It is proposed to deploy this technique at the Lindner Site and to calibrate the TL results in the upper part of the deposit with existing or available C14 samples.

As far as the basal rubble is concerned, apart from being able to say that it must be older than the oldest sand, it may be very difficult or impossible to date. The pieces of sandstone within this rubble are friable with thick weathering skins. The flakes of quartzite within it are also heavily weathered and in many cases so friable that they can be snapped in the fingers and they also show thick weathering skins on such a broken face. Artefacts of quartz resist such chemical weathering and flakes of the latter, together with a nicely flaked small core were found in the lowest excavation unit from the base of the rubble. Other sites in the region such as Anbangbang 1 (Jones and Johnson 1985, 45-60) have artefacts stratified within gravel or rubble deposits which have no charcoal in them, but which certainly date from Pleistocene times and may be of considerable antiquity.

Given that the oldest secure dates for human occupation of the Australian continent extends back to some 38,000 years BP, which is close to the theoretical maximum age obtainable from conventional C14 dating, we need to investigate sites where stone artefacts are securely stratified in deposits below the lowest surviving charcoal and to use new methods like TL dating. My own considered view is that the base of the sand at the Lindner site (Nauwalabila 1) dates to about 25,000-30,000 years ago at least and that the rubble may be considerably older.

The earliest evidence for human occupation of the Australian-New Guinea continent has been obtained from a series of uplifted coral reefs, some mantled by volcanic ash, at the Huon Peninsula, eastern Papua New Guinea. This dates from 40,000-45,000 years ago. At the very least the evidence from the Alligator Rivers indicates that early human colonists had managed to occupy the tropical savanna region of north Australia soon after this period. At 20,000 years ago the region was inland with the floor of the Arafura Sea being exposed and the shoreline close to the continental shelf some 400 km to the northwest.

Ice Age Conditions

The climatic variations during the last Ice Age did not have much effect in northern Australia in terms of temperature but they had profound effects on other parameters particularly rainfall. The low sea level meant that many of the major cyclone producing areas on the present-day shallow Arafura Sea or the Gulf of Carpentaria did not exist. In addition the dry cold glacial conditions resulted in a smaller world rainfall in general. Both of these factors would have meant that at 18,000 years ago the tropical rainfall of the north may have been half or less of its present value with a precipitation regime being rather similar to that at Tennant Creek on the northern edge of the present Australian desert, some 700 km to the south (Jones and Bowler 1980; Jones 1985, 18).

In Schrire's original excavations at Malangangerr and Nawamoyn, her basal sands dated to about 20,000 years ago, were directly overlain with estuarine shell middens dated to between 6000 and 7000 years BP at their basal levels. The question then arose, was this due to a disconformable sequence, with perhaps the top of the sand having been eroded off before the midden was laid down, or had there been a genuine hiatus of occupation corresponding with a drier phase of the last Ice Age? The issue had more general interest in terms of some current theories concerning the colonisation of the Australian continent. Some workers had posited this as having been carried out exclusively in coastal or lacustrine environments, with colonisation of the truly island areas to say nothing of the desert core itself having occurred only in terminal Pleistocene or early Holocene times (Bowdler 1977). The 20,000 year old dates from the East Alligator might seem to have refuted the main thrust of this argument, at least in the tropical north but it had been argued that may be occupation had occurred before the height of the last Ice Age when the sea, although not at its present level was nevertheless closer to the present coast than what it became several thousand years later. The question of occupation of the region during the last Glacial maximum might therefore be a good test of whether or not people had the capacity to maintain their occupancy during the drier conditions.

Our age-depth curve for the Lindner site (Nauwalabila 1) was fairly constant throughout the period under review with values of about 10 cm per 600-700 years in the top 0.8 m back to 6000 years ago, and then a somewhat slower rate of 10 cm per 1500 years in the lower part of the deposit between 6000 and 20,000 years ago. There was no apparent influence on the rate of this accumulation related to any of the climatic environmental changes referred to above. We excavated our pit in 80 superimposed excavation units, each being on average some 3.5 cm deep. In all cases, some artefacts such as small flakes were found, and there was no correlation of artefact densities with any of the putative climatic changes of the last Ice Age.

These data refute the hiatus theory and show that people have continuously occupied this region from the earliest times to the present.

Fire and Sand Movement

A factor influencing the movement of sand into the valley may have been due to humanly induced changes in the fire regime. It is of interest to note that in all of the vast period before human occupation, the rate at which sand was leaving the site and adjacent valley floor was roughly equal to or less than the rate at which it was being removed. Then two events seemed to coincide. Firstly, there was the human presence and secondly sand started to accumulate not only in the site itself but also in the adjacent valley floor, which built up a depth of 3-4 m in the vicinity of the site. At the base of the sandsheet were numerous pisoliths which accounted for some 6-10 per cent of the total weight of deposit in those units, the rest being fine sand. These pisoliths, as their name implies, are pea-shaped laterised iron-stones which formed in the B-horizon of extremely ancient, viz. Tertiary, soils on the escarpment top. They had been stripped from this location and dumped into the valley floor, during an early phase of the sandsheet accumulation.

One way to account for these changes is to consider the impact of a greatly increased fire frequency following human arrival in the region. A major factor in ground slope instability occurs when a large rainfall event follows soon after a fire, when the sands are exposed without vegetation cover. Although natural lightning-induced fires have been a feature of this ecosystem long before man's arrival, the latter may have increased the frequency of the fire regime by several orders of magnitude. Thus the probability of suitable sand-moving episodes following such fires was also greatly increased. It is interesting to speculate to what extent the formation of these valley sandsheets has been influenced by the human impact. At present the supply of sand seems to have diminished with the sandsheets moving down the valley and with some minor downcutting in the upper reaches (Hope et al. 1985). The greater amount of sand in the middle reaches of these streams might also have enhanced the formation of lagoons due to seasonal impoundment by levee embankments such as at the Anbangbang Lagoon, just south of Nourlangie Rock (Fig. 1), which was probably formed some 3500 years BP.

Other workers in Australia such as the pollen analysts Singh and Kershaw have interpreted major changes in the floristic composition in the upper parts of their long pollen sequences; in Lake George, southeast Australia and the Atherton Tableland, north Queensland, respectively; as being due to human impact of a higher fire regime on a continental scale. Kershaw (1985) dated this event in his sequences; at about 45,000 years BP, which would be consistent with current archaeological thinking for a putative arrival of man in Australia. Singh suggested a significantly older date of 100,000-120,000 years BP (Singh and Geissler 1985) which is too old given the conventional picture. An alternative estimate of the relevant zone F in the Lake George sequence has been suggested at 60,000 years BP by Wright (1986). The question is still an open one.

Along the escarpment edges, there are relict communities of fire sensitive rainforest and vine-thicket species with a highly disjunct distribution. In general, they exist in fire shadow areas and there is no doubt that the fire regime is an important ecological parameter in their distribution. Many modern ecological studies now favour the view that the Aboriginal fire regime has been an important ecological factor in the distribution of various floristic communities and also in the structure of frequently fired ecosystems such as the open eucalypt/savanna (Werner 1986).

Edge Ground Axes

Schrire's discovery of Pleistocene, edge-ground axe heads from volcanic rocks, which also had worked grooves on their sides indicating that they had been hafted, caused considerable consternation in the literature when they were first announced in the late 1960s. The issue can be related to an old fundamental division within the classification of archaeological cultures; 'Palaeolithic' or old stone age as represented by flaked stone tools, and 'Neolithic', the new stone age, characterised by edge-ground stone tools. Yet here in northern Australia, the continent of hunters, were found edge-ground axe heads at 20,000-24,000 years ago; three times as old as the earliest Neolithic in western Asia and eastern Europe. Schrire's data were carefully rechecked, including field geomorphic assessments by J.N. Jennings and independent C14 assessments (White 1967).

In the Lindner site (Nauwalabila 1), we were able to find tiny flakes of dolerites which had smooth edge-ground facets on their dorsal sides, indicating either that they were chips off the edges of edge-ground axes or that they had been flaked off such axes in order to reshapen them. Such tiny edge-ground flakes were found in most units down to a depth corresponding to some 14,000 years ago. Below this chemical decomposition of the dolerites made positive identification impossible. One can note however that at the very base of the excavation at a level approximating our presumed 30,000 year old antiquity, there were several pieces of extremely eroded dolerite which in shape and weight could have conformed to the Schrire-type hatchet heads. At the very least, it can be stated that these eroded dolerite pieces had been brought into the site from a long distance away, at least 50 km. Our data from Nauwalabila 1 confirms Schrire's evidence for edge-ground technology extending back into late Pleistocene times in this tropical region of Australia.

The issue has more general importance following the discovery of large, waisted bifacially flaked and in some cases edge-ground pieces often referred to as 'waisted blades' from Papua New Guinea. Some of these are large, weighing 2-3 kg, and have been found in the highlands of New Guinea both in open and in cave sites, back to 25,000-30,000 years ago (White _et al._ 1970). More recently they were dicovered in uplifted coral reefs, off the Huon Peninsula in eastern PNG, dated as discussed previously to at least 40,000 years ago (Groube _et al._ 1986). Les Groube in a characteristically original (unpublished) note has suggested that these may have been used to ringbark trees of the closed canopy, tropical lowland rainforest. By so doing, the canopy would have been broken allowing light to the forest floor and giving natural encouragement to the growth of colonising species which in PNG included many of the preferred human food species, such as yams, taro, sugar cane, bananas, tree fruits and in some places perhaps sago and breadfruit. If we follow Groube's suggestion, people may have been manipulating the New Guinea part of the 'Greater Australian' continent at a time when the last Neanderthalers were still living in Europe.

It is likely that the edge-ground axes of tropical Australia may have had a similar function to the analagous waisted blades of New Guinea. It is also interesting and perplexing that edge-ground axes appeared in the archaeological record of southern Australia only in the past c.3000 years. The question is now raised - what were the adaptive advantages of edge ground axes in tropical Australia from at least 20,000 years onwards, which were not obvious in the ecological adaptation of people in the central and southern parts of Australia, until recent times? The presence of some 'waisted blades' in surface collections on Kangaroo Island off the coast of South Australia (Lampert 1981) is beyond the scope of this discussion.

Points and Small Tools

The archaeological record throughout the whole of mainland Australia was transformed by the appearance of new stone tool industries in mid-Holocene times. Several quite different industrial assemblages were involved, and these had different distributions on the continent. Significantly, none of these new industries have been found in Tasmania, which was cut off from Australia by the terminal Pleistocene rising sea levels 12,000 years ago. Across the entire southern half of the continent from the south coast of New South Wales, the lower Darling, Lake Eyre Basin and extending to Port Hedland on the Western Australian coast, have been found a complex group of 'microlithic' industries. These were characterised by the manufacture of true microblades which were steeply backed to form geometric microlithic and curved backed 'Bondi points', which were probably hafted armatures of knives and spears. Another group of assemblages found in the Top End of the Northern Territory and the Kimberleys and extending southwards through the central desert, were characterised by unifacial and bifacial points. Another element with the points were what are called adze or chisel flakes which were hafted as the cutting edges of wooden chisels. When such flakes became blunt or their edges matted with wood or other fibre, their edges were rejuvenated by being flaked back until no further working could be done, when they were removed from their gum hafts and discarded. These adze 'slugs' are highly distinctive. In central and southern Australia, what are called 'tula adze slugs' were hafted and worked parallel to the platform, whereas in the Kakadu area and in Cape York, they were hafted sideways to the platform so that steep retouch on both sides form rod-like slugs.

These various industries are sometimes grouped together under a convenient rubric of 'small tool traditions'. They have been recognised in the archaeological record as being dated within mid-Holocene times since Hale and Tindale's excavations at Devon Downs near the mouth of the Murray River in 1929. Research over the past 25 years has given regional definition to such industries, and the dating of their appearances have been narrowed to the mid-Holocene between about 3500 and 6000 years ago. Some industries such as the points, persisted into modern ethnographic times; whereas others such as the microlithic industries ceased being used in prehistoric times 1500 to 2000 years ago. Most archaeologists sense instinctively that all of these small tool industries are somehow manifestations of the same cultural process, perhaps to do with development of superior hunting technologies and/or integration of wider networks of people, serviced by more standardised tools whose raw materials came from specialised quarries. In particular these tools were the cutting parts of composite tools, be it spear or chisel, woomera, etc.. It is significant in this regard that the Tasmanian ethnographic technology consisted entirely of single-piece spears and clubs and hand-held scrapers and this gives a clue as to the kind of technology that might have been used in mainland Australia before the small tool innovations.

However, despite this general unity for the 'small tool tradition', there are real problems when we seek to give some ecological explanation for their relative efficiencies. Why were backed microliths so efficient across all the diverse environments from Sydney to Perth, and yet were not found in the tropical north? Why were hafted points, the main hunting tool from Arnhem Land to the desert and yet were not found in equivalent ecological zones in a similar north-south transect of Cape York and Queensland? There is thus a lack of coherence between artefact distribution and ecological zonation, a question which Jack Golson posed in an unpublished lecture in 1963 and which has continued to puzzle me ever since (Jones 1977, 192-3).

A crucial problem relates to dating. Did all of these diverse industries appear in the archaeological record at the same time in different parts of the continent, or conversely did the various industries appear at significantly different time periods? If the latter was the case, then any direct cultural relationship between the causes for these technological innovations becomes much more difficult to sustain. The problem is harder than it might appear at first sight, because of the precision of dating that is required. The issue is not one of the technicalities of the C14 dating but rather to do with stratigraphic issues, such as contamination of deposit; reworking of materials into old living floors by later occupants; being able to find the earliest manifestation of a cultural change in any one region and so on. These difficulties can be seen in Ian Johnson's analysis of the earliest dates for the Bondian industries of New South Wales which he placed as having happened some 4000 years ago (Johnson 1979).

A major research aim of the 1981 Kakadu Archaeological Project was to gain an accurate assessment of the dates for the introduction of the point technology. Schrire (White 1971), in her original work, confused the technological change, i.e. introduction of points, with ecological changes which resulted in the first deposition of shell middens, which she dated between 6000 and 7000 years ago. Her oldest points came stratigraphically within this midden at a significant but unrecorded depth above its base. Later analysis by Schrire (1982) of her own data, especially the Jimeri 2 site and White and O'Connell's (1983) assessment of the Kakadu evidence, suggested a date for the introduction of points occurring between 4500 and 5000 years ago (two standard deviations spread of the oldest reliable date).

The Lindner site (Nauwalabila 1) offered ideal circumstances for addressing this problem. There was a deep stratigraphic sequence; the deposits of fine sands had built up steadily throughout the period under review; all excavation units contained numerous stone tools and debris of manufacture and retouching.

One important issue was not only to date the first appearance of the new technology but also to date the final phase of the industry which clearly <u>predated</u> the innovations. It is important not only to analyse the distinctive finished tools, e.g. points, which may be relatively rare in the total assemblage, but also the much more sensitive other indicators of technological change such as the process of manufacture, the byproducts of manufacture and use of the different raw materials used. Using all of these criteria we were clearly able to demonstrate that the point technology had not been introduced as recently as unit 29 (0.85-0.88 m below surface) and dated by us with a sample 5990±180 BP (ANU 3181) (Jones and Johnson 1985, 206).

Technological changes associated with point manufacture together with one partially made and broken point were found in the overlying unit 27 (0.78-0.81 m below surface) and dated by us to 5860±90 BP (ANU 3180) (Jones and Johnson 1985). Thus our interpretation was that use of the new point technology at this site, taking two standard deviations on the dates, occurred between 6000 and 5500 years ago. This is about 1000 years older than the previous considered estimate but our stratigraphic precision at Nauwalabila is superior to any other site spanning this time period in tropical Australia. Also it would appear from these data that points were introduced in the Kakadu region of northern Australia some 1500 years earlier than the microliths of southern Australia.

Obviously further work of the same fine honed quality as at Nauwalabila needs to be done at other sites in northern Australia to confirm or refine this assessment.

The introduction of points did not have an immediate effect on such factors as artefact densities at the site which began to increase markedly some 3000 years ago and reached their peak some 1500 years ago before dropping back. Three thousand years ago was also the time of introduction of adze-chisel slugs. It is probable that the long blades sometimes called 'leilira' and used ethnographically as spear points may also have been more recent introductions, perhaps 2000 or 3000 years after the appearance of the small uni- and bifacial points. The important issue here is to realise that not all elements of the so-called 'small tool tradition' were introduced as a single 'package' at the same time. Rather, it seems, that different elements were added onto the total stone tool technology at different times during the middle to late Holocene period. Finally, one can but remind onself that some elements of the stone technology of the ethnographically recorded Aborigines of the region had their antecedants in late Pleistocene times. In particular this was the case with edge-ground axes, which had been continually used and resharpened at this site over the past 14,000 years at least.

Mangroves and wetlands

Following the post glacial sea-level rise which flooded the lower reaches of the Alligator Rivers, these supported a dense forest of mangroves, up to 50 km inland from the present river mouth, in the case of the South Alligator River (Hope et al. 1985; Woodroffe et al. 1986, 120). A systematic programme of carbon-dating the remains of these trees has indicated that the main phase of mnagrove growth occurred between about 6800 and 5500 years ago. These drastic ecological changes in the river valleys were directly reflected in the archaeological record. In the East Alligator valley, in the northern part of the park, the sites of Malangagerr and Nawamoyn have the upper part of their deposits consisting of thick shell midden, the initial layers of which were dated to about 6000 and 7000 years old respectively (Schrire 1982, 85, 118), i.e. exactly coinciding with the earliest dates for mangrove formation. The shell species in these earliest midden deposits consisted of the edible mangrove species, the bivalve clam *Geloina* sp and the gastropod *Telescopium telescopium*. Meehan (1982) has given detailed ethnographic descriptions of the Aboriginal use of these species in contemporary times on the central Arnhem Land coast at the mouth of the Blyth River.

At the Nourlangie Rock outlier, some 30 km to the east of the South Alligator river channel, and close to the southern limit of this palaeomangrove zone (Fig. 1), the influence of this ecological change could also be noted in the archaeological record at the Anbangbang site. In this case, the evidence was indirect, in that the rate of deposition of the matrix and the included artefacts suddenly increased by many orders of magnitude. The basis of this phase was dated to about 6500 years ago, indicating a much greater density of occupation of this site corresponding with the transformation of the ecology of the river valley, almost a day's walk to the west.

Following this great mangrove phase, processes of valley progradation took place, and in many parts of the South Alligator river floodplain, there were hyper-saline salt flats (e.g. Hope et al. 1985). From the point of view of human foragers, these did not have a great potential. However, one potential phase of the progradation is when river-fronting levèes or other deposits are formed which block the Equinoxal King Tides and their salt water incursions. Natural billabongs or polders can be ponded and with the heavy rains of the wet season, can be rapidly transformed into freshwater lagoons and wetlands. With their plants of Eleocharis dulcis spike rush, Nymphaea water-lilies and Oryza wild rice, these can be immensely productive systems. Not only were these plants prized foods for humans, but also for birds, huge populations of which are found on the freshwater wetlands of today. Species include magpie geese, ibis, jabiru, brolga, ducks and pelican. Other animal species include fish of many species, fresh water terrapins ('turtle'), file snakes, crocodiles, and varanid goannas. Modern ethnographic studies of Aboriginal hunting and gathering economies, in northern Australia, have shown that such wetlands supported the highest population densities of people, the greatest degree of sedentism and the highest degree of 'packing' of local group territories (e.g. Jones 1980). This is a direct result of the much higher primary productivity of such natural wetland systems compared with the more general savanna woodlands which surround them.

In the southern part of the South Alligator river valley, south of the confluence with Nourlangie Creek (Fig. 1), Hope et al. (1985) were able to show that some of the major freshwater wetlands such as the Kina Lagoon, were only formed as recently as 1000-1500 years ago. This ecological event had a profound effect on the archaeological record of the immediate vicinity to these wetlands. Huge open sites occur on the wetland edges. These have millions of stone tools on their surfaces, and they were probably dry season sites, when people came to congregate to exploit the abundant plant and animal foods. Some of their wet season equivalents were in the caves of the outliers, 30 km to the east, such as Anbangbang which contains plant material related to the exploitation of water lilies and wet season fruits, and also a host of wooden and fibre artefacts. The basal units of the rich uppermost layer of this site is dated to about 1200 years ago, corresponding well with the date for the first formation of the nearest large wetland at Kina. Bordering this wetland itself is an extensive flat mount with freshwater mussel shells in the matrix. The base of this mound has been dated to as recently as about 700 years ago. It can be seen that there is evidence in this region of a large increase in population density, which occurred during the past 1500 years or less. There is also evidence that this was related to a great increase in the natural productivity of the environment itself following the natural formation of the freshwater wetlands.

These data have direct bearing on one of the most important questions of Australian prehistory. To what extent were the documented increases of prehistoric Aboriginal population in mid and late Holocene times, due to inherent processes of social 'intensification', and to what extent were these related in some areas at least to changes in the basic productivity of the environment?

Artistic traditions and cultural continuity

It has been shown that over the past 20,000-30,000 years, there have been profound cultural and environmental changes in the Alligator Rivers regions. It is also worth considering the strands of cultural continuity. It has been said that a stone tool need not contain a great deal of cultural 'information', since there are so many physical and technical constraints in its manufacture and use. Conversely, another archaeological artefact, namely art, as found prolifically preserved on the rock walls and shelter roofs of Kakadu, can contain a vast amount of cultural 'message'. The most recent rock paintings in the region were made during living memory, and they are similar in style to some of the bark paintings made nowadays by western Arnhem Land painters. There is growing evidence that some of the oldest art in Kakadu is extremely old.

Some of the evidence for this has been marshalled by Chaloupka (1985 and reviewed in Jones 1985). Briefly, whereas the most recent phase of art has numerous depictions of coastal and freshwater animals such as barramundi fish, terrapins and crocodiles; the older art which often is weathered and lies under the more recent one, consists almost entirely of inland motifs, and lacks fish and other coastal animals. The 'old' art has depictions of hunters using spears lacking hafted stone points, but some carry boomerangs. This 'older' art is in many places covered with silicate and other mineral skins. There are depictions of now extinct animals such as thylacines, or 'Tasmanian wolves' (which became extinct on the mainland of Australia some 4000-5000 years ago). Mineralogical analysis of the skins shows that some of them consist of compounds such as polyhalites, not being formed under present climatic conditions (Watchman 1985). One mineral was an oxalate, which contained carbon atoms which were fixed there via an organic pathway of lichens etc. These can thus potentially be dated directly by the radiocarbon method. This has recently been done in a virtuoso effort by the mineralogist Alan Watchman and the C14 chemist John Head. A date for a multi-layered crust covering paintings at the Ngarradj Warde Djobkeng site yielded a result of 8880±590 years BP (ANU 4271) (Watchman 1987, 39). Further work on the innermost layers of such crusts, using accelerator mass spectrometer methods is almost certain to prove conclusively that some of the art dates to late Pleistocene times.

At the very base of the sand unit at the Lindner Site (Nauwalabila 1) in Deaf Adder Gorge, we recovered several large pieces of high grade haematite, with polished facets showing they had been ground to obtain ochre. Their date would be 25,000-30,000 years old, if the reasoning outlined previously is correct. They show that at this time, people were bringing into sites in the Kakadu region, haematite from specialised quarries at least 50 km away and were using them to make high quality red pigment. This date is equivalent to the Aurignacian the earliest cultural phase for the appearance of art in western Europe. Perhaps in these manifestations of art, roughly at the same time in northern Australia and western Europe, on opposite ends of Asia, we are seeing the reflection of one of the profound events of human history; the emergence and geographical spread of modern *Homo sapiens*. I have no doubt that the Kakadu region is one of the most important regions in the world wherein we can explore the history of man as a hunter and gatherer. It is, of course, specifically a history of Aboriginal ancestors, but it is also more generally a history of ourselves, representatives of all the peoples of the world.

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APPENDIX 2

CHANGES IN ABORIGINAL EXPLOITATION OF WETLANDS IN NORTHERN AUSTRALIA

Dr. Betty Meehan
Division of Prehistory
Australian Museum
P.O. Box A285
Sydney South
N.S.W. 2000

Map 1	Arnhem Land
Map 2	Balpildja Swamp

Examination of archaeological, historical and contemporary anthropological evidence has made it possible to monitor both continuity and change in hunter gatherer exploitation of wetlands in northern Australia. This story begins at least 20,000 years ago and is still being acted out today by Aboriginal communities who continue to exploit wetland resources for both food and manufacturing products. This exploitation is but part of a wider strategy which incorporates many material, social and political elements of European origin.

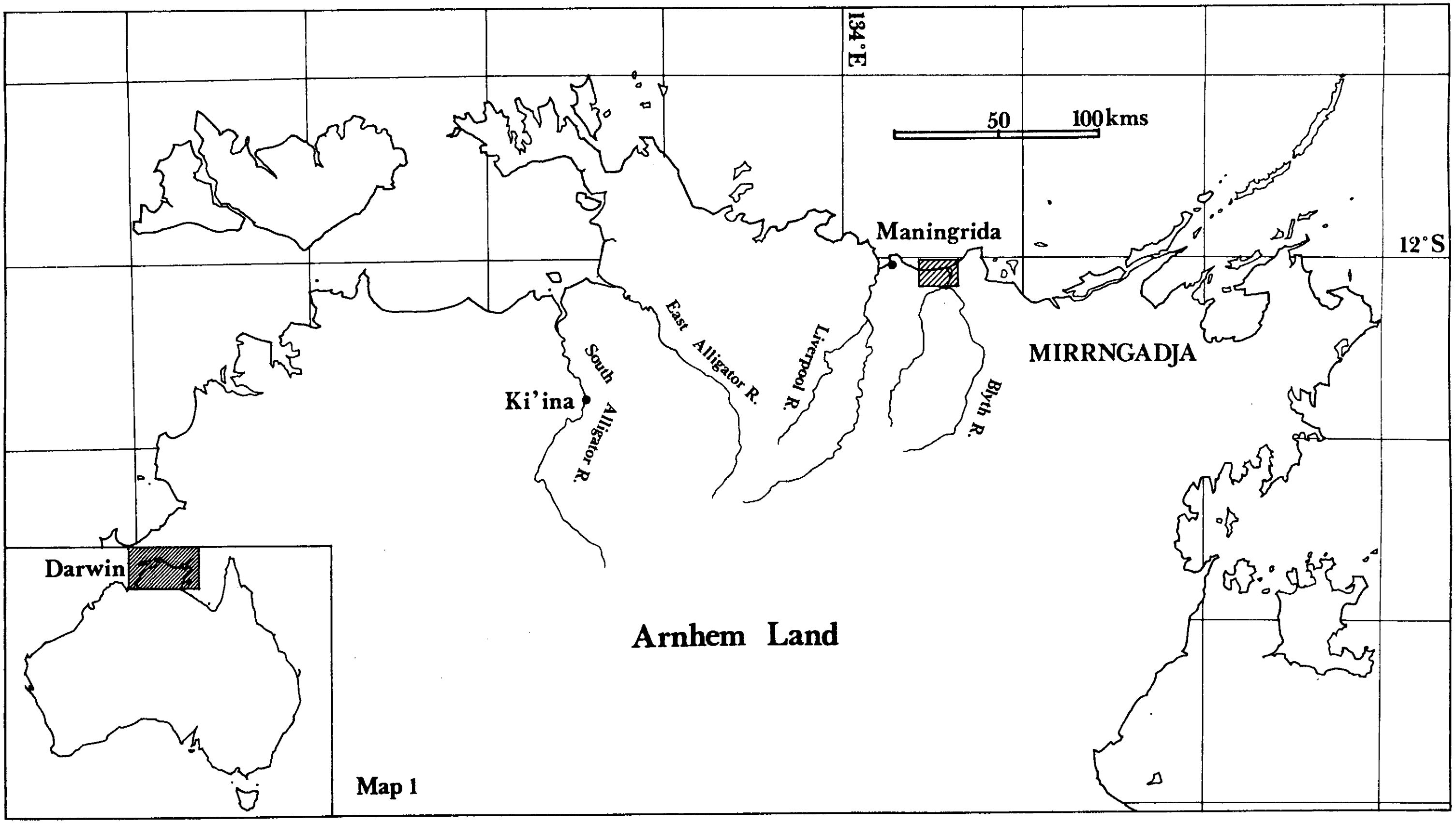
Prehistoric use

The prehistory of northern Australia is still being pieced together by archaeologists but it is accepted by scholars that people using a hunting, fishing and gathering subsistence technology have inhabited the region for at least 20,000 years. Ground flakes from axes dated to that period have been excavated (Schrire 1982). Today's coastal plains have been exploited by humans since the present sea level stabilised some 5-6000 years ago (Jones 1985). After that time wetland areas became established. Throughout their existence these coastal plains have been dynamic. New areas of land have been formed while others have been eroded away into the sea.

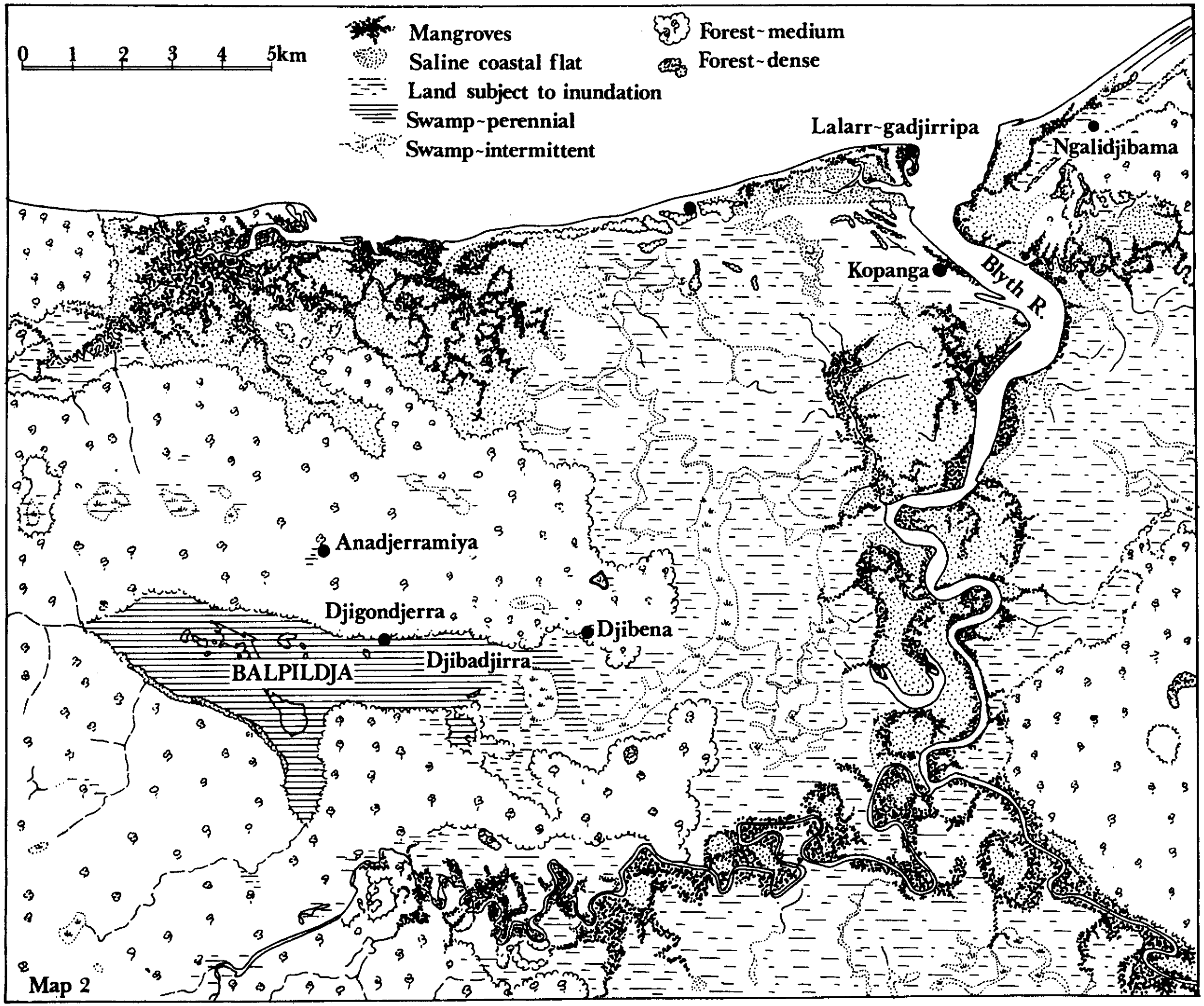
Archaeological evidence indicating human use of wetland areas is common throughout northern Australia. In central Arnhem Land, between the Liverpool and Blyth Rivers (Map 1), the shores of a large freshwater swamp called Balpildja (Map 2) are dotted with a series of humanly constructed mounds all of which are about 20m long, 10m wide and two metres high (Meehan in press). They are found where the highest level of the swamp merges with the woodlands. Gun-gapila, as they are called by the Gidjingali or Burarra speakers living in the region today, are composed of nodules of termite nest, still used as a cooking agent by Aboriginal cooks, plus the remains of human meals and manufacturing activities such as bones, molluscan shells, egg shells, stone tools and charcoal.

Preliminary results from a long term archaeological project being carried out on this area by Rhys Jones and myself has indicated that the construction of the mounds started around 1500 years ago when they began to accumulate on pristine beach sand. When this accumulation began the coastline was probably several kilometres further south than it is today.

Until recently little archaeological work completed in western Arnhem Land had been focused onto wetland sites. However in 1982, a team led by Rhys Jones (1985) from the Australian National University specifically investigated wetland sites on the Alligator Rivers system for evidence of human use. Brockwell (1983) has expanded the findings of the original fieldwork and is continuing research on this topic.


134°E
50
100 kms
Maningrida
12°S
MIRRNGADJA
East Alligator R.
Liverpool R.
Blyth R.
South Alligator R.
Ki'ina
Darwin
Arnhem Land

Map 1


0 1 2 3 4 5km
Mangroves
Saline coastal flat
Land subject to inundation
Swamp~perennial
Swamp~intermittent
Forest~medium
Forest~dense
Lalarr~gadjirripa
Ngalidjibama
Kopanga
Blyth R.
Anadjerramiya
Djigondjerra
Djibena
Djibadjirra
BALPILDJA

Map 2

Most western Arnhem Land wetland sites consist of dense scatters of stone tools covering large areas. Only one earth mound was investigated during the project though others were known to exist. Compared with those at Balpildja it was small. Charcoal from the bottom of Ki'ina mound indicated that it was about 700 years old.

Northeastern Arnhem Land contains many wetland areas. Mirrngadja or Arafura Swamp is one of the most famous. While there is substantial evidence to suggest that these wetlands were exploited in prehistoric times no systematic archaeological work has been yet carried out in the area. Mounds, large and small, and sites consisting of surface scatters of stone tools have been noted by various scholars working there (e.g. Peterson 1976).

It is clear from archaeological evidence accumulated so far that the present wetland areas on the coastal plains of northern Australia have been exploited by peoples for about 2000 years. We know that these people sometimes constructed large earth mounds around water bodies in order to do this. They also lived in flat open sites on the margins of wetland areas as is evidenced by large areas containing considerable numbers of stone tools. The antiquity of this prehistoric use and the details of the settlement patterns and subsistence strategies associated with it have yet to be finalised by further research and analysis.

Historic use

During historic times explorers, missionaries, government servants and anthropologists have described the lifestyle of Aboriginal people living in wetland environments of northern Australia. Their words paint a picture of communities living well on the products they were able to harvest from their land.

For example, in November 1845, as Leichhardt neared the end of his epic journey from Jimbour Station in Queensland to the settlement of Victoria on the shores of Port Essington in northern Australia, he recorded glowing descriptions of a wetland environment at the end of the dry season when waterbirds were congregated on diminished areas of fresh water:

> Since the 23rd November, not a night has passed without long files and phalanxes of geese taking their flight up and down the river, and they often passed so low, that the heavy flapping of wings was distinctly near. Whistling ducks, in close flocks, flew generally much higher and with great rapidity. No part of the country we had passed, was so well provided with game as this; and of which we could have easily obtained an abundance, had not our shot been all expended (Leichhardt 1847:496-7).

Elsewhere in his invaluable journal Leichhardt described other food sources available in the wetland areas of western

Arnhem Land such as fish (1847:518) and the water chesnut Eleocharis dulcis (1847:504). The latter plant can still be found in abundance in Kakadu National Park.

He spoke highly of the Aboriginal people living on the coastal plain through which he passed:

> ... they were well-made, active, generally well-looking, with an intelligent countenance, they had in fact all the characters of the coast blacks of a good country ... (1847:507).

Leichhardt's journal contains the earliest references to the presence of feral buffalo in northern Australia:

> When we approached the forest, several tracks of buffaloes were seen; and, upon the natives conducting us along a small creek which came into the plain from the NNE, we found a well-beaten path and several places where these animals were accustomed to camp (1847:524).

More recent descriptions of the way in which Aborigines exploited the wetlands since Leichhardt walked through the Alligator Rivers' area have been recorded by missionaries, anthropologists and people who had lived and worked in the area at mines, timber mills and in buffalo processing camps. Drawing on a range of available historical evidence Brockwell (1983 and in prep.) has concluded that the Aboriginal people living in this area in historic times occupied sites around the wetland edges for most of the year where they collected wetland foods such as goose eggs, ducks, geese, fish, terrapins, file snakes, and water plants as well as products such as yams growing in areas of forest adjacent to wetland camps. During the height of the rainy season camps were re-located onto higher ground but still within a kilometre or so of the wetland areas.

In the mid 1950's some Aboriginal people known as the Anbarra were observed by a government officer, Gordon Sweeney (1939), actually living on several of the earth mounds around the edge of Balpildja swamp in central Arnhem Land. Some of the people that Jones and I have worked with during the last 15 years, Frank Gurrmanamana and Nancy Bandeiyama in particular, remember Sweeney's visit. These same Anbarra people have also described to us how, when they were younger, now they are both over 50 years of age, and before the arrival of balanda or non-Aboriginal people in this region, they themselves had camped on Balpidja mounds during the early dry season when large quantities of spike rush (Eleocharis dulcis) and other aquatic plants foods and the eggs of waterfowl were collected. Because much of Anbarra land is covered with water at this time of the annual cycle the mounds provided a dry area for living and some relief from mosquitoes.

It is well-documented in historical sources (e.g. Thomson 1949) that Aboriginal inhabitants of northeastern Arnhem Land lived around wetlands for a large part of the year. They shifted to higher ground only when the land became flooded as a result of wet season rains.

Contemporary use

Today, more than a century and a quarter since Leichhardt wrote his journal, groups of Aboriginal people in central Arnhem Land continue to hunt, fish and gather for food in a landscape which they still own, and into which Europeans and feral animals have only recently began to penetrate.

Food collected from the sea and from estuarine rivers, creeks and mangrove forests play a major role in the diet of these people. At certain times of the year so do foods that are available from inland habitats such as - black soil plains, monsoon thickets, open forests, and ephemeral and permanent fresh water swamps. The richness of this coastal plain is reflected in the high population densities it supported in the recent past and by the social and cultural diversity that has been well-documented for the region (e.g. White 1979).

Contemporary exploitation of wetland resources by Aboriginal communities in Arnhem Land highlights the persistence of certain subsistence strategies in northern Australia despite marked changes that have occurred there over the past 200 years due to the arrival of Europeans with their vastly different ideas, technology and feral animals.

The Anbarra are an example of an Aboriginal community who continue to exploit wetland resources. Their country lies around the mouth of An-gatja Wana or the Blyth River in central Arnhem Land. The 50 sq km or so of coastal plain that they own has been formed since the present sea level ceased to fluctuate. Evidence from radio carbon dating accumulated so far suggests that all the land they own is probably younger than 2000 years. The Anbarra also have access to a further 150 sq km of land adjacent to theirs which belongs to people who speak the same language (Gidjingali or Burarra) and with whom they have close social ties (Hiatt 1965).

About 1957, when a government outpost was established at the mouth of the Liverpool River, on land owned by Gunavidji speakers, many Aboriginal people from the region, including Anbarra, gravitated to this outpost, Maningrida, which over the next decade grew to be a small town (Meehan 1982). However, by 1970 the Anbarra along with many other groups began to leave this outpost and settle once more on their own land in what have become known as "outstations" or "homelands" (Meehan & Jones 1980). From their outstation, Kopanga, the Anbarra procured animal and plant foods and supplemented these with European goods such as flour, tea and sugar which they purchased from the supermarket at Maningrida. This pattern was, and continues to be, common throughout the central Arnhem Land region (e.g. Altman 1987).

During a series of field trips carried out over the last 17 years Rhys Jones and I have been able to record quantitative details of foraging strategies employed by the Anbarra people (e.g. Jones 1980, Meehan 1982). This research has indicated that Anbarra people today enjoy an adequate and varied diet containing both European and bush food.

Swamp foods in Anbarra subsistence 1972-73

I have discussed the products culled from the wetlands by Anbarra people in detail elsewhere (Meehan in press). Suffice to say here that they gather a suite of water plants including species of *Eleocharis* and *Nymphaea*, birds such as ducks and geese and their eggs, several species of fish including the highly prized barramundi, long-necked terrapins, a few small crustacea, and in the past both fresh and saltwater crocodiles.

During 12 months of dietary observation covering part of both 1972 and 1973 Anbarra people collected only a small quantity of food from Balpildja, the largest freshwater swamp in their territory. They did however harvest food from a series of small, ephemeral swamps which lay closer to their home bases. This failure to exploit the considerable resources of Balpildja persisted throughout our fieldwork despite the fact that for part of that time (July-November) Jones and I possessed a four wheel drive vehicle which would have made expeditions to the big swamp possible and easy.

In 1972-73 the Anbarra had not lived permanently on their own land for some 15 years. They had based themselves at Maningrida and sometimes returned to their own estates for 'holidays' or to perform ceremonies. During this absence they appear to have lost touch with the subtleties of the foraging strategies they had used before moving to the government outpost. They seemed unable to predict precisely when and where certain products would be available for harvesting. For example, a day trip to Balpildja (12 September 1972) found the swamp dry and hard. No geese or ducks were there feeding on water plants and the corms of the *Eleocharis* were buried under many centimetres of hard, grey clay.

Swamp foods contributed only two per cent of the gross weight of all food eaten by the Anbarra during the 12 months extending from July 1972 until July 1973. About one quarter of this was plant food the rest was animal flesh derived from five species. Despite the meagreness of this data it contained trends that have been confirmed by subsequent fieldwork. For example, more swamp foods were eaten during the late dry season than at any other time of the year; and, the range of species procured were the same as these gathered today in larger quantities.

During this field season Anbarra people lived at four home bases: Ngalidjibama, Kopanga, Inanganduwa and

Lalarr-gadjirripa (Meehan 1982). None of these were situated on the edge of a swamp. Foraging camps established in the middle of the day, rrauwa djigudaridja or "dinnertime camps", were sometimes located adjacent to fresh water resource area. These were set up on flat open areas and beneath the shade of a tree where possible. Ground was cleared and one or several cooking areas prepared but the camps were never occupied over night.

Swamp foods in Anbarra subsistence since 1973

The Anbarra people have continued to live on their own estates since returning to them in 1970. Gradually they have regained familiarity with the subleties of the annual cycle. Swamps of various sizes and permanency, including Balpildja, have once again became an integral part of foraging but Anbarra methods of exploitation have altered somewhat as have the materials and objects they use.

Foragers continue to use pre-contact technology such as digging sticks and fishing nets. Nowadays the former are often made from metal while fishing nets, in the past made from reeds and weighted with stones, today are made from nylon thread and purchased from the supermarket at Maningrida. European items have also been incorporated into the wetland subsistence strategies.

The most important of these are four wheel drive vehicles and guns. Communities who own or have control over a vehicle continue to occupy home bases in preferred coastal positions such as Kopanga and make day trips to exploit swamp resources. In vehicles people are able to transport larger quantities of food to home bases than they ever could have done if they were walking.

Shot guns are used by men to procure geese, ducks and other waterbirds. The use of firearms does not necessarily mean that hunters capture more game in a day than they would have done in the past when they were using goose sticks and spears but it does mean that they spend much less time actually doing it - one as opposed to six hours.

The swamp area exploited most frequently by Anbarra foragers today is Balpildja. It is around the edges of this large swamp that many prehistoric earth mounds are found. They are not used as living sites any more for while people occasionally exploit swamp resources in the late wet and early dry season they do so from distance home bases not from these mound sites. However, during one late dry season expedition to the then dried up area of Balpildja a young hunter shot two wallabies with his shot gun. These were taken to the edge of the Djibena mound excavated that same season by Jones and myself, and there cooked in an oven containing approximately 50kg of termite nest which was collected from the black soil plain nearby. This process was identical to those which, over 1500 years, have caused Djibena mound to rise to two metres above the level of the plain.

Many mounds today are of religious significance and are said by local Anbarra people to have been made or visited by particular ancestral beings.

During five months in 1978 the Anbarra people and their neighbours exploited the freshwater swamps frequently. Between 11 September and 12 October for example, seven expeditions went to Djibadjirra a named location on the northeastern bank of Balpildja swamp. In that month the men shot 340kg of magpie geese with their shotguns while with digging sticks and pandanus baskets the women harvested 180kg of spike rush. At that time some of the foragers had been keen to camp for a few days on the edge of the swamp away from Kopanga home base as they had done in the past. They were afraid to do this because of buffalo herds grazing in the area.

Consequently expeditions left Kopanga after breakfast, travelled to Djibadjirra, and there set up dinnertime camps on open flat ground at the edge of the swamp beneath shade if available. These camps provided a focus for child minding and resting but geese were butchered and cooked here as well. The expeditions always returned to Kopanga home base in the late afternoon.

Members of the Anbarra community participated in a Rom ceremony that was held at the Nakara site Anadjerramiya in 1979 (Meehan & Jones 1986). During this ceremony Balpildja swamp was exploited extensively for food. Between 11 September and 12 October, 520 kg of fish, plants, tortoises and geese was collected.

While exploiting the resources of Balpildja swamp people lived about a kilometre away at Anadjerramiya which was a large home base, on flat ground in open forest. Stone tool scatters within the camp area suggested that it had been occupied in prehistoric times as well. When expeditions exploited the resources of Balpildja swamp they made "dinnertime camps" at Djigondjerra adjacent to where they were foraging on flat, open shaded areas as always.

In 1986 I spent two and a half months (June-August) with the Anbarra community. Throughout this time we were camped at Ngalidjibama on the eastern side of the Blyth River where a Kunapipi ceremony was in progress. At Ngalidjibama, the Anbarra were separated from the heartland of their own estates by the river. On the east bank they exploited swamp resources much less than they would have done had they been based at Kopanga. Tortoises were procured from swamp areas adjacent to the Ngalidjibama home base but other important swamp foods such as geese, fish, spike rush were collected from wetland areas distant from the home base mainly by traditional owners of those resources.

I visited the Anbarra community for 12 days in October 1987 - an important time of the calendar for exploiting swamp lands for food. In the Australian Museum's four wheel drive vehicle we visited Balpildja six times. Geese, tortoises and fish were collected. The only spike rush that was procured came from the craw of geese that had been shot by Anbarra men. On these six expeditions Anbarra foragers accumulated 300kg gross weight of swamp food.

Importance of swamp foods in Anbarra diet

Data collected since 1973 combined with extensive discussions with Anbarra people allows an assessment to be made about the importance of swamp foods in Anbarra diet.

In 1972-73 the 45kg collected represented two per cent of the total gross weight of all food eaten during September. Quantities recorded after that year - 520kg, 520kg and 300kg for 1978, 1979 and 1986 respectively - suggested that normally swamp foods may have made a more significant contribution to the diet especially during certain seasons. For example, if the 520kg collected in 1978 or 1979 was substituted for the 45kg procured in September 1972 swamp foods would have contributed somewhere in the order of 30 per cent of the total gross weight of food eaten during that month - a more realistic contribution than the two per cent recovered in 1972 just after the Anbarra had returned to live on their own land following a long absence.

It seems likely that in the past, before Europeans settled in Arnhem Land, swamp foods, both animal and plant, would have played a significant role in Anbarra diet twice during the annual cycle. The first period of plenty would have been during the late wet and the early dry season when goose eggs and some water plants would have been collected. At the end of the dry season another time of abundance occurred - this time the prizes to be won would have been geese, fish and spike rush.

Swamp products are still collected by Anbarra people on these occasions but the late wet early dry period has become much less important than it was in the past. Significantly, products from the late dry season have become more important. The swamp region is then dry, vehicles and guns can be used and people are able to return to home bases or Maningrida each night.

The water buffalo

Vehicles and guns are not the only factors to have caused change in the way Aboriginal people have exploited swamp land resources in northern Australia. Feral animals, especially buffalo, have contributed significantly to this process.

Water buffaloes were released on mainland Australia after they had been introduced to Melville Island from Timor in 1828 (Letts 1979). When Leichhardt was travelling through western Arnhem Land their impact on the floodplain environment appears to have been minimal. Since that time however, environmental changes have occurred in the region much of which has been the result of buffalo damage. Gillespie (1979) believes that buffalo herds have caused considerable degredation of the wetland area and, by implication, Aboriginal subsistence. Aboriginal social life also has been adversely effected because of stress caused by economic and environmental results of the establishment of buffalo industries (Gillespie 1979). Aborigines attracted to buffalo camps became acquainted with alcohol, European diseases, prostitution as well as a wide range of new foods and material objects.

About 800 Aboriginal people live in the region of the Alligator Rivers today whereas at least 2000 were thought to have lived there prior to European settlement (Keen 1978). The buffalo population has been as high as 15-20,000 (Letts 1977).

Since the arrival of buffalo contractors in western Arnhem Land Aboriginal people have come to rely more and more on buffalo meat in their diet. Eventually this was supplemented with flour, tea and sugar. Indigenous foods, especially those culled seasonally from the wetlands, continued to be collected by them but only as an adjunct to the staple diet of buffalo flesh and European carbohydrates (McGlaughlin 1982; Gillespie and Lindner pers.comm.; and pers.obs.).

An attempt has been made to arrest the destruction of wetland resources over the past decade by the Australian National Parks and Wildlife Service by reducing the buffalo population. The regeneration of wetland areas in Kakadu National Park indicates that the programme has been relatively successful.

As yet buffalo meat does not play a significant role in the diet of Anbarra people but the presence of these cloven-hooved animals has already began to damage the wetland environments of central Arnhem Land and caused Anbarra people to modify their foraging behaviour.

Wells and swamps once providing fresh water during the late dry season now dry up much earlier or are polluted because of buffalo usage.

A few beasts were noted during 1972-73 but their flesh was included in the diet on a couple of occasions only. A few years later buffalo numbers began to increase and herds containing up to 30 animals were sighted on the Blyth River floodplains. Anbarra hunters were wary of these animals, the largest Arnhem Land people have ever had to deal with in their foraging environment. Daring young men attempting to kill one usually did so from a moving vehicle with a gun. For the first time in 30 years of visiting the Anbarra community I was present in 1982 when a buffalo was shot, butchered and eaten. This animal was killed within a kilometre of Kopanga home base by a young man on foot with a shot gun.

Anbarra people, especially women and children, remain convinced that buffaloes will attack them. They have altered foraging strategies for most inland foods in order to diminish this danger. If foraging parties travel in a vehicle these concerns are overcome. However, it they have to walk to a particular area children, normally an integral part of foraging expeditions, are frequently left at home bases because parents fear for their safety.

In the past, experienced foragers fanned out over the inland plains on their way to chosen resource zones such as freshwater swamps. Now when buffaloes are known to be grazing on these open plains however, foragers travel along wooded tracks of land which they suppose will give them some protection from hostile animals. This altered strategy means that people are unable to examine large tracks of land for food which they can harvest at a later date. Monitoring of food resources in this way has always been an important element in Anbarra subsistence strategies. If they are unable or unwilling to continue it because of the presence of buffalo herds they are in danger of losing control over the availability of food in their environment in much the same way as they did immediately prior to 1972 when they had been living at Maningrida.

Figures compiled in 1988 by the Brucellosis and Tuberculosis Eradication Campaign unit (1986) for the central Arnhem Land area "Milingimbi", which encompasses Anbarra land, indicate that the area contains about 6500 buffalo and 500 cattle. So far this population has not been tested for the two diseases. If these herds are eventually destroyed, and it seems likely that they will be, presumably wetland areas will regenerate and past foraging practices could be re-instated.

Home bases on the swamp's edge

An important development took place in the Anbarra community in 1987. A new outstation, Djibena, was established on the northern edge of Balpildja swamp adjacent to one of the prehistoric earth mounds. This is to have permanent mud brick houses and a windmill and will probably be accessible by road from Maningrida for most of the year. Some Anbarra people were already living there when I visited the area during September and October. They were exploiting swamp foods, mainly geese and tortoise, every day and intended to live at the outstation all the year round.

It has taken 30 years for the Anbarra people, having been attracted initially to Maningrida, to once again occupy home bases on the edge of Balpildja swamp. They have exchanged earth mounds for mud brick houses, use vehicles to move around the countryside and guns to hunt but they continue to harvest the same suite of swamp foods that they probably did in the past for as long as the wetlands have existed.

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