Management of Vertisols under Semi-Arid Conditions

IBSRAM PROCEEDINGS No. 6

MANAGEMENT OF VERTISOLS UNDER SEMI-ARID CONDITIONS

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The International Board for Soil Research and Management (IBSRAM)
in cooperation with

- The Ministry of Agriculture and Livestock Development (Kenya)
- The Kenyan National Research Council for Science and Technology (NRCST)
- The International Council for Research and Agro-Forestry (ICRAF)
- The International Crops Research Institute for the Semi-Arid Tropics (ICRISAT)
- The International Livestock Centre for Africa (ILCA)

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Scientific Editors
Marc Latham and Peter Ahn

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Colin R. Elliott

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CONTENTS

SUMMARY

The First Regional Seminar on the Management of Vertisols under Semi-Arid Conditions in Africa and Southwest Asia took place in Nairobi, Kenya, from 1-6 December 1986. The sixty-nine participants from 23 countries (see Appendix IV) included formal representatives from 14 countries inside the region: Botswana, Burkina Faso, Egypt, Ethiopia, India, Kenya, Mali, Pakistan, Sudan, Tanzania, Tunisia, Uganda, Zambia and Zimbabwe, and one from the Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD).

The meeting was organized by IBSRAM in coordination with the Kenyan Ministry of Agriculture and Livestock Development, the Kenyan National Research Council for Science and Technology (NRCST), the International Council for Research and Agro-Forestry (ICRAF), the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), and the International Livestock Centre for Africa (ILCA). The British Overseas Development Administration (ODA) provided the main support for the seminar.

The meeting was officially opened by the Director of Research of the Ministry of Agriculture, M. Wapakala, with an introductory address by the IBSRAM Director, Dr. Marc Latham, and a welcome address by Dr. Wang'ati, Secretary of the National Council for Science and Technology.[1]

The first two days of plenary sessions introduced various aspects of the approach and methodology to be adopted by a proposed IBSRAM Regional Network on the Management of Vertisols under Semi-Arid Conditions in Africa and Southwest Asia. A total of 26 papers were presented and discussed. They were concerned with IBSRAM's network approach to Vertisols, site selection, site characterization, management systems, implementation of the Vertisols network, and the sustainability of improved systems.

During the first day, the papers dealt with the taxonomic aspects of Vertisols in the region, the soil physical and mechanical properties, and water management. On the second day, papers were presented on management systems – particularly the ICRISAT, ILCA, ICRAF and ACSAD technologies – implementation practices, tillage, supplementary design, fertilizer management, the design of experiments, and methods to evaluate the sustainability of these systems with regard to control, cropping systems or soil fertility.

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[1] For more details of the seminar programme, see Appendix III.

On the following day, fourteen project proposals were presented and reviewed, and these proposals were discussed during the fourth day of the seminar in an enlarged Network Coordinating Committee (NCC), while different groups drew up guidelines on site characterization, physical and chemical analytical methods and the monitoring of soil properties (see Appendix I).

In the enlarged NCC it was felt that particular attention should be given to three major problems which are common to the region as a whole: the elimination of temporary excess surface water, water deficiency, and erosion. A basic core experiment designed to remove these constraints was designed. The ICRISAT "broadbed-and-furrows" technique was mentioned as the most promising on slopes. In addition – and superimposed on this basic treatment – low-input and recommended-input techniques with regard to fertilizers, tillage, varieties and weeding were suggesed. Support trials or component experiments may also be conducted in the screening of improved varieties, fertilizer inputs, alternative cropping systems, and tillage.

On the fifth day, there was a field tour, which took the participants into the Mwea Area, where Typic Pellusterts are cropped in depressions for irrigated rice, and rainfed crops are grown on the adjacent slopes. The main problems faced by farmers for their rainfed crops were low rainfall, distributed in two seasons, and the occasional surface ponding. This last consideration explains why sowing is often left until late in the season, as farmers are afraid that the seedlings may be destroyed, and this means that the subsequent crops suffer from drought in the dry months.

On the final day of the seminar, twelve cooperators indicated their willingness to revise their project proposals so that they would comply with the agreed network approach and methodology. Finally the seminar adopted a resolution to form a network to be known as the Management of Vertisols under Semi-Arid Conditions in Africa Network (MOVUSAC). Agreement was also reached on a general organizational strategy for the network (see Appendix II), and the meeting was closed by Dr. F. Wang 'ati.

INAUGURAL ADDRESS

by William W. Wapakala
Director of Research, Ministry of Agriculture

Mr. Chairman, distinguished guests, delegates, ladies and gentlemen.

On behalf of the government and the people of the Republic of Kenya, it gives me great pleasure to welcome to this country and to the City of Nairobi all of you who have come from outside Kenya to this Regional Seminar on the Management of Vertisols under Semi-Arid Conditions. We are particularly happy that you have chosen Nairobi as the venue of your first seminar on this topic.

The subject of soil and water management is an important one, particularly in developing countries where agriculture is the mainstay of the economy and the majority of the population depend on it for their livelihood. In recent years severe droughts have threatened many parts of the African continent, with resultant serious food deficits affecting millions of people and animals. While emergency intervention by the international community in provision of food aid to the affected countries has helped to alleviate the situation, it is becoming clear to us in Africa that the long-term solution to the food crisis is not food aid but increased efforts by national governments to promote food production. Soil and water are the cornerstones of agricultural production. It follows that one of the most important areas which requires the attention of the national governments and international support for increased food production is development and conservation of the soil and water resources.

It has been observed that the rate of population growth in most developing countries is higher than the rate of increase in food production; and while this inbalance prevails the resources for agriculture, i.e. land and water, are decreasing in acreage in most countries because of the use of agricultural land for nonagricultural purposes such as residential accommodation, roads, factories, etc., and the loss of good agricultural land due to erosion, encroachment of desertification, salinity, alkalinization, and waterlogging. This progressive reduction of agricultural land inevitably reduces the land:man ratio; and in order to provide food to the increasing population in the coming decades it is therefore essential to increase agricultural productivity per unit area of land. This can only be done through integrated, well-organized and efficient agricultural research systems capable of generating new technology suited to the various soil types in different agroecological environments. Although expansion of the cultivated areas is still possible in some parts of Africa for increased food production, it should be noted that good soils are unevenly distributed and that most of the soils in Africa are fragile and subject to degradation and erosion. Hence there is a great need for their proper management in order to increase their productivity.

Mr. Chairman, referring to my own country, Kenya, agriculture is the mainstay of our economy. More than 80% of Kenya's population who live in the rural areas live and depend on agriculture for their livelihood. In view of this, the government development plans over the last two decades have laid emphasis and given priority to programmes aimed at developing the rural areas, particularly the smallholder farm sector, and at devising methods of developing the moderate- to low-rainfall (semi-arid) areas in order to promote a more even development in the country and at the same time increase food production. However, the agricultural sector is faced with a number of problems, among which is the restricted access to good agricultural land. The per capita availability of land was about 0.75 ha in 1977 and is expected to decline to about 0.30 ha or less by the year 2000. This trend is very disturbing when it is realized that less than 20% of the land is suitable for arable agriculture without resorting to irrigation. A small part of the remaining 80% can only support arable farming under irrigation or under proper soil and water management practices.

Mr. Chairman, one of the first and most important steps in intensifying agricultural production is to know the state of the soil resources. This can be done through a soil survey which indicates the location and extent of each kind of soil and its potential and limitations for various uses. Unless a country knows the productive capacity of its soils, agricultural planning can be greatly constrained. Intensification of land use also requires more efficient management of soil moisture and plant nutrients. In addition there is a need to reorientate irrigation to water-saving types of irrigation and to develop the poorly drained soils. This too, is only possible if we know our soils and their likely response to various management practices.

The theme of this seminar is a very important one in that it addresses itself to the management of one of the soils that occurs extensively in humid, subhumid, semi-arid and arid climates, and has high potential for agricultural production. It is estimated that Vertisols, popularly known in this country as "black cotton soils" or "black cracking clays" occupy approximately 103 million ha of the total land area of sub-Saharan Africa. In Kenya these soils occupy approximately 2.8 million ha, which constitutes about 4.9% of our total land area. They are found under different climatic conditions, but the majority of them are in the semi-arid areas. As I mentioned earlier, the semi-arid or arid areas constitute about 80% of Kenya's land area and support 20% of the country's people and half of its livestock.

The Vertisols in Kenya are being used for extensive grazing as well as for production of a variety of crops. Due to their occurrence in terrains which are relatively flat, they are suited to irrigation; hence these soils are used extensively for growing irrigated rice in the Mwea, Ahero and West Kano irrigation schemes; for sugarcane production in the Nyanza

Sugar Belt (Mumias, Chemilil, South Nyanza and Muhorini); cotton in the Bura and Hola irrigation schemes; and vegetable production in the Athi River area. They are also used for production of maize, cotton, chickpea, beans and other crops under rainfed conditions. The yields of the various crops obtained from these soils very much depend on how they are managed. Under poor management they have been known to yield only 40 t of cane per hectare in the Nyanza Sugar Belt. However, in the same area, and under proper management and adequate water supply, yields of up to 175 t of cane per hectare have been realized. Rice yields ranging from 5 to 6 t per hectare have been obtained at the Mwea irrigation scheme. Irrigated cotton on these soils in the Bura and Hola irrigation schemes give yields ranging from 3 to 5 t seed cotton per hectare.

Although these soils have a very high potential for agricultural production, high levels of production are rarely reached due to management problems. They are waterlogged or flooded during the rainy seasons, making them difficult to cultivate when wet. When dry too, they have physical properties that render them difficult to till, especially with simple tools. Some of them have unfavourable chemical properties – for example in those with high pH, phosphorus availability is low. Nitrogen dificiency may occur as a result of poor drainage and relatively low content of organic matter. They may also have management problems when irrigated. In summary, there is a need for research to solve problems of workability, water availability and nutrient availability of these soils.

I do not intend to go into the details of various aspects underlying the theme of this meeting, but I do realize from the programme that the seminar is going to consider all aspects of managing Vertisols for increased agricultural production, and in the end you will be making specific recommendations as to how you intend to carry out collaborative research. This seminar is being held at the time when we in this country are reorganizing our agricultural research system. In this reorganization, which involves developing priorities among commodities/factors, major emphasis is being laid on management and conservation of soil and water resources. Collaborative research and strong interlinkages with local and international organizations such as yours has been emphasized in the organizational process. I can thus assure you of our support and future collaboration.

I am pleased to note that you have included in your programme a field excursion to the Mwea area to enable you to see various environmental conditions existing in the area and particularly the use being made of Vertisols. I also hope there will be time for visiting our game reserves, and that you will enjoy your short stay in this country.

Mr. Chairman, without taking too much of your time, I would like to wish you all the best in your deliberations. However, let me reiterate once again my pleasure at being invited to participate in this seminar.

It is now my humble duty and pleasure to declare this First Regional Seminar on Management of Vertisols under Semi-Arid Conditions officially open.

INTRODUCTORY ADDRESS

Marc Latham
Director, International Board for Soil Research and Management

Director Wapakala,
Your Excellency, ladies and gentlemen,

It is my honour to be with you for this Seminar on the Management of Vertisols under Semi-Arid Conditions. I am happy to see that so many of you have responded to our invitation. Even if the charms of Nairobi are amongst the reasons which induced you to come, I am sure that the importance of the subject we are dealing with this week is the main motive for your being here.

Soil management and food production are one of the major issues affecting this continent, especially in the semi-arid zone which has been hit so severely by a drought in recent years. The population increase will require in the coming years more and more food and agricultural production. All the resources need to be exploited, and Vertisols are one of the underexploited resources of this area. They are potentially rich soils and we all know that Indian regur, Egyptian black cotton soils, or Morrocan tirs can be a real source of wealth. But they are complicated to manage. Their clayey texture make them difficult to plough, and farmers often prefer to use proper sandy soils for this reason. They are too hard to be ploughed when dry, and too sticky after heavy rain.

Moisture is also a major constraint, as these soils absorb water easily but release it with difficulty to the crops. The nutrients are sometimes presumed to be sufficient, mainly in the case of extensive farming like that practiced in Queensland, Australia; but phosphorus, nitrogen and micronutrients may rapidly become a limitation under intensive exploitation. Erosion can also be a high risk, even if the slopes are not unusually steep.

Moreover Vertisols are not a uniform soil entity, and they occur under very different agroclimatic environments, which is a limitation to the transfer of technology for managing them. In most classification systems, Vertisols do not appear to be very diversified in comparison with other great groups like Oxisols or Ultisols for example. But variations in their constitution or in their organization have often been hidden to the pedologist because of the uniform colour, texture or structure which they present. In these semi-arid zones, which extend from a maximum annual rainfall of 1000 to 1200 mm to such limited rainfall as 200-300 mm, moisture regimes and cropping possibilities are also very diversified.

The search for soil management technologies adapted to these difficult agroenvironments is one of the priorities for the development of these zones. Solutions exist: some have been successfully tested by ICRISAT in India, by ILCA in Ethiopia, and CIRAD in western Africa. Major progress has been obtained in the selection of adapted germ plasm, in the irrigation systems, and in the tillage practices. They now need to be tested, adapted, validated and transferred to the farmers.

The IBSRAM aim, which is to promote coordinated research efforts by national research organizations in collaborative research networks, is specifically designed to meet these needs. Even if our knowledge of these soils is more limited than that which we can bring to bear on many others, we are not starting from nothing. We have to build on the results we already have, while at the same time trying to generate new knowledge. We must have a two-phase strategy: on the one hand adapting the available results in order to find out – rapidly – improved alternatives to the existing farmers' practices, and on the other hand a longer-term strategy which consists of ascertaining carefully the fertility components of these soils by means of a coordinated research programme.

Strategic research and adaptive research cannot be disassociated. Adaptive research may bring improvements but may rapidly be limited by a lack of sound knowledge of the components. Strategic research will bring into play the strong scientific understanding needed to find solutions to the management problems which these soils present. However, this is a long-term effort and it may discourage donors, who will not see tangible results in a reasonable period of time. It may also be too comfortable an approach for the scientists, who will set out to achieve a remote target without regard to the immediate applicability of the results.

In the six days of this seminar, I count on your efficient efforts to bring into effect this network on the management of Vertisols under semi-arid conditions in Africa and Southwest Asia. In the two first days, general presentations will be made in order to establish the basis of the methodology to be applied by you, the future cooperators. This basis will be discussed in working groups and then coordinated later with the results of the other IBSRAM seminars in order to provide scientific guidelines for conducting IBSRAM programmes.

On Wednesday, you will present your country papers and project proposals. This is the most important aspect of this meeting. We want to establish a soil management network, and for this we need good realistic projects which can be integrated into a network scheme. In 1985 we had, thanks to ICRISAT, USAID and ADAB, our Inaugural Workshop on the Management of Vertisols for Improved Agricultural Production, held in Hyderabad, where the target of the network was established and where guidelines for the preparation of project proposals were prepared. Dr. J. Burford has been able to visit some of you since then in order to help you draft your projects. We now need to review and revise these projects in order to ascertain their scientific and socioeconomic relevance, and to put together a network from this collection of national projects. Discussion after the presentations, and later on individually with the NCCs, are designed to secure this integration.

On Friday, during the field tour, you will be able to see some of the management practices conducted in Kenya, and also you will have the chance to discuss what you observed amongst yourselves and with the resource persons who have been invited. Hopefully, by Saturday the basis of the network will have been established, and a core of three to five projects will be outlined in a suitable form for presentation to potential donors.

I would like now, after having described the aims and the scheduled contents of this seminar, to thank those who have made the seminar possible. We all gratefully acknowledge the assistance provided by the British Overseas Development Administration in supporting this seminar financially, and we hope that the results – in terms of inaugurating an efficiently integrated network – will measure up to this contribution and the expectations which have prompted ODA's initial effort.

We also wish to thank the participants from Australia, the Netherlands, Botswana, Italy and France, who have come to the seminar through the support provided by their governments. And moreover I would like to thank ICRISAT, ILCA and ICRAF for their strong input in promoting this seminar. Finally, I must express our sincere thanks for the hard work which has been put in by the local organizing committee, who have made every effort to solve all the details involved in organizing this seminar.

Your Excellency, ladies and gentlemen, we have a long week of work in front of us. The inputs you contribute are the only way to achieve our aim – which is to build a network on the management of Vertisols under semi-arid conditions. I count on your interest and your enthusiasm to make this seminar a success. Thank you.

First session: IBSRAM's network approach

Chairmen: Dr. Wang'ati

Dr. Kanwar

IBSRAM AND MANAGEMENT OF THE VERTISOLS NETWORK

Marc Latham*

Abstract

The International Board for Soil Research and Management (IBSRAM), which was set up in 1983, is in the process of developing three regional programmes – one for Africa, one for Africa and Southwest Asia, and one for Monsoon Asia. These regional programmes are related to IBSRAM's three soil management targets: (i) management of Vertisols, (ii) management of acid tropical soils, and (iii) tropical land clearing for sustainable agriculture.

IBSRAM wants to promote sustainable improved soil management technologies in order to remove soil constraints to food and other agricultural production. The practical adaptative investigations which IBSRAM advocates require multidisciplinary efforts from soil scientists, agronomists, and socioeconomists if the results obtained are to be transferred to the farmers concerned. In order to achieve these objectives, IBSRAM has chosen a collaborative network approach.

It is intended that the proposed network organization should comprise three components: (i) cooperators – who can be simple, active, basic or support participants; (ii) IBSRAM – which will act through a coordinator backed by a Network Coordination Committee (NCC); and (iii) the donors. The mechanism of acceptance involves submitting the project to IBSRAM, a review by the NCC, approval by the IBSRAM Board, and regular discussion and review of the results. In order to be accepted as part of the network programme a project should conform to network objectives, and should adopt the defined approach and methodology. It should also be economically acceptable and have a broader scope than purely country objectives for basic research.

The aim of this seminar is to define the common approach and methodology, revise national project proposals, and establish a regional network on the Management of Vertisols under Semi-Arid Conditions in Africa and Southwest Asia.

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* International Board for Soil Research and Management (IBSRAM), PO Box 9-109, Bangkhen, Bangkok 10900, Thailand.

Introduction

IBSRAM was set up three years ago in September 1983, which was when the first Board was elected. At that time, it was decided, as a first priority, to promote four soil management concerns. After four inaugural workshops from December 1984 to September 1985, three soil management targets were considered to be of special interest by virtue of their great potential for developing agricultural resources:

- Management of Vertisols (IBSRAM 1985a);
- Management of acid tropical soils (IBSRAM 1985b);
- Tropical land clearing for sustainable agriculture (IBSRAM 1985c).

In order to establish networking arrangements to cover these topics, three regional network programmes have since been proposed. They are:

- Land Development and Management of Acid Tropical Soils in Africa, for which a regional seminar took place in Douala, Cameroon, in January 1986;
- Land Development and Soil Management in Monsoon Asia, for which a regional seminar took place in Khon Kaen, Thailand, in October 1986;
- Management of Vertisols under Semi-Arid Conditions in Africa and Southwest Asia, which is the object of this meeting.

This paper will discuss the IBSRAM soil management network approach, the main features of the proposed regional network on the Management of Vertisols under Semi-Arid Conditions, the proposed organization of this network, the mechanism of approval for project proposals, and finally the objectives of this particular seminar.

IBSRAM Soil Management Network Approach

The IBSRAM soil management network approach has been described earlier (IBSRAM, 1985d, 1985e, 1985b and 1986c), but it may need to restated for those who are not yet familiar with it. The overall goal of IBSRAM is to promote sustainable improved soil management technologies in order to remove soil constraints to food and other agricultural production. To implement this goal, the IBSRAM approach is to help cooperators, through soil management networks, to conduct the investigations necessary for the practical adaptation and validation of improved soil management and land-use practices.

Soil management, in the IBSRAM view, is a multidisciplinary undertaking which must combine inputs from soil science, agronomy and socioeconomics. Soil knowledge for soil management has to envisage the soil as a whole in its environmental context, and to classify it according to recognized reference systems in order to provide the means for a general transfer of agrotechnology. However, it must focus on the layers prospected by roots, on the lateral variations of their characteristics, and on the dynamics of their most mobile components – air, water, ions, fauna and flora. These components are related to the climate and seasons, since they are controlled by rainfall and temperature. In turn, the climate and seasons are also the direct causes of erosion, taken in conjunction with the slope and the land use. For proper application to management, a good soil knowledge must be comprehensive so that a sound interpretation of experimental data can be made and the results can be promulgated extensively.

New technologies have been produced by agronomists. International agricultural centres and other research organizations have found new germ plasms, improved phyto-sanitary protection, and appropriate tillage and fertilizer practices, which have led to what has been called 'the green revolution'. Unfortunately, these techniques, which can be applied successfully on good agricultural soils, have been difficult to extend to the more marginal lands, which is where the current pressure for agricultural development is becoming more intense. Also, more complexity is involved in marginal lands – Ultisols, Oxisols, Vertisols, and steepland Inceptisols – than there is in good agricultural lands such as alluvial Inceptisols, Entisols or Mollisols. This means that there is a great deal of work to be done in adapting and testing these new improved technologies, taking into account the variability of the environments involved.

Socioeconomic inputs are necessary because they are the means by which these new technologies can be applied. A knowledge of the farmers and of their traditional practices is essential in the search for acceptable technologies. Agricultural habits derived from long experience represent a very rich source of information. The attempt to integrate familiar habits into the proposed technologies, and at the same time to improve them, will save time and will make them more acceptable. Finally, soil management technologies must adapt to the farmers' possibilities and to national priorities regarding the lands and crops to be developed.

Individual efforts are long and costly in agricultural research. The use of the existing knowledge, the sharing of new findings by national institutions working on the same subject, and the coordination of these efforts, are the most cost-effective ways of tackling these problems. This is why IBSRAM has chosen a collaborative research approach to achieve its objectives.

MOVUSAC Network in Africa and Southwest Asia

The network on the Management of Vertisols under Semi-Arid Conditions (MOVUSAC) in Africa and Southwest Asia will concentrate on the dark swelling clay soils which occur extensively in the semi-arid regions of Africa, the Middle East and the Indian subcontinent. Because of their topographical position, their depth, the nature of their clay and their mineral content, they possess a very high potential for agricultural productivity. However, high levels of crop yields are seldom reached due to various limitations – tillage difficulties, low infiltration rates and permeability, and nutrient deficiencies – that can be overcome by improved management techniques.

The inaugural IBSRAM workshop on the Management of Vertisols for Improved Agricultural Production, held at the ICRISAT headquarters in India in February 1985, showed that:

- o improved techniques are available for achieving better soil management;
- o such techniques and others need to be tested and adapted in a range of semi-arid

zones in order to determine those which can be introduced most easily and effectively into farming practices; and

- o further research is especially needed on tillage, water conservation, nutrient management, and cropping systems.

Following the report of the inaugural workshop and the guidelines proposed, research project proposals have been sent by different future cooperators in order to join the IBSRAM Vertisols network.

The proposed regional network will focus on one part of the initially envisaged network on the Management of Vertisols for Improved Agricultural Production – the subarid nonflooded Vertisols. The area concerned will be Africa and Southwest Asia. Other programmes for the management of Vertisols may be developed in other parts of the world on different types of Vertisols. It is hoped to link participants from different regional programmes through a Vertisols newsletter and other information media, and eventually through global activities such as specific meetings or training courses.

Organization of the Regional Network

The proposed organization of this regional network will be similar to that envisaged for the initial networks. It will comprise three components, namely:

1. Cooperators

Cooperators will initiate and operate the soil management programme activities connected with one of the following types of participation:

- o simple participation in the different programme activities, mainly with a view to sharing information;
- o active participation – both by having an accepted programme, and by participating in all the various programme activities;
- o basic participation – by having an approved programme, some basic research related to the objectives of the network, and also participation in all the programme activities;
- o support participation by international and other research agencies, by undertaking some part of the basic research related to the objectives of the network, either alone or in conjunction with other cooperators.

2. IBSRAM

Through a programme coordinator, backed by the Network Coordinating Committee, IBSRAM will catalyze, coordinate, and assist cooperators in conducting their activities. IBSRAM provides assistance in the preparation and presentation of the projects to donor agencies. The coordinator acts as a link between the cooperators and IBSRAM. He helps strengthen the national cooperators' programmes by regular visits and consultations and by backstopping the following network activities:

- o site characterization;
- o exchange of control soil samples and analytical methods;
- o design of experiments, analyses and interpretation of data arising from these experiments;
- o technical assistance;
- o regular meetings during which programmes are reviewed and eventually revised;
- o monitoring tours;
- o training courses;
- o creation of a data base;
- o a review of past and ongoing research and bibliographic information services;
- o production of a programme newsletter, publications, and documentation.

3. *Donors*

The role of the donors will be to fund the programme coordination and, in part, the activities of the individual national cooperators.

Mechanism of Approval of National Project Proposals

One of the main objectives of this meeting is to revise and approve national project proposals in order to establish the regional network programme. The mechanism of approval, which is already being applied, consists of the following steps:

1. A project proposal on soil management is presented to IBSRAM by a national institution. Coordination between national organizations is favoured.
2. The project is reviewed by the Network Coordination Committee (NCC). Until now, the initial interim NCC formed during the inaugural workshops has been used. During this meeting, one question to be discussed is the formation of an NCC for this regional network on the management of Vertisols. The NCC will consist of scientists with useful expertise in the management of Vertisols, the main donors, and the IBSRAM coordinator.
3. The IBSRAM Board must then endorse its acceptance of the project proposals.
4. After approval, an official letter of acceptance will be sent to the cooperators, who may use it as a letter of support for fund seeking. During the regular meetings of the network, cooperators will present their results, and these will be discussed and reviewed by the participants in order to maintain a high scientific and development standard in the programme.

The criteria for the approval of a national project proposal are as follows:

- The project must fulfill the network objectives as defined during the inaugural workshops and as clarified during the present seminar.
- The project must be technically acceptable, i.e. it should follow the approach and methodology to be defined during this seminar. An example is given by the results

of the Cameroon seminar that you have to hand (IBSRAM 1986a).
- The project is thought to be scientifically and economically acceptable.
- The country is already involved in research of the type proposed, or is willing to invest in training for its personnel to achieve worthwhile participation.
- If a basic research project is proposed, it should have a broader objective than the country objectives *per se,* and should have implications on a wider scale. This criterion will not apply to validation projects.

Objectives of this Seminar

This seminar, then, will have three major objectives:

1. To define a common approach and methodology. The review papers presented in the first part and the following discussions are designed to help the working groups to design this common methodology and approach – without which no exchange amongst cooperators can function. The results of these working groups will be discussed and provisionally approved on the last day of the seminar: they will be the basis of our future work. In order to harmonize the work of the three regional network programmes and of the future ones, the Board will review these results and those of the other regional programmes during its meeting in March 1987. However, the results obtained here can serve as a basis to start the projects.
2. To revise the national project proposals. An exchange of correspondence has already taken place with regard to the national project proposals received. Improvements have been made, but further discussions and revisions will be conducted during this week when it is hoped to finalize some of these projects. Others, which have not yet been discussed, will be reviewed. Finalized projects will be submitted to the Board immediately after the seminar in order to get its final approval. They will be published separately as the basis of the regional programme.
3. To establish the regional network on the Management of Vertisols under Semi-Arid Conditions in Africa and Southwest Asia. Some donors have expressed their strong interest in this network and we expect that a coordination plan will be funded by the beginning of 1987. Your requests will be discussed and finalized on the last day of this meeting.

This network must be yours. This means that in addition to your national project proposals, we must work out in more detail the rules governing the functioning of the network and the common activities which can be implemented. A regional NCC must be formed which will serve as an advisory body to the coordinator. Finally, three publications will be produced after this seminar:

1. A report of the seminar in the format of the report of the Cameroon seminar. This will be ready by March 1987 and will be widely distributed.
2. A document including the approved projects, to be circulated internally in the network as a base document and for donor support purposes.
3. Proceedings of the seminar, which will be largely a compilation of the papers present-

ed during the first two days. In order to keep a standard level in these proceedings, we will form an editorial committee which will look at the scientific aspects of the papers. I hope that we may have these proceedings published before the end of 1987.

Conclusion

We now have six days of heavy work ahead of us to cover our tightly packed schedule; but I feel that you will lend your very best efforts to the task since we are building your network. Monday and Tuesday will be devoted to lectures on specific points related to the implementation of the network. Wednesday will see the presentation of country reports and project proposals. On Thursday, we will split into working groups and look at the common methodology to be employed in the network. On Friday, we will have the chance to visit sites in the Mwea district, where Vertisols are being used for paddy rice and rainfed agriculture; and on Saturday we will finalize our discussions.

This seminar is an opportunity for you to meet each other, and it is also a unique chance to discuss your specific problems regarding your projects on the management of Vertisols for improved agricultural production. So your enthusiasm and your work will be the best start for the cooperative activities which the network can foster.

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CHARACTERIZATION OF VERTISOLS FROM INDIA AND IRAQ AND THEIR TAXONOMIC PROBLEMS

Jawahar L. Sehgal and J.C. Bhattacharjee*

Abstract

Vertisols are deep, dark-coloured clayey soils with considerable uniformity, and are found in semi-arid to subhumid climates.

The dominance of smectite clay and high swell-shrink phenomena with changes of moisture results in cyclic movement which inhibits horizonation and has significant genetic implications in the development of Vertisols. These soils are characterized by deep, wide cracks, gilgai microrelief, intersecting slickensides and/or wedge-shaped structural aggregates in the subsoils. In India they are found extensively in the central peninsular region, while in Iraq they are confined to the intermontane valley plains in the northeast and the basins of Mesopotamia. In central peninsular India, the soil moisture regime is predominantly ustic, and accordingly Vertisols are classified as Chromusterts with a hyperthermic/isohyperthermic temperature regime. In Iraq, they are classified as Chromoxererts and Salitorrerts, depending on the moisture regime and other factors. The climatic pattern reveals variations in the number of dry and humid days in a year, indicating appreciable differences in soil moisture storage during the growing season of the crop, although soils apparently have a uniform moisture regime at the great group level.

It is considered necessary for Vertisol classification to subdivide the ustic moisture regime into aridic, typic and udic subgroups on the basis of climatic parameters, indicating differences in soil moisture storage. Similarly xeric and aridic moisture regimes have been subdivided into dry-xeric and extreme-aridic subgroups. In view of the high salinity in the Torrerts of Iraq, it is proposed that the classification of Torrerts should be completed at great group level by introducing groups called Salitorrerts, (Calci-, Gypsi-, and Haplotorrerts).

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* National Bureau of Soil Survey and Land Use Planning, Amravati Road, Nagpur – 440 010, India.

Generalities

Vertisols are deep, dark-coloured clayey soils of predominantly smectitic mineralogy. They are characterized by deep and wide cracks and at places have gilgai microrelief with frequent microknolls and microdepressions. These soils have characteristic cyclic pedons, which make them different from other soils. The slow and steady process of haploidization induced by argillipedoturbation (Hole, 1961) inhibits the process of horizonation (Simonson, 1954; White, 1967; Buol *et al.*, 1973) and favours the development of Vertisols having characteristic structural profiles.

Vertisols are remarkably homogeneous soils; but differences within their taxa may be caused by climatic components, slope and landforms, the amount and composition of smectite minerals, and the nature of saturating cations. The soils are fine to very fine in texture, have a high CEC, base saturation, bulk density (dry), coefficient of linear extensibility, predominance of saturating cations such as Ca^{2+}, Mg^{2+} and Na^{3} (either singly or in combination), a high water storage capacity, low saturated hydraulic conductivity, and a neutral to alkaline reaction. They are normally low in plant-available nutrients.

The proper understanding of their characteristics in relation to their potential use for food production is a justifiable aim of research on Vertisols, which should lead to the effective management and viable use of these soils. In the present paper an attempt has been made to review and compare the soil characteristics of Vertisols from India and Iraq, highlighting their taxonomic problems and their potential for normal rainfed-crop husbandry.

Distribution

Vertisols and associated vertic soils are the most widely dispersed soils in the world, and can be found under varied climatic conditions. Such soils are spread over five continents from 45°S to 45°N, mainly in tropical and subtropical areas, and their major areas of distribution are located in Asia and Africa (Dudal, 1963) (Figure 1). There are about 310 million ha of these soils in Asia (mostly in India), in America (mostly in the USA, Venezuela and Argentina), in Australia, and in the African continent.

In India, Vertisols and associated soils are mostly observed in the peninsular region extending from latitudes 8°45′ to 26°0′N and longitudes 68°0′ to 83°45′E. They occupy approximately 72.9 million ha and constitute 22.2% of the total geographical area of the country (Table 1). They occur in the states of Maharashtra (7.9%), Madhya Pradesh (5.1%), Gujarat (2.6%), Andhra Pradesh (2.2%), Karnataka (2.1%), Tamil Nadu (1.0%), Rajasthan (0.7%), Orissa (0.4%), Bihar (0.2%), and Uttar Pradesh (Murthy *et al.*, 1982).

In Iraq, such soils are confined to areas with level to nearly level landscapes, and occupy an estimated 30% of the land area in the intermontane valley plain (in the northeast) and 1% of the basin area (in the Mesopotamian Plain of central Iraq) (Table 1). The associated Mollic subgroups and/or Mollisols in the hilly areas are observed on the higher elements of the topography (Sehgal *et al.*, 1980a, 1980b).

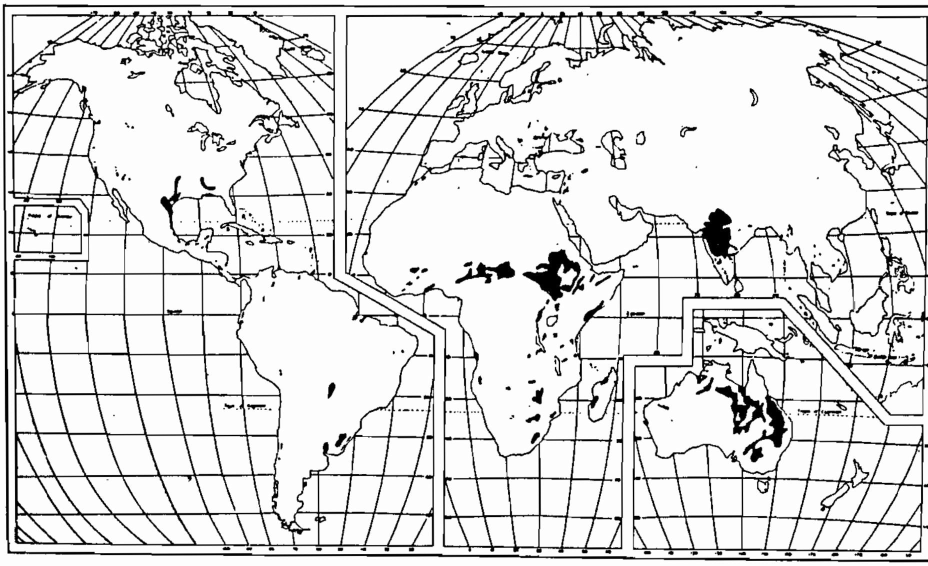

Figure 1. Dark clay soils of tropical and subtropical regions: areas of major distribution (Dudal, 1965).

Table 1. Extent of different taxa of Vertisols and associated soils in India and Iraq.*

Order	Area representation of total black soils area		Soil group	Percentage representation within order
	%	million ha		
	INDIA (Peninsular India)			
Vertisols	38	27.7	Chromusterts	61
			Pellusterts	39
Inceptisols	37	27.0	Typic subgroup	4
			Vertic subgroup	96
Entisols	21	15.3		
Aridisols	0.6	0.5	Salorthids	
Alfisols	0.4	0.3	Vertic Haplustalfs	
Undifferentiated soils	3.0	2.2		
	(100)	(72.9M ha)		
	IRAQ (Shahrazur and Middle Tigris projects)			
Vertisols	31.7	0.3	Chromoxererts	96
			Torrerts	4

*Source: Murthy *et al.*, 1982; Sehgal, 1980; Sehgal *et al.*, 1980a, 1980b.

Climatic Environments

The climatic conditions in the central peninsular region of India supporting Vertisols vary from semi-arid to subhumid tropical (Figure 2). The area is characterized by hot and dry premonsoon summer months (March to May), followed by well-expressed summer

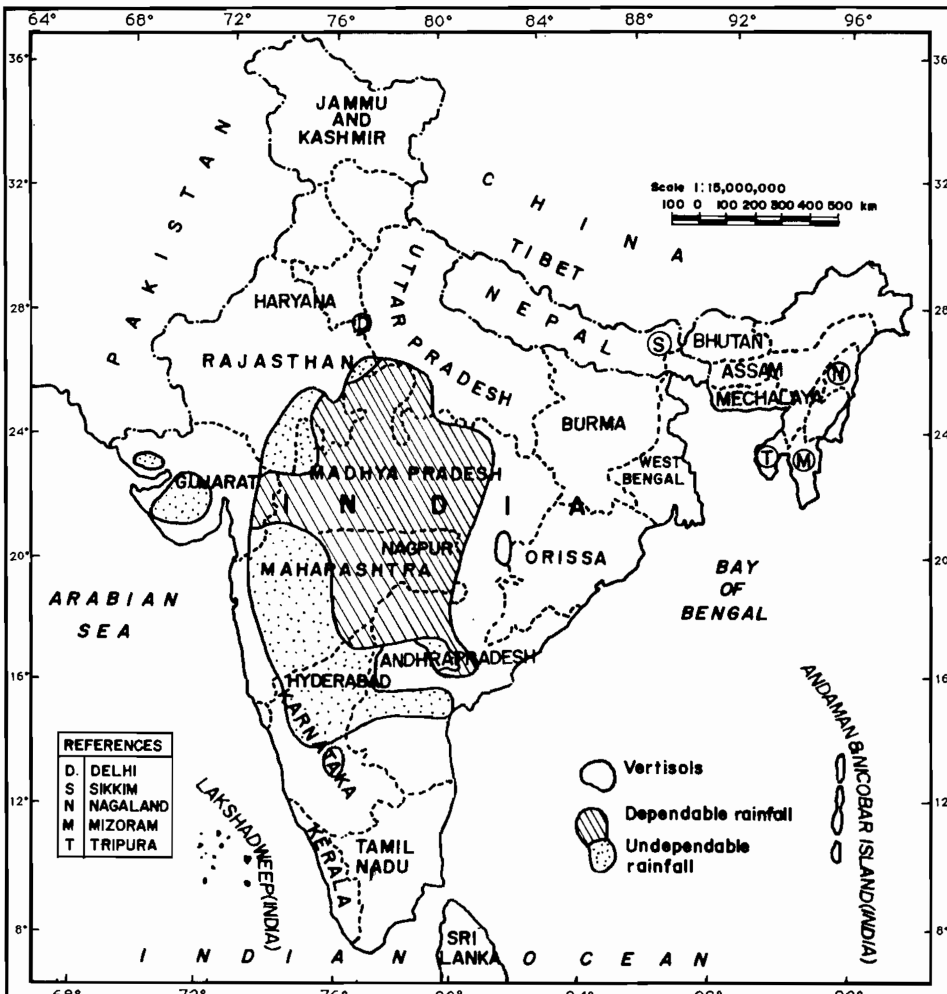

Figure 2. Assured-rainfall (750-1500 mm) and unassured-rainfall (below 750 mm) regions in central peninsular India (Virmani *et al.*, 1978).

monsoon months (June to September). The subsequent short period from October to November receives uncertain showers with a low probability of occurrence, followed by a fairly dry spell of mild winter (December to February). The mean annual (air) temperature ranges from 24 to 27°C. The mean summer (April, May and June) and mean winter (December, January and February) temperatures vary from 30 to 33°C and from 15 to 22°C respectively. The mean annual rainfall ranges from 500 to 1500 mm, of which 80 to 90% is received during the monsoon period. It covers 42 to 77% of the mean annual potential evaporatranspiration (PE). The area experiences 4 to 8 months of dry weather in a year, when the soil moisture control section (MCS) remains dry, either completely or in parts, suggesting a ustic moisture regime (Figure 3) (Bhattacharjee and Landey, 1984).

The intermontane valley in northeast Iraq, supporting Xererts, has a subtropical semi-arid Mediterranean climate, and the Mesopotamian Plain, supporting Torrerts, has a hot subtropical desert climate. The mean annual (air) temperature and rainfall in northeast Iraq is 18.5°C and 765 mm respectively; it is 24.7°C and 136 mm in major parts of the Mesopotamian Plain. Here rainfall occurs from December to March (winter season) which is typical of a Mediterranean climate. The summer and autumn (June to November) are dry in most years. The MCS remains dry for about 4 to 5 months in the northeast sectors, and almost throughout the year in the central Mesopotamian Plain, suggesting xeric and torric soil moisture regimes respectively (Figure 3) (Sehgal *et al.*, 1980a, 1980b).

Characterization

Typical Usterts of the central peninsula, India

Usterts occur extensively in central peninsular India and are represented by many soil series, including the benchmark soils of Kheri, Linga, Aroli, Sarol and Mimone. The salient morphometric, physical and chemical characteristics of these soils are given in Table 2.

Typical Usterts are deep (100 to 150 cm) and clayey. Their colour is predominantly in hues of 10YR with values of 4 (dry) and 3 (moist) and chromas of 2 and/or 3 (dry and moist) (Table 2). The soils are classified as Chromusterts (NBSS, 1982a).

The Kheri, Linga and Aroli series are found in the subhumid tropics and experience a hyperthermic temperature environment. They occur on the level to very gently sloping piedmont and flood plains of the Wardha and Narmada river systems, and receive assured rainfall ranging from 1000 to 1500 mm p.a., with moderate to considerable runoff in the monsoon season, resulting in moderate to severe erosion. Runoff and soil-loss studies on some soils comparable to the Aroli series with bunded fields (used as a normal soil conservation practice) under cotton and sorghum crop covers indicate an annual soil loss of 12-15 ton/ha/yr, which occurs from runoff amounting to 15-20% of the total rainfall. During dry periods, the soils crack, with widths ranging from 2 to 5 cm, separating the surface 30 to 40 cm soil mass into hard, massive, deep prism-like blocks (polyhedrons).

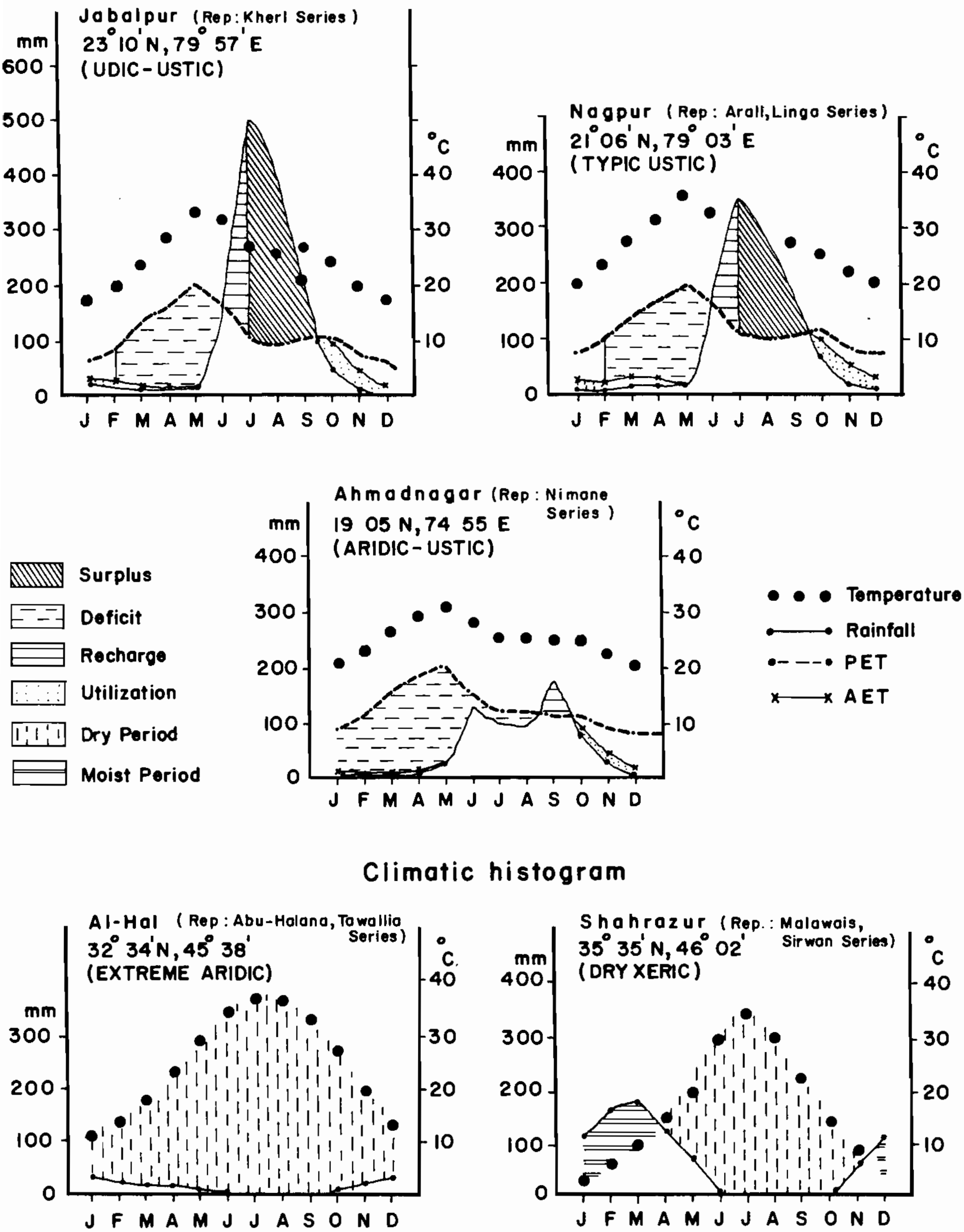

Figure 3. Climatic data and water balance (*Bioclimatic Bulletin of India*, 1982, and Sehgal *et al.*, 1980).

Table 2. Morphological and physicochemical properties of some Vertisols in India.

Horizon	Depth (cm)	Colour	Texture	Structure	Slicken-sides/ pressure faces	Particle size (%) Clay	Silt	Bulk density (dry)	COLE	AWC mm/m	pH	O.M. (%)	CaC03 (%)	CEC me/100 g	Exch. cations (% of CEC) Ca	Mg	Na	ESP	Mineralogy	Other special features
	Morphological characteristics*				Physicochemical properties															Other features
KHERI clay (Typic Chromusterts) Location: Jabalpur district, M.P.; 23°10'N 79°57'E Drainage: Moderately well to imperfect																				
Surface	0-37	10YR 3/2	c	2m pr 2msbk	–	62.6	22.6	1.85	0.11	220	7.2	0.41	Tr	53.9	> 40	> 42	–	–	MT 5 MI 2 CL 2 KK 1	Cracks 2-3 cm wide, brittle surface crust
Subsoil	37-129	10YR 4/2	c	3cabk	Prominent slicken-sides	63.9	19.8	1.95	0.14	–	7.5	0.26	2.6	49.5	–	> 50	–	–	–..–	Common basalt fragments
Sub-stratum	129-150	10YR 4/2	c	2cabk	Common slicken-sides	65.7	20.6	2.07	0.11	–	8.1	0.26	4.7	53.7	–	–	–	–	–..–	Common basalt fragments
LINGA clay (Udic Chromusterts) Location: Nagpur district, Maharashtra; 21°6'N 79°3'E Drainage: Imperfect/poor																				
Surface	0-16	10YR 3/2	c	3cabk	–	74.6	20.6	–	0.18	227	8.3	0.51	1.9	59.3	> 60	–	–	8	Montmoril-lonitic	Cracks 3-5 cm wide, thin surface crust
Subsoil	16-117	10YR 3/2-2.5Y 4/2	c	3cabk	Well-developed slicken-sides	74.3	17.1	–	0.18	–	8.2	0.46	5.3	63.2	–	> 50		7	–..–	Well-developed parallel piped structure
Sub-stratum	117-140	2.5Y 4/2-2.5Y 4.5/2	c	3cabk	–..–	70.9	19.0	–	0.16	–	8.1	0.27	8.5	65.1	–	–	–	6	–..–	Few basalt fragments
AROLI clay (Typic Chromusterts) Location: Nagpur district, Maharashtra; 21°8'N 79°4'E Drainage: Moderate																				
Surface	0-42	10YR 3/2	c	3m-cabk	Weak pressure faces	67.4	29.7	1.75	0.09	176	8.4	0.38	4.7	57.9	> 60	–	–	–	MT 5 MI 2 CL 2 KK 1	Cracks 3-4 cm wide, gilgai relief
Subsoil	42-67	10YR 3/2	c	3cabk	Strong inter-secting slicken-sides	58.9	32.8	1.90	0.09	–	8.4	0.31	1.6	54.5	–	> 50		–		Faint dark brown mottles
Sub-stratum	67-190	10YR 3/3-10YR 7/3	c	3cabk	Strong inter-secting slicken-sides	57.1	31.9	2.0	0.07	–	0.5	0.12	15.3	56.1	–	–	–	–		Common lime pockets

Table 2. (Continued)

Horizon	Depth (cm)	Colour	Texture	Structure	Slicken-sides/ pressure faces	Particle size (%) Clay	Particle size (%) Silt	Bulk density (dry)	COLE	AWC mm/m	pH	O.M. (%)	$CaCO_3$ (%)	CEC me/100 g	Exch. cations (% of CEC) Ca	Exch. cations (% of CEC) Mg	Exch. cations (% of CEC) Na	ESP	Mineralogy	Other special features
	Morphological characteristics*					Physicochemical properties														Other features
					SAROL clay (Typic Chromusterts); Location: Indore district, M.P.; 22°43′N 75°48′E Drainage: Moderately well drained															
Surface	0.29	2.5Y 3.5/2	c	2msbk	–	57	31	1.89	0.16	230	8.0	0.37	1.8	49.0	70	–	–	8	MT 5 MI 2 CL 2 KK 1	Cracks 3-4 cm wide, loose granular mulch; gilgai microrelief
Subsoil	29-147	2.5Y 3.5/2	c	3m-cabk	Prominent inter-secting slicken-sides	56.1	35	1.96	0.16	–	8.1	0.30	2.7	54.0	–	> 35		8.7		Parallel piped structures
Sub-stratum	147-160+	2.5Y 3.5/2	c	3mabk	Moderate slicken-sides	52.5	38.1	2.0	0.16	–	8.2	0.27	14.9	43.5	–	–	–	11		
					NOMONE clay (Typic Chromusterts); Location: Ahmednagar district, Maharashtra Drainage: Moderate to imperfectly drained															
Surface	0-47	10YR 3/2	c	2msbk-abk	Faint	49.39	27.39	1.81	0.12	200	8.35	0.54	6.60	35.45	> 80	–	–	0.12	MT 5 MI 2 CL 2	Cracks 3-4 cm wide, loose granular mulch
Subsoil	47-107	10YR 2/2-10YR 4/4	c	3cabk	Strong well-developed slicken-sides	53.83	28.87	1.80	0.15	–	8.5	0.40	9.68	35.23	–	> 50	–	0.26		Strong parallel piped structure; many basalt fragments coated with lime; few yellowish brown mottles
Sub-stratum	107-155	10YR 4/3, 4/4	gc	2msbk	–	52.32	20.16	1.56	0.17	–	8.65	0.29	17.23	35.10	–	–	–	0.21		

Source: *Benchmark Soils of India,* 1982, NBSS.
*Abbreviations as used in *Revised Soil Survey Manual,* 1978, SCS, USDA, and *Soil Survey Manual, All India Soil and Land Use Survey,* 1970.

These blocks break into hard and firm, subangular to angular blocky peds and these structural peds impose great limitations on normal tillage operations. The surface soils are covered by a 5 to 10 mm-thick crust, which is broken into fine particles by the heating action of the rain, and the crust seals the surface pores and partly moves into the cracks (Anonymous, 1986).

Among these soils, the soils of Kheri and Linga are more clayey (with more than 60% clay content) and are classified at the family level as very fine in texture. The Aroli soil series (like the Sarol and Nimone soils), however, have a slightly lower clay content (50-58%) and qualify at the family level as fine in texture (NBSS, 1982a).

Sarol soils occur in the transitional belt of the dry subhumid to semi-arid tropics with hyperthermic environments on nearly level to very gently sloping piedmont plain with assured rainfall from 800 to 1000 mm.

Nimone soils occur extensively in the dry semi-arid tropics with an isohyperthermic regime. They occur on a nearly level to very gently sloping piedmont plain. The area receives unassured rainfall of from 500-700 mm, covering only 42% of the PE.

The gilgai microrelief is a prominent feature of the Linga, Aroli and Sarol soils. The amplitude of microknolls over the microdepressions varies from 10 to 20 cm. Unlike the soils of the subhumid tropics (Kheri, Linga and Aroli series), besides cracking the Sarol and Nimone soils have a dark grey, 20-30 mm-thick pulverized granular surface mulch that partly covers wide open cracks (Bhattacharjee and Landey, 1984). The Vertisols having surface mulch have a comparatively friable and finer surface structure with more void space between the peds in the dry season than those without mulch (Blokhuis, 1982).

The dominant saturating cation on the exchange complex in the surface horizons of these soils is Ca^{2+}, except Kheri soils which are saturated with Mg^{2+} (Table 1). The presence of high Mg^{2+} (in Kheri soils) results in dispersion and probably leads to restricted drainage, and limited use for paddy followed by wheat cultivation.

The coefficient of linear extensibility (COLE) in general varies from 0.10-0.19 (Table 2). It is significantly higher in the subsoils as compared with the surface soil. The Linga soils show the highest value, indicating high swelling potential. The high swelling, coupled with Mg and/or Na saturation in most of the subsoils is suggestive of possible dispersion, resulting in limited root ramification and oxygen availability in the rooting zone.

Xererts of northeast Iraq

The soilscape in northeast Iraq, supporting Xererts, is an intermontane valley plain. The Xererts are represented by the soils of the Malawais and Sirwan series developed on calcareous alluvium (derived mainly from limestone, dolomite and marls) under semi-arid (submoist) thermal Mediterranean climate and supporting steppic grass vegetation (Sehgal *et al.*, 1980a). On the lower slopes with nearly level soilscape, Malawais soils are replaced by hydromorphic soils of the Sirwan series (Sehgal, 1980). The soils are very deep, dark-coloured, and clayey, with a relatively high CEC. Ca^{++} constitutes the dominant saturating cation on the exchange complex (Table 3).

Table 3. Morphological and physicochemical properties of some Vertisols in Iraq.

Morphological characteristics*						Physicochemical properties														Other features
Horizon	Depth (cm)	Colour	Texture	Structure	Slicken-sides/ pressure faces	Particle size (%) Clay	Silt	Bulk density (dry)	COLE	AWC mm/m	pH	O.M. (%)	$CaCO_3$ (%)	CEC me/100 g	Exch. cations (% of CEC) Ca	Mg	Na	ESP	Mineralogy	Other special features
					MALAWAIS silty clay (Palexerollic Chromoxererts); Location: 8 km from Said-Sadia to Arbel Road Drainage: Poorly drained															
Surface	0-38	7.5YR 3.5/4	sic	2m sbk-cr	–	50	43	1.55	–	179	7.9	1.3	11.4	42.2	–	–	–	2.3	Montmoril-lonitic	Angular rock fragments, self-mulching
Subsoil	38-61	5YR 3/3	c	2m pr	Common slicken-sides	49	39.0	1.8	–	–	8.0	–	11.2	43.0	–	–	–	2.3		Patchy dark clay coatings
Sub-stratum	61-166	5YR 3/3-7.5YR 3/4	c to sic	2m pr	Common slicken-sides	42	52.0	–	–	–	8.0	–	18.6	36.1	–	–	–	2.7		Fine lime mycellium; clay coatings on ped faces; few charcoal pieces
					SIRWAN silty clay (Auentic Chromoxererts); Location: 1 km from Sirwan village Drainage: Imperfect/poorly drained															
Surface	0-22	10YR 3/1	sic	m cr-abk	–	–	–	–	–	180	–	–	–	–	–	–	–	–	Montmoril-lonitic	Self-mulching seen at places
Subsoil	22-70	10YR 3/2	sic	2m sbk	Moderately developed slicken-sides	51	44	–	–	–	7.55	0.96	25.0	40.8	–	–	–	0.6		Lime nodules and mycellium, few Fe-Mn reduction mottles
Sub-stratum	70-120+	10YR 3/3	sic	2m pr m	Thick clay coatings	49	44	–	–	–	7.7	0.61	30.2	36.4	–	–	–	0.7		Diffuse organic black Fe-Mn mottles; common lime mycellium
					ABU-HALANA silty-clay (Salorthidic Torrerts); Location: Nomania area 32°34'12"N, 45°38'18"E Drainage: Imperfectly drained															
Surface	0-17	10YR 6/3-10YR 4/3	sic	1f-mabk pl.	–	49	49	1.47	–	232	7.0	1.05	26.6	23	–	–	48.6	28.9	Montmoril-lonitic	Microgilgai relief, well-developed cracks; moderately developed slickensides
Subsoil	17-57	10YR 5/3-10YR 4/3	sic	1f-mabk pl.	Common slicken-sides	53	46	1.46	–	–	7.2	0.67	25.8	25.0	–	–	52.8	10.0		A few salt efflorescences on ped faces; a few gypsum veins
Sub-stratum	57-123	10YR 4/3, 4/4	sic	if-m c-mabk pl.	Common moderate to weakly developed slicken-sides	48	50	1.48	–	–	7.6	0.59	25.4	26.0	–	–	63.3	40.2		A few gypsum crystal veins

Table 3. (Continued)

Horizon	Depth (cm)	Colour	Texture	Structure	Slicken-sides/ pressure faces	Particle size (%) Clay	Silt	Bulk density (dry)	COLE	AWC mm/m	pH	O.M. (%)	$CaCO_3$ (%)	CEC me/100 g	Exch. cations (% of CEC) Ca	Mg	Na	ESP	Mineralogy	Other special features
*Morphological characteristics**						*Physicochemical properties*													*Other features*	
TOWAIJIA silty clay loam (Fluventic Torrerts); Location: Suwaira area; 31°5′7″N; Drainage: Moderately well/imperfect																				
Surface	0-25	10YR 5/3	sic	lf – m sbk, pl.	Few pressure faces in 7-25 cm	–	–	–	–	220	7.6	0.88	27.6	22.0	–	–	–	4.3	Montmorillonitic	Characterized by cracks, very hard crusty surface; a few salts on ped faces, weakly developed gilgai relief;
Subsoil	25-92	10YR 5/3, 4/2	sic-c	lf-cpr mabk	Few slicken-sides	59	38	–	–	–	7.6	0.50	24.9	22.6	–	–	–	7.2		Partly decomposed roots
Sub-stratum	92-165	7.5YR 4/4-10YR 3/3	sic-c	1 pr 2 mabk	Few weak pressure faces	59	39	–	–	–	7.9	0.40	26.1	25.6	–	–	52.6	17.9		Bands of sandy stratified material; few mottles of 5YR 5/2, few gypsum, mycellium and crystals

Source: 1. The soils of the Middle Tigris Project (Mesopotamian Plain) for land-use planning by Jawanhar L. Sehgal *et al. Soils Bulletin* Feb, 1980. Directorate of Soil Investigations and Land Classification, Baghdad, Iraq.
2. *Soil Survey Report – The Soils of the Shahrazur Area (NE Iraq) and their Suitability for Land-Use Planning,* by Jawahar L. Sehgal *et al.* 1976. Bureau of Soil Studies and Design, Baghdad, Iraq.

*Abbreviations as used in *Revised Soil Survey Manual,* 1978, SCS, USDA, and *Soil Survey Manual, All India Soil and Land-Use Survey,* 1970.

The Malawais soils have a hue of 7.5YR or redder and chromas of 3 to 4, whereas the Sirwan soils have a hue of 10YR throughout the chromas of 2 or more, except in the surface horizon where the chroma is 1. This is because of flooding in the area. The Malawais soils with a higher chroma indicate relatively better drainage conditions than the Sirwan soils. In the dry period (June to November), the soilscape develops cracks (10-15 cm in width) and gilgai microrelief with linear frequency of microknolls and microdepressions occurring at intervals of 100 cm or so. The deep cracks separate the soil into massive prism-like blocks (polyhedrons), about 30 cm deep, that break into hard to very hard and firm angular blocky peds. The dark brown, clayey, slightly alkaline subsoils show a typical prismatic structure, breaking into blocky peds with slickensides close enough to intersect. These features are characteristic of these soils.

The soils of Sirwan, on the other hand, show evidence of hydromorphic characteristics, such as rusty root channels, Fe-Mn nodules, distinct dark mottles, and high groundwater (< 1.5 m) (Table 3).

Torrerts of the Mesopotamian Plain, Iraq

The Torrerts, represented by the soilscapes of the Abu-Halana and Towaijia series, are deep, calcareous, imperfectly drained, and strong to moderately saline. They occur in the shallow basin (Playa) of the Mesopotamian Plain under extreme hot and arid environments.

The Abu-Halana soils are highly calcareous throughout with a salic horizon at their surfaces. The soils crack and have gilgai microrelief with a dendritic, gully-patterned landscape (Figure 4). The detailed morphometric features along with the physical and chemical characteristics are given elsewhere (Sehgal *et al.*, 1980a). The groundwater table varies from 123 cm to 80 cm from the surface. These soils are comparatively more saline (ECe 34.8 mm/hos/cm) than Towaijia soils (ECe 13.5 mm/hos/cm) (Table 3). The Abu-Halana soils are uncultivable, while those of the Towaijia series are cultivated for wheat, but give poor yields.

The weighted means of some important soil properties calculated on a number of pedons occupied by Usterts, Xererts and Torrerts are given in Table 4.

Pedogenesis

Parent material that is primarily basic in nature and which contains a high proportion of alkaline earth, favouring the development of the smectite group of minerals, is essential for the genesis of Vertisols and vertic associates. The high coefficient of expansion and contraction of these minerals results in a three-dimensional volume change of soil mass during alternate wet and dry cycles, as conditioned by the climatic environments and topography. The net result is the development of deep and wide cracks with or without gilgai microrelief. Simultaneously, the volume changes set up a cyclic movement of soil materials (autoinversion) to cause vertical mixing (pedoturbation) of the soil material. Such phenomena cause one mass to slip over another, resulting in the formation

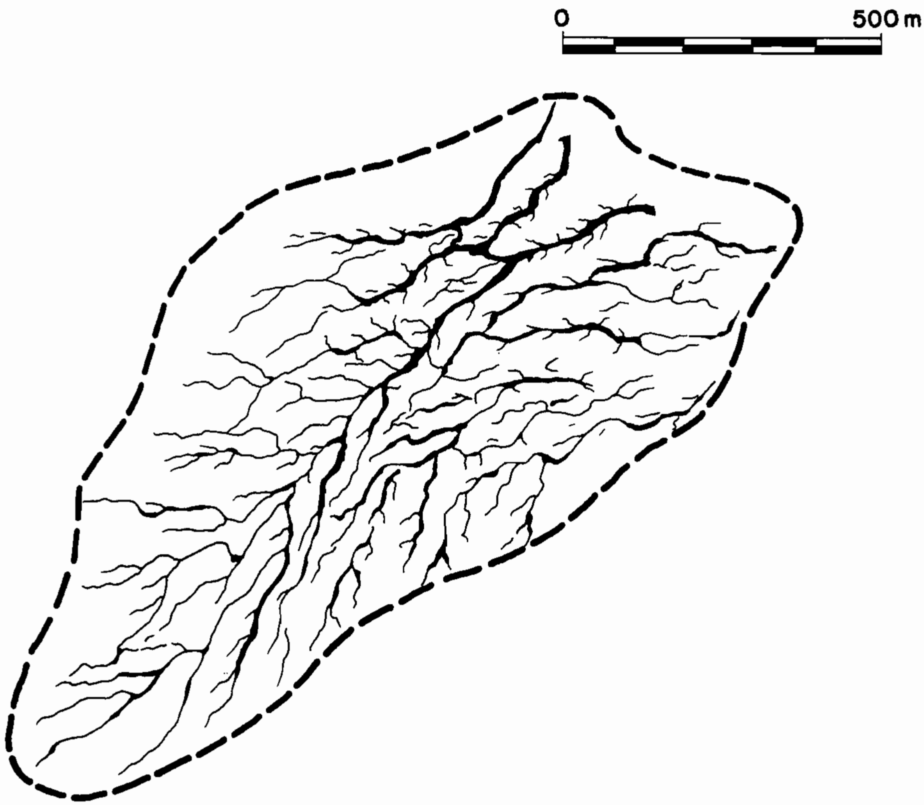

Figure 4. Dendritic gullied pattern.

Table 4. Brief resume of physicochemical properties of Vertisols from India and Iraq.*

Soils	pH (1:2.5) H_2O	CEC me/100g	Base saturation %	Clay %	Bulk density g/cc
Typic Chromusterts	8.2	53.0	100.0	58.3	1.75
Typic Pellusterts	8.7	66.0	97.0	64.0	–
Palexorollic Chromoxererts	8.0	39.9	–	46.3	1.80
Aquentic Chromoxererts	7.6	38.5	–	50.0	–
Salitorrert	7.3	24.3	100.0	49.3	–

*Weighteu means from several pedons within each soil group.

of slickensides in the lower part of the pedon (Bhattacharjee *et al.*, 1977). The slickensides intersect or are close enough to intersect, resulting in wedge-shaped structural aggregates which constitute the most characteristic feature of Vertisols (Figure 5). The slipping occurs when shear strength is surpassed by shear stress caused by swelling acting upon a soil mass. The shear stress is a major force that develops when volume expansion results in soil pressure during the wet cycle, and the tensile stress develops upon soil shrinkage during the dry cycle (Blokhuis, 1982).

The deep wide cracks separate the soil into strong and massive prism-like blocks in the upper part of the pedon that break into angular blocky peds which have a hard and firm consistency.

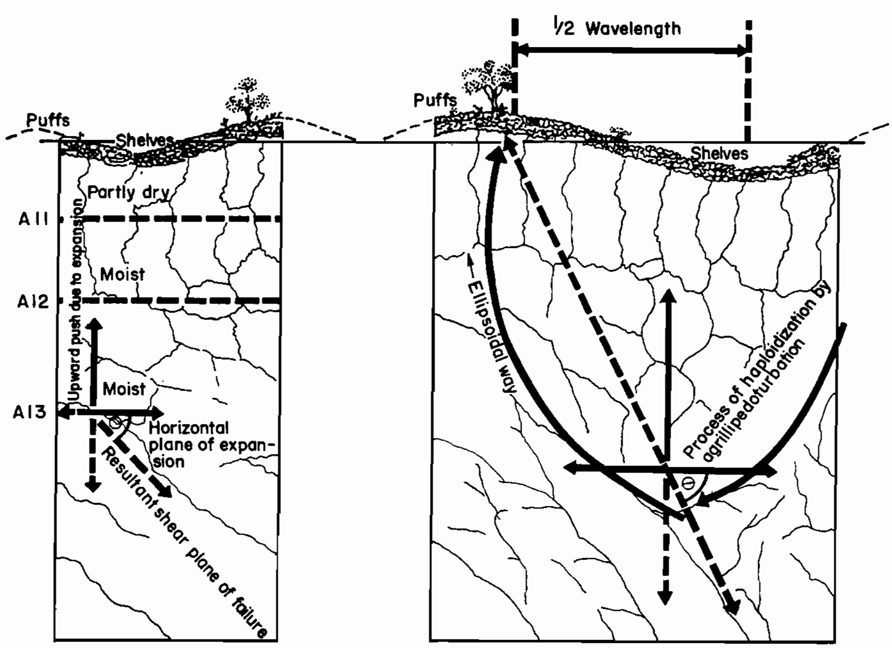

Figure 5. Mechanism of pedoturbation forming gilgai microrelief and slickensides in Vertisols.

Taxonomic Problems – Some Considerations and Criteria

Soil temperature regime

The principal climatic parameters are temperature (including air and soil temperature) and precipitation. Variation in any of the principal parameters affects the significance of the others, resulting in different rates of evapotranspiration, crop phenology and biomass production. Flohn (1969) considered that global radiation, albedo and radiation balance on the one hand, and duration of flows of sensible heat and of latent heat from soil to atmosphere and vice-versa on the other, are of vital importance.

The striking feature of the climate of central peninsular India is the sharp rise in air temperature from March onwards. The highest temperatures are reached during the months of April, May and June when the environment remains dry. The MCS during this period remains completely dry and the growth of mesophytes is not possible (NBSS, 1982). The summer monsoon sometimes arrives in the second half of June. The temperature drops sharply, and remains more or less consistent throughout the entire monsoon period (June-September). The temperature drops further during the postmonsoon period. The summer is the period when the temperatures are highest. Since the temperature during the monsoon period (June-September) drops significantly, these months should not be considered as summer months. This being so, the MST should be based on the mean monthly temperature of April, May and June – and not on June, July and August as defined in *Soil Taxonomy* (1975). Strahler and Strahler (1978) have made similar observations.

In India, the mean annual soil temperature (MAST) is calculated by adding 3.5°C to the mean annual air temperature in areas located below latitude 18°N, by adding 2.0°C to areas located between latitudes 18° to 23°N, and by adding 1.5°C to areas located above 23°C (NBSS, 1982b).

For calculating the mean summer and mean winter soil temperatures (MSST, MWST), we need to add 2.5°C to the MWT (air) and substract 2.5°C from the MST (air) to arrive at the mean difference of the temperatures at 50 cm depth which define 'iso' and 'noniso' soil temperature regimes.

The differences between the MSST and the MWST, calculated using NBSS (1982), *Soil Taxonomy* (1975), and SMSS/USDA (1981) criteria, are presented in Table 5. The data show no significant differences between the two approaches (NBSS and *Soil Taxonomy)* for computing the 'iso' and 'noniso' temperature regimes. However, the data show significant differences using the SMSS approach. The difference between the MSST and the MWST suggests a nonisohyperthermic temperature regime for Indore, Najpur and Jabalpur, and an isohyperthermic regime for the Ahmednagar station using NBSS and *Soil Taxonomy* criteria. However, the SMSS approach suggests a nonisohyperthermic temperature regime for the Ahmednagar station. Consequently it would seem that the NBSS criteria (NBSS, 1982) holds good for logistic calculation of the temperature regime under Indian conditions.

Table 5. Soil temperature regime of Vertisols.

Station (location)	Air (°C) MAT	Air (°C) MST	Air (°C) MWT	Soil (°C) MAT 1 NBSS	Soil (°C) MAT 2 SMSS	Soil (°C) MAT 3 *Soil Taxonomy*	Difference (°C) (MSST & MWST) *1 NBSS	Difference (°C) (MSST & MWST) *2 SMSS	Difference (°C) (MSST & MWST) *3 *Soil Taxonomy*	Soil temperature regime 1 NBSS	Soil temperature regime 2 SMSS	Soil temperature regime 3 *Soil Taxonomy*
India												
Jabalpur (for Kheri)	25.2	31.8	18.7	27.2	27.7	–	8.1	8.7	7.8	Hyperthermic	Hyperthermic	Hyperthermic
Nagpur (for Aroli, Linga)	26.8	33.4	21.6	28.8	29.3	–	6.8	7.9	7.0	Hyperthermic	Hyperthermic	Hyperthermic
Indore (for Sarol)	24.5	30.5	18.7	26.5	27.0	–	6.8	7.9	7.0	Hyperthermic	Hyperthermic	Hyperthermic
Ahmadnagar (for Nimone)	25.4	29.7	21.5	27.4	27.9	–	3.2	5.4	4.9	Isohyperthermic	Hyperthermic	Isohyperthermic
Iraq												
Shahrazur (for Malawais, Sirwan)	18.5	31.7	5.3	20.0	21.0	–	21.4	17.7	15.8	Thermic	Thermic	Thermic
Al-Hai (for Abu-Halana, Towaijia)	24.7	35.9	12.8	26.2	27.2	–	18.1	15.5	13.9	Hyperthermic	Hyperthermic	Hyperthermic

*1 NBSS (ICAR, 1982) MST – 2.5°C = MSST; MWT + 2.5°C = MWST
The season months were December, January, February, or April, May, June respectively for winter or summer months in the area.

*2 *SMSS Technical Monograph no. 2,* 1981 (p. 5) The amplitude of temperature variation at 50 cm depth between winter and summer was reduced by 33% of the difference between the air temperature for the same season. The season months were December, January, February, or June, July, August respectively for winter or summer in the northern heimsphere. But in this case April, May, June, which are the real summer months of the area, have been considered.

*3 *Soil Taxonomy* (1975) The summer months for calculation of the MST were the months with high temperatures in summer, while the MCS remains completely dry.

Soil moisture regime

From the water balance calculated according to Thornthwaite and Mather (1955) (see Figure 3), it is evident that there are significant differences in the quantum of moisture reserves in different regions. The number of dry months in the year varies from 3 to 7 in India, and 4 to 10 in Iraq. Accordingly, the areas with 3 to 7 months of dry spell can be classified as having ustic soil moisture regimes, and those with 10 months of dry spell as having aridic moisture regimes. The areas (northeast Iraq) with winter rain which remain dry for 4 months can be classified as having xeric moisture regimes.

The quantum of optimum moisture and the duration of moisture availability are some of the vital elements of a successful rainfed cultivation. Consequently, the apparent uniformity in moisture regimes (ustic, xeric and torric), as determined by the above criteria, may not have a practical application for rainfed agriculture. The data (Table 6) show that the percentage coverage of the potential evapotranspiration (PE) by rainfall ranges from 42 to 100% per year. The moisture index (IM) varies from –57 to 3.3 in the moisture regime of the ustic great group. Because of the differences in the length of dry periods, and the coverage of PE by rainfall, aridity, humidity and moisture indices, it is necessary to subdivide the ustic great group into udic, typic and aridic subgroups (Smith, 1979).

In *Circular Letter no. 1* of the International Committee on Moisture Regimes in Tropical Areas (ICOMMORT), it was proposed that soils with an (iso) hyperthermic or an isomesic temperature regime should be included in the "tropo" great groups, e.g. Tropaquods, Tropohumods, Tropaquolls, Tropudolls, Tropepts, etc. (Smith, 1979). However, in view of the varying crop responses on Chromusterts with isohyperthermic temperature regimes (Nimone series) and Chromusterts with hyperthermic temperature regimes (Sarol series), such a merger may not find a rationale under Indian conditions (Anonymous, 1986).

We believe that for practical considerations, the great group with a ustic moisture regime should be subdivided into aridic, typic and udic subgroups, based on the number of days the water is available in MCS. Hence soils with 'iso' or 'noniso' temperature regimes in which the MCS is partly or wholly moist for a specific number of days (when soil temperature at 50 cm depth is 8°C or more) can be classified as

aridic-ustic : MCS moist for less than 180 days
typic-ustic : MCS moist for 180 to 270 days
udic-ustic : MCS moist for 270 days or more.

In the case of the xeric great groups, the criterion proposed (Anonymous, 1981) for dry-xeric subgroups, namely that they are "soils in which the MCS is dry in all parts for more than 90 consecutive days during four months following the summer solstice", can be adapted as the climatic parameter (Table 6), and this allows the Malawais soils to be classified in dry-xeric subgroups. Similarly, the Torrerts can be classified as an extreme-aridic subgroup because of the prolonged dryness of the MCS (Table 6).

Table 6. Some climatic parameters of different stations in India and Iraq.

Station location	Elevation above MSL (m)	MAR (mm)	MAT (°C)	Max. summer temp. (°C)	Min. winter temp. (°C)	Percentage coverage of PE by rainfall	No. of dry months	No. of humid months	Humidity index (IH)	Aridity index (IA)	Moisture index (IM)	Moisture regime (subgroups)
India												
Jabalpur 23°10′N; 79°57′E	393	1448	25.2	39.4	9.1	100	3	3	47	–44	3.3	Udic-ustic
Nagpur 21°06′N; 79°03′E	310	1127	26.8	42.8	12.1	77	6	4	20	–43	–23	Typic ustic
Indore 22°0′N; 75°48′E	567	1085	24.5	39.9	9.9	60	6	4	13	–55	–42	Typic ustic
Ahmednagar 19°05′N; 74°55′E	657	677	25.3	39.4	13.1	42	7	2	0	–57	–57	Aridic-ustic
Iraq												
Shahrazur 35°35′N; 46°02′E	742	765	18.5	32.8	4.0	–	4	4	–	–	–	Dry xeric
Al Hai 32°34′N; 45°38′E	15	137	24.7	43.5	5.5	6	10	0	–	–	–	Extreme aridic

Soil depth

A minimum depth is essential for a soil to qualify as a Vertisol. During field surveys in the Vertisol areas, we rarely observed characteristic Vertisols on soil with a depth of 50 cm or less. We believe that a shallow soil depth does not permit the development of the characteristic structure in the subsoil. The deep wide cracks, prismatic- and wedge-shaped structures, and slickensides, which are the essential requirements of Vertisols, are not observed in shallow soils (< 50 cm depth).

Soil colour

According to *Soil Taxonomy,* the concept of "pell" and "chrom" is based on the prevailing drainage conditions. The Chromusterts are supposed to be better drained than Pellusterts. The criteria, viz. chroma (moist) of 1.5 or more for Chromusterts and less than 1.5 for Pellusterts, is arbitrary and not based on field reality. Intensive field study of such soils indicates that a chroma (moist) of 1.5 or more and chroma (moist) of less than 1.5 do not always represent well-drained and ill-drained Vertisols as envisaged in *Soil Taxonomy.* Many soils from central peninsular India and soils from Iraq show chroma of 2 or more, even though many of them are imperfectly to poorly drained. They are classified as Typic Chromusterts (Nimone, Dhanduka, Otur, Aroli series) of India and Chromoxererts (Malawais series) of Iraq. In contrast, many moderately to moderately well drained soils developed on basic metamorphic rocks showing chroma of less than 1.5 have been classified as Pellusterts (Table 7). Therefore the concept of "pell" and "chrom" in different situations of drainage and topography does not conform to the field reality. It is felt that chroma (moist) for better-drained Vertisols should be higher than 2, indicating oxidation potential in the soils in contrast to poorly drained soils, since drainage is a parameter which influences the agricultural use of the soils.

Table 7. Colour (chroma) and drainage condition in different taxa of Vertisols.

Soil series	Drainage	Chroma (moist)	Classification
India			
Nimone	imperfect	2	Chromustert
Umbraj	poor	2	Chromustert
Dhandhuka	poor	2	Chromustert
Sarol	moderately well	2	Chromustert
Malegaon	moderately well	1	Pellustert
Achamatti	imperfect	1	Pellustert
Raichur	moderately well	1	
Iraq			
Malawais	imperfect	3-4	Chromoxerert
Abu-Halana	imperfect	3	Salitorrert

Horizonation

The Vertisol profiles are generally designated as A-C profiles because of haploidization (Dudal, 1965, Buol *et al.,* 1973). But in view of the strong structural development due to swelling and shrinking phenomena there is a school of thought which believes that such soils should be designated as having A-(B)-C or A-B-C profiles rather than A-C profiles (Yalon and Kalmar, 1978; Singer, pers. comm. 1985; Eswaran, pers. comm. 1986).

The view taken here is that in most soils with cambic B horizons (structural and/or colour B), the organic-matter content decreases regularly with depth because of the pedogenesis. While colour and structural B horizons are predominant in Inceptisols, structural B horizons are generally observed in Vertisols, since in the latter the structural development results from the mechanical forces due to alternate swell-shrink phenomena, concomitant to accretion and depletion of moisture during wet and dry cycles. Although the organic-matter content in Vertisols remains almost uniform with depth, the structural aspects are well expressed. Such structural B horizons in Vertisols should be designated as vertic B horizons, such as argillic (Bt), spodic (Bhir) and calcic (Bca) horizons. Accordingly, a letter "v" could be suffixed to B to designate the vertic horizon as Bv and to highlight its vertic character.

Saline cracking clay soils

Torrerts, by definition, are Vertisols with a torric moisture regime. They have high clay (> 30%), cracks (1 cm or more wide at 50 cm depth) and slickensides close enough to intersect (Soil Survey Staff, 1975). Many such soils with gilgai microrelief have developed locally on alluvium in close depression areas of Mesopotamia, which are flooded once every few years by runoff from higher areas. Harris (1958) reported that montmorillonite and mica are the main constituents in gilgaied Tigris soils. Some such soils in Mesopotamia (Abu-Halana series) have an accumulation of salts at their surface, or within 75 cm of the surface, and may qualify as having a salic horizon. The most likely source of salts is the saline groundwater which renders the soil saline as a result of capillary rise. The high salts are generally associated with restricted or poor permeability. Although the system provides phases within a taxonomic unit to take account of high salts, yet we believe that a high salt content, when associated with poor permeability resulting from the swelling of clayey soils, may restrict the easy removal of salts and hence make the reclamation process difficult.

Such soils, according to the current class definition, are classified as Torrerts or Salorthids (if the salts are high enough to qualify as having a salic horizon) or both. The Torrerts enjoy priority over Salorthids in exemplifying such soils (Soil Survey Staff, 1975) as the cracking clay properties are of a permanent nature. Accordingly, such soils are classified as Typic Torrerts. But this does not clearly indicate their saline nature. The diagnostic horizons in *Soil Taxonomy* which are followed are of the great group level. Some comparable soils (saline with high ESP and clay) in the Indo-Gangetic Plain in India have been logically classified by introducing salic subgroups within Halaquepts, Natrustalfs, Natraqualfs, Natrargids, etc. (Sehgal *et al.*, 1975) to take into account a salt content which is high (1% or more), but not high enough to define the horizon as salic. For practical considerations, we proposed the introduction of a Salitorrert great group of Torrerts to complete the classification of Torrerts at the great group level.

On similar grounds, we propose Calcitorrerts, Gypsitorrerts, and Haplotorrerts. The modification proposed not only places due emphasis on the salic horizon but also appears logical and results in a better grouping for practical land use. This modification also finds support from the distribution of these soils on the landscape, with Salorthids occurring in close association.

Vertisols in India and Iraq have been classified in accordance with the existing class criteria, and this classification is given in Table 8.

Table 8. Classification of benchmark soils from India and Iraq.

Soil series	Locality	Soil Family			Subgroup
		Texture	Mineralogy	Temperature	
India					
Kheri	Jabalpur	Very fine	Montmorillonitic	Hyperthermic	Typic Chromusterts
Linga	Nagpur	Very fine	Montmorillonitic	Hyperthermic	Udic Chromusterts
Aroli	Nagpur	Fine	Montmorillonitic	Hyperthermic	Typic Chromusterts
Sarol	Indore	Fine	Montmorillonitic	Hyperthermic	Typic Chromusterts
Nimone	Ahmadnagar	Fine	Montmorillonitic	Isohyperthermic	Typic Chromusterts
Iraq					
Malawais	Shahrazur	Fine	Montmorillonitic	Thermic	Palexerollic Chromoxerert
Sirwan	Shahrazur	Fine	Montmorillonitic	Thermic	Aquentic Chromoxerert
Abu-Halana	Al-Hai	Fine	Montmorillonitic	Hyperthermic	Salitorrert
Towaijia	Al-Hai	Fine	Montmorillonitic	Hyperthermic	Fluventic Torrerts

Use and Management

In India, Vertisols and their associated vertic soils are widely cultivated under rainfed conditions. Rainfed crop husbandry is dependent primarily on some factors such as soil variability and management practices. The marked changes in volume associated with moisture changes pose problems in the use and management of these soils. The workability of these soils in the rainy season becomes poor because they become extremely sticky. Tillage operations are difficult in dry periods because of the development of wide cracks and a hard massive structure between the cracks. Consequently, these soils can be worked only under a narrow range of moisture conditions.

Sorghum, maize and pearl millet are the main cereal crops; pigeonpea, greenpea and chickpea are the main pulses; safflower is the main oilseed crop; and cotton is the main commercial crop. Recently, soybean has become popular in the assured-rainfall areas of central peninsular India. Wheat as a postmonsoon crop is grown at places on residual soil

Table 9. Grain yields (kg/ha) of sorghum and wheat grown on Usterts in central peninsular India.*

Crop and management	Soil series	SAROL	AROL	LINGA	KHERI	NIMONE
	Temperature regime	Hyperthermic	Hyperthermic	Hypthermic	Hyperthermic	Isohyperthermic
	Moisture subgroup	Typic-Ustic	Typic-Ustic	Typic-Ustic	Udic-Ustic	Aridic-Ustic
Sorghum (sole) (rainfed in rainy season)		2783	1838	2615	–	3860†
Wheat (sole) (irrigated farming in postmonsoon season)		3607	1874	2611	3192	3404

*Source: *Cooperative Benchmark Soils Project, India* (unpublished).

†With two protective irrigations at panicle and milk stages.

moisture with two life-saving irrigations; otherwise in the majority of cases it is grown under irrigation.

Sorghum is grown either as a sole crop or intercropped with pigeonpea in the rainy season, while postmonsoon sorghum is grown as the sole crop on residual soil moisture under traditional and improved management practices. Sorghum is grown as the sole rainy-season crop on Aroli, Sarol and Linga soils under assured rainfall, whereas it is grown on Nimone soils with two protective irrigations.

The yield of sorghum grown in the monsoon season and wheat grown in the post-monsoon season is given in Table 9. The higher yield of rainfed sorghum on isohyperthermic and aridic-ustic Nimone soils is attributed to two protective irrigations given at critical stages of growth; otherwise the yield would have been far less than from other soils. In the case of Aroli, Linga and Sarol soils, the MCS remains moist during the crop growth and consequently it shows no moisture-stress during the crop growth. From the foregoing it may be concluded that the Isohyperthermic Chromusterts give higher crop yields than the Hyperthermic Chromusterts. In contrast, wheat yield under irrigated farming in the postmonsoon season is higher on Chromusterts with a hyperthermic temperature regime than on Chromusterts with an isohyperthermic temperature regime.

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VERTISOLS IN EASTERN AFRICA

R.F. van De Weg*

Abstract

The paper outlines the extent and distribution of Vertisols in Kenya and Sudan, and discusses their morphology, chemical and physical properties, and classification, with specific examples from Kenya and Sudan. The use and management of Vertisols is reviewed in relation to tillage, irrigation, erosion, flooding, fertility and engineering problems.[1]

Environment

In Kenya, Vertisols occupy about 5% of the country, of which about 80% is in the semi-arid to arid regions. Most of them are scattered all over the country and occur on gently undulating peneplains ("uplands"), alluvial and volcanic plains, flood plains, valley bottoms, and bottom lands. They are developed on parent materials ranging from Precambrian Basement System rocks (ferromagnesian gneisses, etc.), volcanic rocks (basalts, etc.) to alluvial/colluvial deposits derived from various rocks (Muchena and Gachene, 1985).

In Sudan, Vertisols occur mainly on the western, central and èastern clay plains. They cover an area of approximately 500 000 km^2, constituting about 20% of the country. They occur under different climatic conditions, with precipitation ranging from 200-800 mm per year. They have developed on various parent materials of different modes of origin; in the central part on the alluvium of the Nile system, in the east on basaltic rocks, and in the west they were formed on residual and alluvial/colluvial material derived from the Nuba mountains (Hassan, 1985).

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* Netherlands Soil Survey Institute (STIBOKA), P.O. Box 98, 6700 AB Wageningen, Netherlands.

[1] This paper is based on the papers presented at the Fifth Meeting of the Eastern African Sub-committee for Soil Correlation and Land Evaluation held in Wad Medani, Sudan, 1983 (FAO, 1985) and on observations in Kenya and Sudan.

Properties of Vertisols

Vertic properties

Although cracks, gilgai, and slickensides are all referred to in the literature (FAO, 1985) as diagnostic properties of Vertisols, they are not always clearly recorded in the profile descriptions. There is no convention for describing cracks, and often they are not recorded in detail (width, depth, duration). In Sudan and Kenya, gilgai are often absent (or obliterated by cultivation). Slickensides are most commonly mentioned, and they are more pronounced ("intersecting") in the deeper parts of the soils.

Other morphological properties

The morphology of Vertisols exhibits in general a high degree of uniformity. The soils are usually deep and dark in colour to a considerable depth. In Kenya colours of low value (2-4) and chroma (2 or less) are predominant and usually extend to 100 cm. In Sudan, in the central Gezira, a colour contrast is seen within the solum, with a clear colour change with depth from 10YR 4/3 to 10YR 3/1. The cause of this colour difference is not yet clearly understood, and various theories have been put forward.

All Vertisols have a clay texture, predominantly montmorillonitic, ranging from 40-80% clay. Mottling is noted only in some depression Vertisols. In general, drainage appears to be based on permeability, and internal drainage is referred to as either poorly or imperfectly drained. Structure is generally described as coarse angular blocky to prismatic. Often the surface horizon consists of a thin (2-10 cm) loose surface mulch consisting of fine to medium granular/crumby and subangular blocky aggregates. The consistency is hard to extremely hard when dry, friable to extremely firm when moist, plastic and sticky when wet. The content, form, and depth of occurrence of calcium carbonate varies, both hard and soft. In Kenya, Vertisols in depressions have a greater depth (1-2 m) than those on slopes (50-100 cm). By and large, horizon boundaries are gradual or diffuse.

Physical properties

Little work has been done to assess the infiltration rates, permeability and water-holding capacity of Vertisols. Water retention is high. It is recognized that the available water content is low in contrast to other clay soils because the water content at both the field capacity and the permanent wilting point is high. Vertisols are described as extremely active clays, swelling and shrinking with changes in soil moisture.

Chemical properties

Organic carbon content is generally less than 2% at the surface, and decreases with depth below the surface. Total nitrogen is low, and available phosphorus is generally low in Sudan. pH is normally neutral to (slightly) alkaline. Both CEC and base saturation are high, with calcium usually being dominant. Vertisols in Sudan are generally nonsaline within the top 50 cm. Sodicity is, however, of more widespread occurrence than salinity.

Classification

When correlated with USDA and FAO/UNESCO systems of classification, the majority of Vertisols in Kenya become Pellusterts or Pellic Vertisols on account of their dark colours. In Sudan, Chromusterts are by far the most dominant group, but Pellusterts are dominant in the higher-rainfall areas in the south. When they occur in the same climatic belt, Pellusterts occupy slightly lower areas relative to the Chromusterts.

Attention is drawn to the useful distinction between Lithomorphic and Topomorphic Vertisols, differentiating those found over rocks on slopes from those formed due to topographic low-lying positions.

Some Examples from Sudan[2]

Pedons 1 and 2 (Suliemi series) – Gezira scheme

These two are distinguished from other pedons by a clear colour change with depth from 10YR 4/3 to 10YR 3/1 or 4/1. Horizon designation A-C is based on the colour change. Theories put forward as to the cause of this colour difference are:

- The whole profile was once dark and the colour has changed under the more arid climate of the north, causing "brunification". Depth of cracking controls colour change.
- The two colours represent different alluvial deposits, though there is no physical or chemical data to support this. Carbon dating shows no difference in the ages, both approximately 5-6000 BP.
- The dark colours are due to iron-manganese staining.
- The change is due to an increase in fine clay (not shown in analysis). Profile 1 had been under permanent fallow for at least 40 years and showed no obvious vertic properties at the surface.

Gezira Vertisols, in the old scheme area, have been under a 4-crop rotation (cotton, sorghum, wheat, fallow) for more than 40 years; in the newer scheme at Managil, the Vertisols have been under a 3-crop rotation with no fallow since 1958. Both groundnuts and vegetables are now included in rotations, especially onions and tomatoes. A massive land preparation exercise for cotton starts in December and continues until June, including deep ploughing to break up the structure, followed by discing, harrowing, etc.

[2] FAO (1985).

Pedon 6 (Shuheit series) – Gadambalyia scheme

Pedon 6 has been developed over weathered basalt, is situated in a rainfed farming scheme (2 million ha), and is particularly interesting as it shows a very clear horizon of massive structure, 10-15 cm thick, just below the surface. The area has been cultivated for some 40 years (sorghum, cotton, sesame) mostly by tractor, but the surface is only harrowed and has not been deep-ploughed for years, hence the compaction. The area is farmed by absentee landowners, often city merchants, who come at the beginning of the rains, cultivate, sow, then return for harvest. No fertilizers are used; weeding and harvesting are done annually, mainly by hired labour; residues are grazed. There are resident caretakers to guard the crops against itinerant herds migrating to green pastures. Pedon 6 is an outstanding example of compaction by machinery.

Some examples from Kenya[3]

The Vertisols in the Mwea-Tebere area have been developed on olivine basalt. These soils are separated on the soil maps from the black soils developed on Basement System rocks, rich in ferromagnesian minerals (hornblende gneisses). The latter in particular are not related to low topographic position, but can occur on any position in the landscape. The reason why red soils are found on certain places and black soils on others cannot be fully explained yet. One explanation may be that slight differences in mineralogical or chemical composition of the rocks occur which result in the formation of either black or red soils; another explanation may be the difference in structure of the rock. Stratified rocks (like the gneisses) may react in different ways, depending on the direction of the slope, perpendicular or parallel, in relation to the direction of stratification, resulting in different internal drainage conditions.

Use and Management

Vertisols have been partly used for grazing, and particulrly for dry-season grazing in depressions. They are also used for arable farming – by irrigation where water is available. Crops include rice, cotton, sugarcane, wheat, maize, sorghum, sunflower, beans, peas and soybeans, both rainfed and irrigated. The most detailed accounts of management concern irrigated sugarcane (Kenya, Sudan) and cotton (Sudan). Whether rainfed or irrigated, there are problems of cultivating Vertisols which either do not occur in other soils or do not occur to the same extent.

Tillage

The optimum moisture range for tillage is both narrow and, usually, of short duration, which means that the timing of tillage operations is crucial to the successful use of Vertisols. Their extreme hardness when dry makes cultivation with simple implements, e.g. hoe, very difficult. Consequently powerful machinery is required; but rough terrain, resulting from gilgai and cracks, causes heavy wear and tear and leads to machinery breakdown, and tyres can burst if they get wedged in cracks. Rain is needed to soften the surface and close the cracks. When wet, Vertisols are sticky, so the soil clings to tillage implements and tends to form clods on drying, making seedbed preparation difficult. Machinery is then needed to produce a fine tilth. If ploughed when wet, the soil is easily puddled, which causes compaction and thereby creates problems of poor aeration and root penetration; and machinery is liable to get stuck in the soil. Because rain is unpredictable, the farmer must be alert and prepared, and the requirement of both timing and procuring the necessary power to carry out cultivation makes machanized farming of large areas under rainfed conditions more difficult.

The maintenance of a good surface structure has been found essential for the successful use of Vertisols, and may be assisted by deep ploughing and by maintaining organic matter levels. In Kenya deep ploughing has been found to increase water intake and storage, and also to increase rooting depth and produce increased sugarcane yields.

In Sudan deep ploughing is carried out by tractors during the dry season while tractors also perform other tillage operations preparatory to cotton growing.

Irrigation

Under irrigation, the "shrinking" properties which close cracks also give an "automatic water acceptance rate" so that it is impossible to overirrigate Vertisols, provided external drainage is adequate and allows excess water to flow away. Otherwise water standing on the surface will cause poor aeration. Cracks also cause "variable point infiltration" leading to unequal rates of wetting the soil. Closure of cracks lessens losses, thereby increasing irrigation efficiency.

Erosion

Erosion occurs on slopes, particularly under the intense showers of early rains. Severe gullying can result even on very gentle slopes. In Kenya, for example, gullies 90 cm deep and 3 m wide frequently form after the early rains.

Flooding

Vertisols in topographic depressions are liable to flooding, though the incidence and duration of flooding can vary from year to year. Drainage can be a problem because many of these depressions are enclosed basins with no drainage outlet. Flooding reduces the range of crops that can be grown.

Fertility

Vertisols are generally considered to have a high nutrient content, good moisture storage, and to be more fertile than surrounding soils. This base status is high, but N fertilizer is required for most crops. Phosphorus availability is low, because of fixation due to the calcareous properties, and is usually marginal or deficient, as are some micronutrients. High sodium has been recorded in some Vertisols in Kenya, and yields have been improved using gypsum. In Sudan it was found that ESP values of up to 40 had no effect on cotton.

Engineering

The shrink and swell properties of Vertisols give rise to engineering problems which are particularly apparent in irrigation development. Inadequate foundations can result in dangerous cracks. Examples of this may be found in the buildings of the Sudan Soil Survey Administration headquarters, and in the labourers' houses in Ahero (Kano plain, West Kenya).

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THE VERTISOLS NETWORK: OBJECTIVES AND PLANS

J.R. Burford*

Abstract

IBSRAM's network for the improved management of Vertisols has the goal of achieving sustainable increased productivity on Vertisols by the development of improved management systems, initially in a broad African-Southwest Asian region. To achieve this goal, three major activities are planned: projects conducted by cooperators in national programmes, common methodologies for site characterization and experimentation, and dissemination of literature and other information on Vertisols to cooperators. During this workshop to launch the network activities, emphasis will be given to the final formulation of the network's first projects, and to reaching agreement on relevant common methodologies. Projects may consist of two types of experiments: a core management experiment, and side disciplinary experiments.

In preliminary discussions, the nominated national cooperators confirmed that the most widespread problem is the difficulty of manipulating these clay soils, especially with animal-drawn equipment. Lower in priority were difficulties due to variable rainfall, both drought and excess. The need for nutrient inputs appears to vary widely throughout the region, but there seems to be a need for studying the maintenance of fertility in a few well-chosen locations. Cropping systems research will also be required.

Topics that should be identified for some specialized discussion at the workshop are base data analysis, soil variability, and diagnosis of constraints.

* International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru P.O., Andra Pradesh 502324, India.

Introduction

Vertisols are potentially one of the most productive soils under rainfed agriculture in the semi-arid tropics (SAT), primarily because their high water-holding capacity assists crops to best tolerate the consequences of the rainfall variability that is a feature of the SAT. Yet actual productivity of rainfed crops on Vertisols varies greatly across the region. Crop yields under traditional systems are usually very low, often less than 1 t/ha. Only in a few specific situations have systems been developed that have a high productivity that also appears to be sustainable; in some others, current research is identifying the components that will ensure increasing productivity.

Improving the flow of information between those scientists and institutions who are actively conducting research on Vertisols will greatly promote the development of improved management systems on Vertisols throughout the region. This is the overall goal of the IBSRAM network. Achievement of this goal requires more than written or verbal communications: the major thrust will be achieved by projects conducted by cooperators from the national programmes participating in the network. Considerable depth will be given to projects by the adoption of common methods for analyses, monitoring, and site characterizations; this will facilitate comparisons and interpretations between results from different sites, and later between those from different areas of Vertisols. Additionally, there is a need for some commonality in the experimental approaches used in different projects. Hence, the initial objectives of the network will be to develop three major activities:

- Projects, initiated and conducted by national programmes.
- The use of common methodologies for site selection, site characterization, and experimental approaches.
- Dissemination of information on Vertisols amongst cooperating scientists and institutions.

Because cooperators' projects will be the essential building blocks of the network, the finalization of the project proposals will be the most important goal of this workshop. Obviously, to facilitate current planning and the initiation of these projects in the forthcoming year, this workshop will need to provide guidelines on common methods and approaches.

At this stage, projects may aim at solving components or subcomponents of an eventual system, as it is worthwhile at this point to consider the general systems approach.

Developing New Systems

The dramatic increases in productivity in irrigated agriculture that resulted from the introduction of new cultivars of rice, wheat and maize have led to the coining of the now commonly used epithet "green revolution". Dramatic though such increases were, they have in some respects delayed the development of improved systems under rainfed agriculture. For this, it was often assumed that water (or erratic rainfall) was the major limiting factor; but at this workshop examples will be presented of similarly large increases in productivity under rainfed agriculture (see, for example, the presentations by ICRISAT, ILCA, and ICARDA). Commonly the key components of the new systems are similar to those for irrigated agriculture, namely:

- o improved cultivars,
- o improved nutrient inputs, and
- o improved agronomy.

For the development of new systems, the crucial difference between irrigated and rainfed agriculture appears to lie in the importance of improved agronomic techniques to minimize the uncertainties caused in rainfed agriculture by variable soil moisture regimes. Improved agronomy appears to be all the more important in rainfed agriculture: until improved management techniques have been introduced, the full benefits of improved cultivars will not be achieved. Conversely, although research on management techniques will reveal the key components for improved systems, these may not be successful until improved cultivars become available. Relevant for this workshop is the recent release of a new sorghum cultivar in the Sudan; this may considerably assist current plans for improved soil management studies.

Although hopes may be expressed that a new successful system will be developed which would be sufficiently robust to transfer *in toto* from one area to another, this is likely to be feasible only over short distances, i.e. between completely analogous sites. Transferability, however, over quite large distances appears to be possible for techniques within components. Thus, within each project, we would not expect to be able to copy a complete system from elsewhere, but rather to compile one from a composite of components adapted from the most appropriate available components, perhaps from a number of separate, quite different locations.

Activities

Of the three main activities of the network, this workshop will address two – projects and methodologies. Some background is given below.

Projects

Project proposals are expected to contain the background information on the participants' target area, and to include an appropriate description of the tranditional and/or current agricultural systems, plus diagnoses of the major constraints and the current status of attempts to develop improved systems. Comments will be made later on this point.

The next step is the presentation of the proposed experimental approaches. At present, it is envisaged that there will be two main types:

- o A management experiment – in which the experimenter is testing possible systems.

- o Side component experiments – in which the experimenter is conducting disciplinary research on components of his proposed system.

It seems obvious that a project should combine both types of experimentation. The management experiment will assist in the identification of practical problems, and the component experiments will provide any information needed on important components of the management experiment.

For the types of treatments that might be considered in a component experiment, there is a very convenient example. The most widespread management problem, as we will see later, is the difficulty of preparing the land so that a crop can be sown at the optimum time; the need to use only animal-drawn equipment is an added constraint. Part of the experimentation to determine possible solutions could involve comparisons of several different types of equipment – which could include the most advanced, the most appropriate, and the farmer's common practice. Another part could involve comparisons of different timings of primary and secondary cultivation.

At this stage, projects that are primarily strategic in nature are only being encouraged if they have an application wider than the cooperator's own national target area.

Methods

For both types of project, the methods used for site characterization and for monitoring experimental variables need to be standardized, at least to the extent that results can be compared between cooperators within this network. Lack of such characterization and standardization is a major reason for our inability to interpret more fully many of the field experiments that have been conducted in the past. The use of appropriate common methods and approaches will assist in the comparison of results from different experiment sites, such as those which might be involved in the validation example quoted in the previous section.

Useful preliminary indications of the approaches to be considered in the standardization of methods were given in the group discussion on this topic at the inaugural Vertisol workshop at Hyderabad, and in the report of the Cameroon workshop. It is important to mention at this point that the common approaches also apply to site selection, and include the points covered in the first paragraph of the previous section.

Before going into the details of the previous suggestions on common methodologies, it is best to consider the likely priorities for research in the network.

Preworkshop Activities

Project proposals

Table 1 presents a summery of the tentative views of the proposed project cooperators in the middle of this year. Their perceptions of the constraints and priorities for national projects are most useful, even though they must be considered as tentative

Table 1. Network for Vertisol management

Country	Agencies	Environment		Major problems	Comments
		Altitude	Rainfall		
Botswana		Low	Low-med	Diagnosis, develop new systems	Active IBSRAM project not planned
Burundi		High	Medium	Tillage, equipment, crop systems, nutrients	
Ethiopia	IAR* MoA U o Alemaya ILCA ICRISAT	High (2800 m) Medium (2000 m) Low (1100)	1100 mm 900 mm 1000 mm	Drainage, tillage, implements, nutrients, crop systems	Coordination committee formed
Kenya	Soil Survey* KARI U o Nairobi	Medium Low?	550-1000 mm(?)	Water utilization? Maintaining fertility? Erosion?	
Pakistan	Soil Survey* PARC	Low	500 –900 mm(?)	Tillage, equipment, crop systems	Rice-based cropping system
Sudan	ARC	Low	650 mm(?)	Tillage, equipment, nutrients, water utilization	New cultivar available
Syria					
Tanzania	MoL&A TARO	Low Medium?	550 –1000 mm(?)	Tillage	
Zimbabwe	DRSS, MoA* U o Zimbabwe	Low	400 –650 mm(?)	Tillage, equipment, water utilization, crop systems	

*Indicates lead or coordinating institution.

(many cooperators were still in the process of collecting information from others in their country). As you can see from the report of the Cameroon workshop, an upgraded version of this table needs to be completed shortly after we finish the formal sessions of this workshop.

Expressions of interest

All potential cooperators confirmed their interest in the founding of the network. Especially useful were the comments heard from countries in which Vertisols are not a dominant soil. Agricultural development of these soils had been deferred because other soils were easier to work; but with adequate research and development on the more extensive soils, it was now time to study Vertisols. This is an interesting point, because it helps to explain the relatively small amount of research on Vertisols, and also the difficulty in gathering information.

Target environments

Most, but not all, countries have an adequate general delineation of their soils and agroclimates, so the different tracts of Vertisols can be given a priority for research under their network project. Particular mention must be made of the efforts in Zimbabwe, where detailed studies have been made to characterize the soil properties that are probably responsible for the marked differences in the management requirements of their Vertisols. This information was used, in conjunction with socioeconomic considerations, in deciding the target area for their network project. The target Vertisol has a self-mulching surface soil, a higher infiltration rate, and higher water-holding capacity than the other Vertisols examined in Zimbabwe.

Constraints

All cooperators stated that the most important management problem was the difficulty encountered in timely preparation of the soil so that seeding could be accomplished at the optimum time. The usual comment was that the soil was, in the words of the commonly quoted description, "too hard when dry, and too sticky when wet". The general difficulties encountered with tillage appeared to hinder clear appraisal of other constraints.

The next most general problem area is perhaps that arising from rainfall variability. In wetter environments, surface drainage is required to dispose of excess water. In the environments that have suboptimal moistures, better agronomic techniques are needed to minimize drought stress.

Interest was expressed in the development of improved cropping systems, especially in relation to variations in seasonal rainfall. Views on the role of nutrients varied widely; nutrients are an important component in at least two intended projects, but in others there is little evidence of their need, except for suggestions that they are involved in a decline of fertility under intensive cropping.

Experimental approaches

Potential cooperators showed a strong interest in validation approaches for evaluating improved tillage techniques and animal-drawn equipment. But for other topics there was some preference for disciplinary-oriented research. This perhaps reflects a need for a better diagnosis of problems.

Methods

A summary of the conclusions of the group discussion on methods (at the inaugural workshop) is given in Tables 2 and 3. Relevant points are:

1. Base data analysis and description of the existing agricultural situation were seen as being an essential part of project formulation and implementation.
2. Emphasis was given to physical measurements and characterization of the soil physical environment. This emphasis is supported by the priorities indicated recently by intending cooperators.
3. The need for common methodological approaches was considered to be sufficiently important that the committee recommended the convening of training workshops and compilation of a manual on this topic.
4. Several subject areas (land qualities) were identified where current methods needed improvement (Table 3).

Table 2. Standardization of methods for the Vertisols network – initial suggestions.

SITE SELECTION	
Base data analysis	Soil and agroclimatic data Cropping systems Agricultural systems Identification of problems
Interpretation	Extent of main soils Selection of target area(s)
CHARACTERIZATION OF EXPERIMENT SITES	
Description	Detailed soil map (scale > 1:1000) Representative pit(s) (?) Morphological description (s)
Sampling	Gilgais – importance noted By horizons
Analyses	'Standard' characterization analyses, including: pH, CEC, exchangeable bases, total N, organic C, electrical conductivity, SAR particle size analysis (including fine clay), carbonate (including that of clay-size), available water-holding capacity on undisturbed sample, COLE and bulk density of large units, moisture content at time of sampling, liquid limit, plastic index, dispersion index, exchangeable A1 (where soil pH < 5).

Table 3. Standardization of methods for the Vertisol network: Future research needed for land quality evaluation, etc.

LAND QUALITY	CURRENT DEFICIENCIES IN EVALUATION
Tilth	Monitor structural changes
Fertility	P availability, pH & Al in acid Vertisols
Water availability	Water content limits in relation to plant roots
Oxygen availability	Air-filled porosity
Root penetrability	Pore size and continuity
Potential erosion	Structure and cracks
Growing-season model	Water-balance model
Irrigability	
Drainability	
Trafficability	Effect of machinery on rheological properties
Salinity and sodicity	Critical levels of Na (and) salts

OVERALL RESEARCH PRIORITIES SUGGESTED

1. Changes in soil structure (and voids) with moisture changes.
2. Prediction of effects of natural conditions and management on crack and void development.
3. Water-balance models to assist with predictions for tillage, growing seasons, cropping patterns, irrigation needs, etc.
4. Available P methods for both rainfed and irrigated agriculture.
5. Critical air-porosity levels for key crops.
6. Precise field methods for detecting reduced field conditions in the field, including dyes (Dipyridyl?, benzidem, etc.).
7. For acid Vertisols, establish the interactions between effects of pH, Al, bases, and salts on plants.
8. For sodic Vertisols, establish the critical levels of sodium (with and without other salts) in the water regime.

RECOMMENDATIONS

1. To hold workshop training sessions on agreed standard physical methodologies.
2. To develop a document describing the minimum desirable information and methodologies for experimentation in the Vertisols network.

Future Actions

One of the great strengths of a network approach is that the regular gathering of cooperators from different countries facilitates the development of collective views. Below, I give suggestions on aspects that appear to need consideration at this meeting.

Overall strategies

One of the strengths in a farming systems approach is the emphasis that it gives to the need for adequate base data analysis and descriptions of existing systems, and I will elaborate on this point.

Methods

Base data analysis

Most countries have general soil and agroclimatic maps available (or in the process of completion) that give a general description of the soils and climatic resources, and are adequate for planning. Discussion is needed to check the adequacy of the existing information for site selection, and of the agroclimatic analysis for assisting with the selection of management options.

Current agricultural practices and diagnosis

Although general knowledge concerning current agricultural practices is well established, there is in some cases a need to ensure the availability of the detailed knowledge needed for the clear identification of constraints on Vertisols. This appears to reflect the lower priority given to Vertisols in the past; but such compilations and studies are highly desirable. The advantages can be seen from two examples from within this region, notably from Ethiopia and Sudan.

At high altitude in the highlands of Ethiopia, the 'giue' system was practiced in traditional farming. At the end of a long resting phase, perhaps 15-30 years of natural pasture, grass and manure were placed in regular heaps, about 1 per square meter, covered with soil, then ignited. Later the baked soil was spread evenly over the soil surface prior to ploughing and sowing a crop. In the first year, yields were excellent; much lower yields were obtained in the second year, after which the land was allowed to revert to a natural pasture for many years. Analysis of this system has provided useful clues concerning the constraints to introducing more intensive improved cropping systems.

Analysis of the apparently effective shifting cultivation system in the Sudan would seem to be warranted. In this, each cycle consisted of an alternation of cropping and grass-fallow phases, with about 4 years for each phase. At the end of the grass fallow, the grass residues were burnt (the 'hariq' system) providing excellent weed control for at least the first two years of the subsequent cropping phase.

I have given these two examples because they are relevant to the network. One main point is clear: although traditional systems may not now be as productive as more modern intensive systems, there can be valuable clues about constraints that we can learn from the traditional cultivators; after all, their systems presumably evolved in response to their identification of the constraints to effective cultivation.

Experimental methods

Table 2 gives a brief summary of topics and approaches suggested as being of importance, and it thus provides a useful list to consider in the group discussions.

Soil variability

Vertisols are noted for two particular types of variability – their shrinking into large (hexagonal) peds on drying, and gilgais. Both will need to be considered in the recommendations for sampling and other experimental techniques.

The importance of gilgais appears to vary greatly. There are well-documented examples of extreme heterogeneity in Australia, but there is little mention of this phenomenon causing problems amongst the current potential cooperators.

Analytical techniques

Methods currently available for chemical analysis seem to present little difficulty, though a reminder is given that the 'Bal' modification of the Kjeldahl method for determining total nitrogen was developed specifically for Vertisols.

The indicated importance of land preparation and structure indicates the need to give particular thought to the best techniques for soil physical characterization, especially soil moisture regimes and structure. Particularly important will be simple and reliable methods for some of the difficult soil physical measurements. Relevant for water measurements in Vertisols is their swelling and shrinking with changes in water content, and the fact that few experimenters make allowance for this.

Method development

Topics on which some method development may be required are indicated in Table 3. If any are relevant but are beyond the resources of a network cooperator, the emphasis which has been given them at this workshop may motivate external organizations to promote further development.

One particularly relevant aspect of methodology is soil water balances, which can help several of the proposed projects in the planning of experimental strategies – especially in the drier environments.

Experimental approaches

Discussion may be needed to establish any changes in views on the balance between management and disciplinary experiments in the network.

Themes

The widespread interest in improving the farmer's ability to work his soil and achieve timely seeding indicates a common theme for most projects – tillage equipment and techniques. A cropping systems component may also be desired.

For strategic research, a project in the general area of soil physics appears to be of the highest priority, because of the general importance of this field for validation projects. Aspects relevant to the management of Vertisols are the structure of the surface soil (e.g. crusting, self-mulching vs. massive), infiltration, erosion, water-holding capacity, ease of tillage, etc. Complementary to such studies could be long-term research in one or two well-chosen locations, to include other aspects of the maintenance of fertility.

For the drier environments, research should be encouraged into techniques to optimize utilization of rainfall, because of the general lack of information in this field.

Other aspects

Coordination within countries

Dr. Latham (these proceedings) has already indicated the need for a multidisciplinary approach, but this of course may also require coordination between institutions. Such coordination has been formally initiated in Ethiopia, as evidenced by Dr. Mesfin's appearance here as the chairman of the coordination committee. Less formal coordination is developing in other countries, and is encouraged because it can assist so much in overcoming difficulties due to a lack of resources. One point commonly overlooked is that joint projects can be achieved with virtually no loss in freedom of action, and considerable gain in quality of results from each partner.

Consultants and training

The use of consultants or training to provide additional expertise is another useful way of improving resources in a project.

Concluding Comments

The above comments have been compiled mainly on the basis of preliminary discussions with the network's prospective participants in the middle of this year, when all were still gathering information and developing ideas on project development. I would not like current participants to be held to tentative views that they then so freely gave, and which have been so invaluable in the planning for this workshop.

Second session: Site selection

Chairmen: Prof. K. Zake

Dr. S.M. Virmani

SELECTION OF SITES FOR THE VERTISOLS NETWORK: DISTINCTION BETWEEN TYPES OF VERTISOLS

P. Brabant*

Abstract

Particular attention must be paid to the selection of test sites for the Vertisol network if the results obtained are to be truly transposable from one region to another in the same country and from one country to another in the world.

To distinguish between different tropical Vertisols, it is advisable to use other criteria than the slope and soil colour criteria used in the classification systems (FAO, Soil Taxonomy, *C.P.C.S.*[1] *).*

The author recommends that priority be given to the following parameters: the soil moisture regime, the properties of the topsoil, the parent material and the risk of degradation. These are the characteristics that really distinguish between different tropical Vertisols, and they are often the main limiting factors for soil management. These propsals are based on soil mapping followed by detailed field studies in a semi-arid tropical zone.

Introduction

The establishment of a Vertisol network implies two main activities:

1. Selecting representative sites for measurement and experimentation.
2. Transposing the results obtained on these sites to other sites in the same country or elsewhere.

This second activity raises an important question. Are the Vertisols where we transpose the results the same type of Vertisol as those studied on the test sites? The

* L'Institut Français de Recherche pour le Développement en Coopération (ORSTOM), 213 rue La Fayette, 75010 Paris, France.

[1] Commission de Pédologie et de Cartographie des Sols.

answer to this question seems simple, because Vertisols are the most easily recognizable of all the soils in the world. Consequently one might think that it would be easy to find representative sites and then to transpose the results obtained.

The reality is different. There are in fact several types of Vertisol, and they differ widely enough to make it necessary to distinguish between them before the test sites are chosen. When seeking to identify Vertisols and make correlations between them from one country to another, the currently recommended procedure is to adopt the Vertisol definitions given in the commonly used classification systems: FAO, *Soil Taxonomy,* and French C.P.C.S. This may seem to be an adequate method for drawing up a general world inventory of Vertisols; but given IBSRAM's ultimate objectives, we need a procedure for distinguishing between the different Vertisol categories and selecting the network's test sites. The criteria proposed here are based on a recent study made in Cameroon.

Country Background

Cameroon is a central African country covering 475 000 km^2 and has a population of approximately 10 million. It includes three main ecological zones: a densely forested humid equatorial zone in the south, a zone of high plateaux with savanna and forest in the centre, and a semi-arid topical zone in the north. The first two zones have mainly Ferralsols, while the Vertisols are to be found in the third zone.

North Cameroon

This province covers 100 000 km^2, and the annual rainfall varies between 600 and 1400 mm; a continuous dry season lasting 6 to 9 months alternates with a rainy season that fluctuates from year to year. The most extensive Vertisols are to be found between the 600 and 900 mm isohyets; beyond the 1100 mm and up to the 1400 mm isohyet, Vertisols occur only on highly basic rocks. The entire province has been mapped on various scales. Thus we know that Vertisols cover 1 200 000 ha, divided between 300 polygons on the 1:500 000 soil map. That represents 12% of North Cameroon's land area and 2.5% of the total country.

Identification of the Different Types of Vertisols in North Cameroon

Using the definitions of the classification system

Looking at the descriptions given by the different classification systems, Vertisols are defined as having the following characteristics:

- o a 30% clay content, at least to a depth of 50 cm,
- o shrinkage cracks 1 cm wide to a depth of at least 50 cm, and

- o a gilgai microrelief or slickensides or wedge-shaped structural aggregates at depths of between 25 and 100 cm.

They are distinguished from each other in terms of the following features.

- o the colour, with a chroma, moist, more or less than 1.5,
- o the slope – gentle slopes or flat areas and depressions, and
- o the rate of saturation of the exchange complex, by calcareous nodules (FAO system, 1985).

Table 1 shows the results we obtain for North Cameroon's Vertisols using these criteria.

In general, the keys provided by the classification systems are adequate for distinguishing Vertisols from the other soils of North Cameroon. In the field, the French C.P.C.S. system has been found to give slightly more satisfactory results than the two other systems, but none of the systems includes the most important parameters in its definitions, i.e. those which ultimately determine the management of tropical Vertisols. For example, the Pellic Vertisols category includes Vertisols which may differ very widely in their main limiting factors for land use – the control of flooding water for some, gully erosion for others. It is very surprising, then, to see that soil scientists only identify two types among the 1 200 000 ha of Vertisols in North Cameroon, when uneducated local farmers easily identify five or more types of Vertisols and give each a special name: "yaeres", "karal", "karal muskuari", etc.

Using other parameters

To distinguish Vertisols from other soils, we continue to use the criteria which were listed above, i.e. textural and structural properties, shrinkage cracks, etc. A Vertisol always consists of a single horizon, and in Cameroon we have called this the Sv horizon, S being more or less synonymous with "cambic" and v expressing the vertic feature. The Sv horizon contains organic matter in its upper part, except where the soil is eroded.

To differentiate between one Vertisol and another and to choose representative sites for study, we have selected other parameters. These have been chosen on the basis of soil-mapping results, detailed catena studies, and observations of farming practices in the region.

Six parameters have been selected:

1. The landscape (and not merely the slope): alluvial plains or pediments,
2. The pedoclimate and hydrologic regime: dry or humid pedoclimate, with flooding or without flooding,
3. The parent material: recent or old clayey alluvia, acid crystalline rocks, basic rocks, limestone, argillite or marl.
4. The other soils and horizons associated with the Vertisols in the landscape: Fluvisols, Planosols, Cambisols, Regosols, etc.
5. The properties of the topsoil (0-25 cm) with regards to tillage: microrelief, cracks, clay content, structure.
6. The level of potential degradation: topsoil degradation, gully erosion.

Table 1. Types of Vertisols in North Cameroon.

FAO system 1975, revised 1985	
VERTISOLS (soil units)	
Pellic	Eutric
Chromic	Calcic

Soil Taxonomy		
VERTISOLS		Order
USTERTS		Suborder
Pellusterts	Chromusterts	Groups
typic	typic	Subgroups

C.P.C.S., France					
VERTISOLS					Class
TOPOMORPHIC			LITHOMORPHIC		Subclass
coarse	fine medium	Topsoil with structure	fine medium	coarse	Groups
–	–	typic	–	–	Subgroups
–	–	gleyic	–	–	
–	–	sodic	–	–	

Table 2. Characteristics of Vertisols in North Cameroon.

Landform	Parent material and pedoclimate	Associated soils (FAO)	Properties of the topsoil	Level of potential degradation	Primary limiting factor for management	Type Area in ha
Vertisols of alluvial plains	o recent deposits > 3000 yrs BP o clays, silty clays o pedoclimates: humid o flooding: > 5 mths.	o Gleysol o Fluvisol	o very large cracks (5-10 cm) o pronounced gilgai 50-80% clay o medium structure (under grassland)	Very low to low	Water control	1 490 000 ha
	o old deposits 300-10 000 BP o sandy & silty clays o pedoclimate: humid to dry o flooding: < 3 mths.	o Gleyic Solonets o Eutric Planosol o Albic Luvisol (Gleysol)	o large cracks (1-6 cm) o slight gilgai o 40-60% clay o coarse or fine structure	Medium to high Topsoil degradation	Water-balance deficit (years of low rainfall) and risk of topsoil degradation	2 450 000 ha
Vertisols of pediments	o alkaline or acid crystalline rocks o pedoclimate: dry o no flooding	o Gleyic Solonetz o Sodic Planosol o Albic Luvisol	o small cracks o slight gilgai or no gilgai o 20-40% clay o medium or massive structure	Very high Topsoil degradation and gully erosion	Topsoil Degradation	3 80 000 ha
	o basic rocks and limestone o pedoclimate: dry o no flooding	o Chromic Cambisol o Eutric Cambisol	o no cracks or small cracks o no gilgai o 30-45% clay o fine structure	Low	Water-balance deficit	4 30 000 ha
	o argilite, marl o pedoclimate: dry o no flooding	o Regosol o Fluvisol	o large cracks (3-5 cm) o slight gilgai or no gilgai o 60-70% clay o coarse structure	High Gully erosion	Gully erosion	5 20 000 ha

Along these lines, we have distinguished five main types of Vertisols in North Cameroon: two types in the alluvial plains and three types on the pediments. Their characteristics are shown in Table 2.

It should be noted that Vertisols of types 2 or 5, for example, include both Pellic and Chromic Vertisols, Chromusterts and Pellusterts. Also, an examination of Table 2 shows that the moisture regime, the properties of the topsoil, the parent material and the risk of degradation take precedence over colour and slope of terrain as characteristics of a tropical Vertisol.

Recommendations

The results obtained from a test site on type 1 Pellic Vertisols could not be transposed to type 5 Pellic Vertisols, for example. Similarly, the results obtained with type 4 Chromic Vertisols could not be transposed to type 2 Chromic Vertisols. This means that soil scientists in the Vertisol network should not restrict themselves to the classification system criteria, either in selecting sites in the first place, or subsequently when they are making correlations between the Vertisols of different African countries or between African Vertisols and those of other continents in the semi-arid zone (India, Uruguay and Argentina, for example). As a matter of general policy, IBSRAM should pay special attention to the correlation between the test sites of the Vertisol network.

SOIL-SITE CRITERIA FOR SELECTING EXPERIMENT SITES FOR A VERTISOL MANAGEMENT NETWORK

Jawahar L. Sehgal, S. Vadivelu, L.R. Hirekerur and S.B. Deshpande*

Abstract

In India, the dark-coloured, deep, cracking clayey Vertisols and associated vertic soils occur extensively in the peninsular region. They have varying properties. For the selection of sites for agronomic experiments to test technologies for subsequent successful transfer to similar areas, the properties of Vertisols and the environment in which they occur have to be taken into account. In this paper, soil properties, land qualities, climatic parameters, crop plants, management levels and general features are discussed, and criteria based on the most important soil-site characteristics are proposed for consideration.

Introduction

The basic purpose of conducting experiments is to transfer the technologies developed in the experiment sites to similar sites in the region. Therefore the experiment site should be so selected that it represents wide areas in the region defined in terms of the soilscape characteristics and the environmental parameters. To facilitate a fair selection of experiment sites, the criteria to be followed have to be identified and defined. The first step for success in the operation commences with the selection of a proper site. This paper discusses the criteria which need to be followed in selecting experiment sites for a Vertisol management network in India.

* National Bureau of Soil Survey and Land Use Planning, Amravati Road, Nagpur 440 010, India.

Criteria for Site Selection

The criteria to be considered for site selection can be broadly divided as follows:

- o Soil-based criteria
- o Land-based criteria
- o Climate-based criteria
- o Crop-based criteria
- o Management-based criteria
- o General criteria

Though these criteria are listed separately for purposes of convenience, many of them are closely related and interdependent.

Soil-Based Criteria

Some of the soil-based criteria to be considered for site selection are the distribution and extent of Vertisols, soil problems (like salinity, sodicity and high carbonate), the soil moisture regime, the soil temperature regime, the surface texture, and the soil taxonomic units which have been identified.

Distribution and extent

Information on the distribution and extent of Vertisols and associated soils (Murthy *et al.*, 1982a) in India is given in Table 1.

Table 1. Distribution and extent of Vertisols and associated soils in India.

Soil no.	State	Area in million ha	Percentage of the geographical area of the state
1.	Andhra Pradesh	7.30	26.4
2.	Bihar	0.70	4.0
3.	Gujarat	8.66	44.2
4.	Karnataka	6.82	35.6
5.	Madhya Pradesh	16.81	37.9
6.	Maharashtra	25.85	84.1
7.	Orissa	1.43	9.2
8.	Rajasthan	2.22	6.5
9.	Tamil Nadu	3.08	23.7

These soils are the major soil groups in the states of Maharashtra, Madhya Pradesh, Gujarat, Karnataka and Andhra Pradesh, and hence there is a need for selecting experiment sites on a sound footing.

Within-site variation

The within-site variation has to be minimal. The relative purity of the soil units ensures reliable transferability of the results of the experiments and leads to meaningful conclusions.

Soil moisture regime

The soil moisture regimes observed in the Vertisol tracts are mostly ustic and aridic (Figure 1). The ustic moisture regime area which is extensively occupied by Vertisols is further subdivided into aridic and typic tropustic and typic and wet tempustic regimes (Anonymous, 1981), and covers most parts of Andhra Pradesh, Karnataka, Maharashtra, Gujarat and Madhya Pradesh. The weak aridic moisture regime covers some areas in the states of Karnataka, Andhra Pradesh and Gujarat. The moisture regime has to be considered as a criterion for site selection so that technologies can be transferred to other sites in regions with a similar moisture regime.

Soil temperature regime

The Vertisol areas in India fall under two soil temperature regimes, namely hyperthermic and isohyperthermic. The area south of the Tropic of Cancer falls normally under an isohyperthermic temperature regime and that to the north of it falls under a hyperthermic temperature regime.

Surface texture

Some of the Vertisols occurring in regions of granite-gneissic geology have clay loam or a coarser surface texture followed by clayey texture in the subsoils, unlike those developed from basalt which are fine throughout the profile depth. These Vertisols differ from other Vertisols with a clayey texture throughout the profile in respect to infiltration and moisture-retention characteristics. A light-textured surface facilitates easy entry of water, while a very fine-textured surface impedes the downward movement of water, leading to a high runoff.

Major soil units

The experiment sites should be so selected that they represent important soil families. This requires proper utilization of soil survey data as a base, and then large-scale mapping (say 1:1000 scale) for the selected experiment sites.

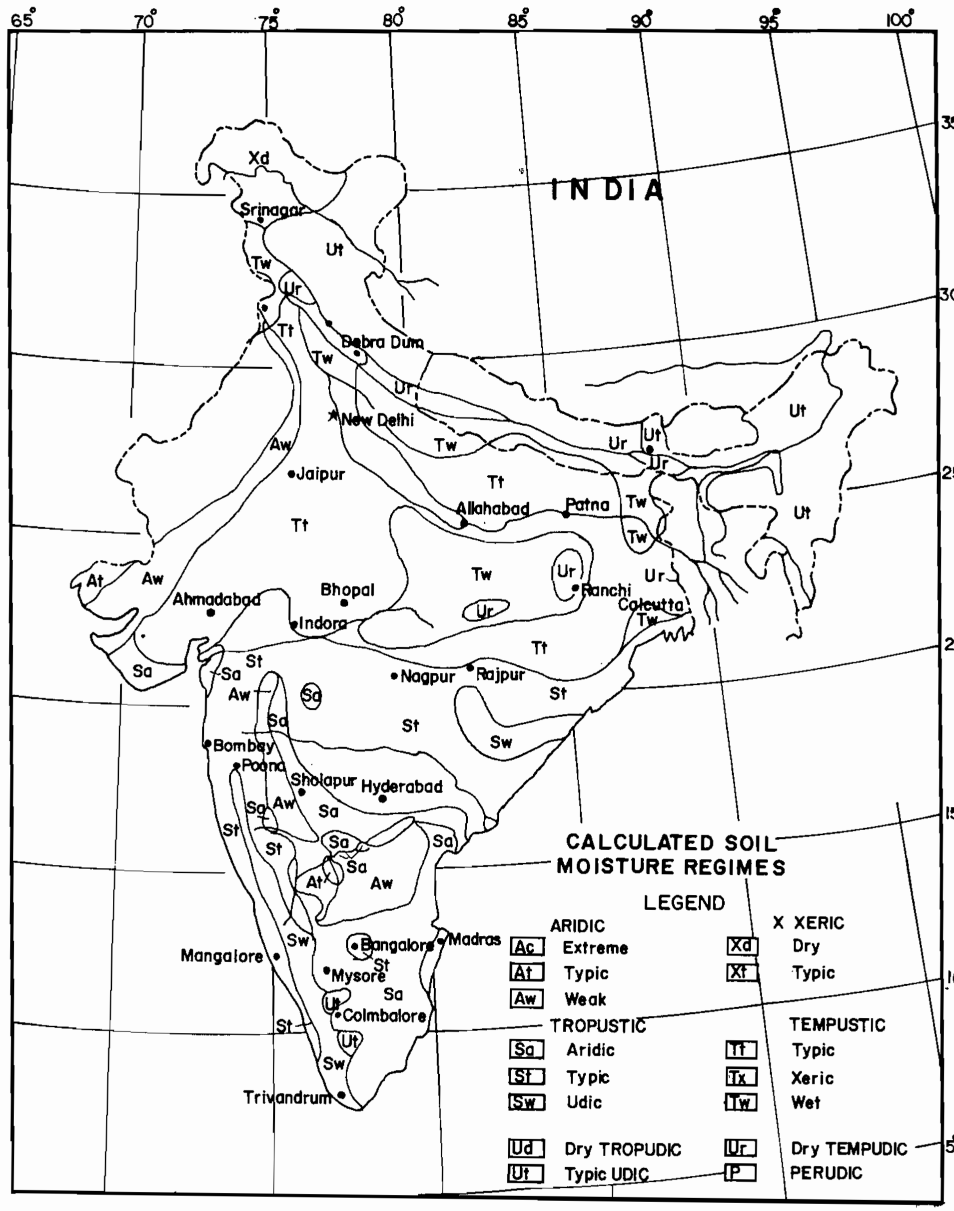

Figure 1. Calculated soil moisture regimes (SMSS Monograph, 1961).

Soil problems

In India, soil problems like salinity, high groundwater, and high calcium carbonate, are common. For example, in the state of Maharashtra alone, it is estimated that salt-affected and waterlogged soils cover about 50 000 ha (Anonymous, 1983). The other major problem, that of sodicity, varies widely among the Vertisols of India (Murthy *et al.*, 1982b), as shown in Table 2.

The ESP varies from insignificant amounts in the Jambha series to critical levels in the Hungund and Achmati series, and very severe limits in soils near Sangli district in Maharashtra. Therefore, sodicity needs to be considered as a criterion in site selection.

The calcium carbonate content also varies widely in the Vertisols in India, as shown in Table 3. The $CaCO_3$ content varies from traces to 32% in the Vertisols referred to in the table. The high content of $CaCO_3$ affects P and Fe nutrition of crop plants. Hence the amount and distribution with depth of $CaCO_3$ needs consideration in selecting an experiment site for the management of highly calcareous soils.

Position of slickensided horizon

The slickensides that break into angular blocky peds develop at some depth below the surface. The depth of the slickensided horizon varies widely among the Vertisols in India (Vadivelu and Challa, 1985), as shown below:

Soil series		Depth at which slickensided horizon starts (cm)
Barsi	(Maharashtra)	36
Hunda	(Maharashtra)	39
Otur	(Maharashtra)	50
Aroli	(Maharashtra)	52
Begamganj	(Madhya Pradesh)	72
Khadoli	(Dadra & Nagar Haveli)	79

The slickensided horizons, which are characterized by angular blocky peds of high bulk density, develop diagonal cracks under moisture stress and hence act as a major constraint in crop production (Murthy *et al.*, 1982a). The effect of these cracks on crop growth is significant when the slickensided horizon occurs at or within 50 cm, as in the case of the Barsi, Hunda, Otur and Aroli series. Its adverse influence decreases when the horizon occurs at lower depths, as in the case of the Begambanj and Khadoli series, since the major root distribution of most annual crops is confined to 50 cm depth.

Land-Based Criteria

The soil and site characteristics vary with the landform on which they occur. In

Table 2. Exchangeable sodium percent in some of the Vertisols in India.

Jambha		Raichur		Linga		Kagalgomb		Hungund		Achmati		Soil near Sangli*	
Depth (cm)	ESP	Depth (cm)	ESP	Depth (cm)	ESP	Depth (cm)	ESP	Depth (cm)	ESP	Depth (cm)	ESP	Depth (cm)	ESP
0-20	1	0-12	3	0-16	8	0-10	4	0-9	3	0-4	4	0-10	74
20-45	1	12-60	4	16-47	8	10-50	6	9-28	6	4-22	7	10-40	44
45-65	1	60-112	6	47-84	7	50-75	13	28-44	11	22-54	14	40-70	50
65-105	2	112-150	5	84-117	7	75-131	19	44-70	13	54-87	17	70-100	44
105-145	5	–	–	117-140	6	131-172	16	70-81	15	87-152	20	100-120	40
145-190	11	–	–	–	–	–	–	81-133	21	152-170	27	120-150	39

Source: Murthy *et al.* (1982b).

Table 3. Calcium carbonate content of some Vertisols in India.

Barsi		Linga		Achmati		Muderai*	
Depth (cm)	$CaCO^3$ (%)	Depth (cm)	$CaCO^3$ (%)	Depth (cm)	$CaCO^3$ (%)	Depth (cm)	$CaCO^3$ (%)
0-12	0.4	0-16	1.9	0-4	16.2	0-15	16.0
12-36	0.4	16-47	4.0	4-22	13.6	15-30	17.4
36-69	0.3	47-84	5.6	22-54	12.8	30-45	17.6
69-114	1.1	84-117	6.5	54-87	15.2	45-60	20.0
114-147	4.7	117-140	8.5	87-152	15.0	60-75	32.2
147-167	5.2	–	–	152-170	13.7	75-90	32.2

Source: Murthy *et al.* (1982b).
* Rama Mohan Rao *et al.* (1980).

India, Vertisols are found to occur on landforms like piedmont plains, flood plains, basins and even coastal plains. The landforms have to be included in the list of criteria for site selection as some of the properties like salinity/sodicity are to some extent influenced by the location of site related with landform.

Vertisols occur on sites of varying relief, and consequently the relief features, and also the intensity of erosional hazards, have to be considered as criteria for site selection.

Climate-Based Criteria

Vertisols in India are found in arid to humid climates. Therefore the mean annual rainfall has to be considered as a criterion for site selection. The distribution of rainfall in the Vertisol tract of India is erratic and uncertain. The mean annual precipitation varies from as low as 338 mm in Bhuj to as high as 2750 mm in Dadra and Nagar Haveli (Table 4).

Besides the total quantity of rainfall, the distribution pattern from June to September (Kharif) and from October to December (Rabi) is very important in Indian agriculture. Kharif crops are grown where more rains are received from June to September, and Rabi crops are grown where the rains are received from October to December. The following example (Table 5) will explain this situation.

It is evident from the table why crops are sown in June in the Nagpur area and in October in the Coimbatore area. Therefore the distribution of rainfall in both the growing seasons (Kharif and Rabi) has to be taken as a criterion for site selection. Figures 2 and 3 show the distribution of rainfall in India during June-September and October-

Table 4. Mean annual precipation at some selected stations in India.

Stn. No.	Station		MAR (mm)
1.	Bhuj	(Gujarat)	338
2.	Bijapur	(Karnataka)	574
3.	Coimbatore	(Tamil Nadu)	612
4.	Ahmednagar	(Maharashtra)	677
5.	Hyderabad	(Andhra Pradesh)	764
6.	Indore	(Madhya Pradesh)	1053
7.	Nagpur	(Maharashtra)	1127
8.	Jabalpur	(Madhya Pradesh)	1448
9.	Silvasa	(Dadra & Nagar Haveli)	2750

Source: India Meterological Department.

Table 5. Mean monthly rainfall at Nagpur and Coimbatore during the Kharif (June-September) and Rabi (October-December) seasons.

Station	Rainfall (mm)						
	June	July	Aug.	Sept.	Oct.	Nov.	Dec.
Nagpur	174.3	351.5	277.1	180.5	66.6	8.7	1.7
Coimbatore	34.0	41.7	33.9	37.3	148.7	125.3	33.5

Source: India Meteorological Department.

December respectively. Most of the Vertisol area receives high rainfall during the period June to September, and therefore crops are generally grown during this season.

Crop-Based Criteria

The major crop grown on Vertisols is a regional feature associated closely with climatic and socioeconomic conditions. Some of the major crops grown on Vertisols are shown in Table 6. The major crops grown have to be considered as criteria for site selection.

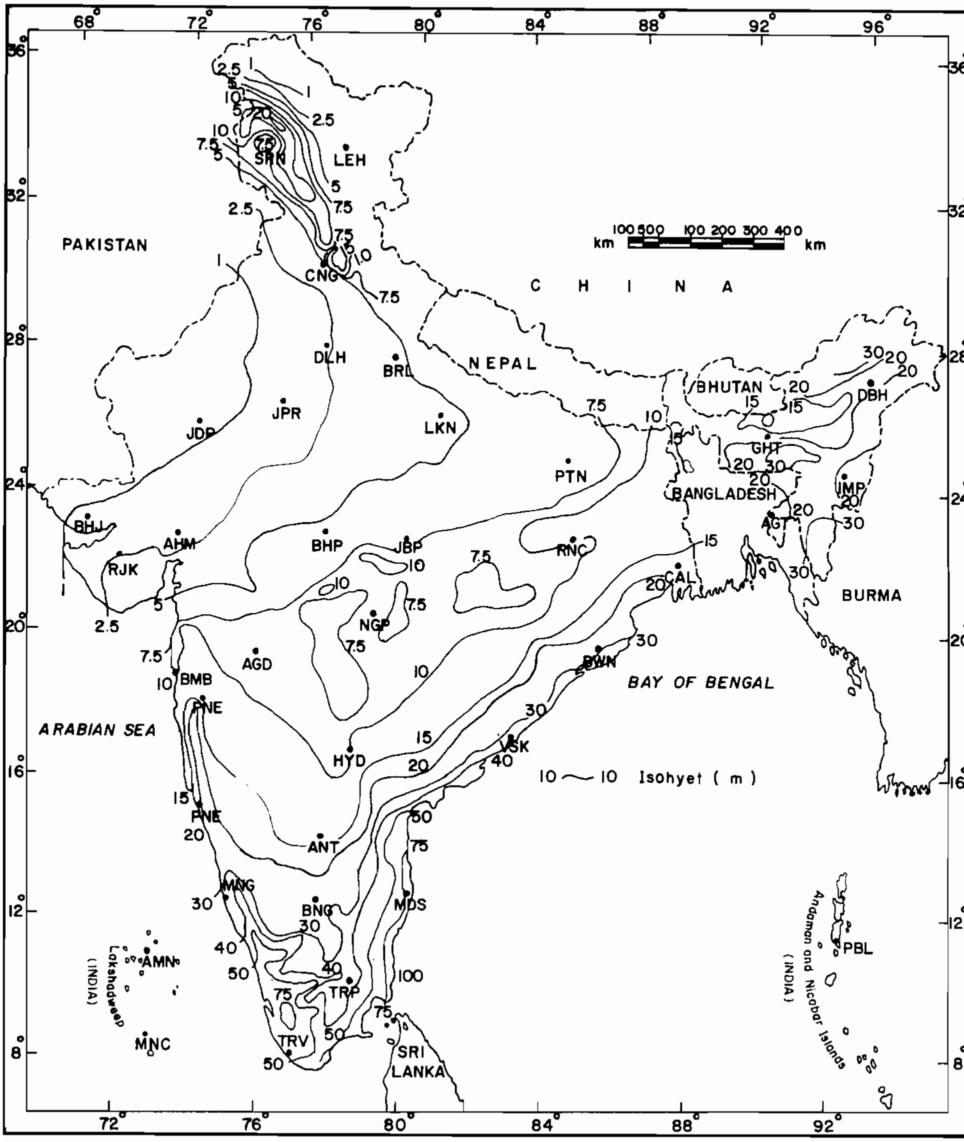

Figure 2. Distribution of rainfall in India during June-September.

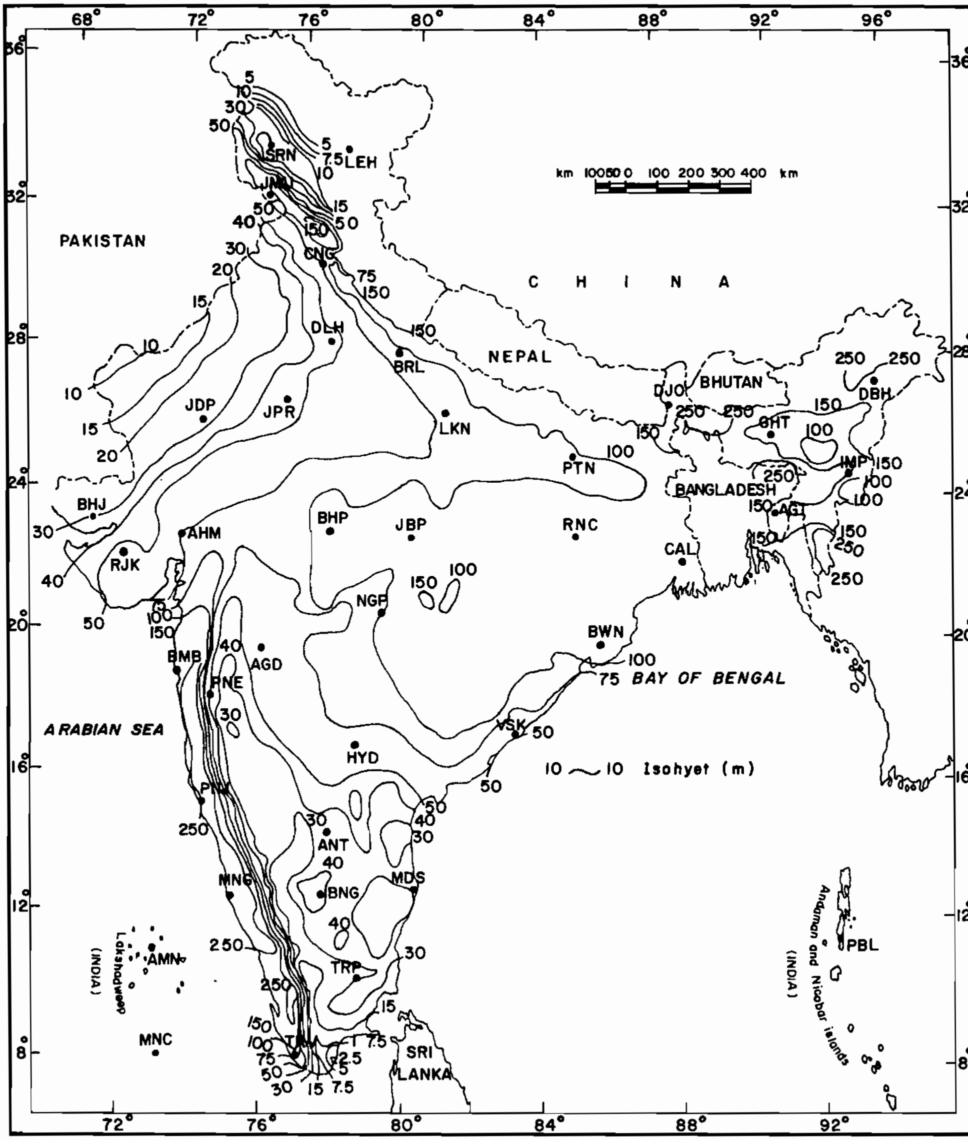

Figure 3. Distribution of rainfall in India during October-December.

Table 6. Major crops grown on Vertisols in different regions under rainfed conditions.

Region	Crop grown
Jabalpur	rice, soybean (Kharif)
Nagpur	cotton, sorghum (Kharif)
Ahmadnagar	sorghum, safflower (Rabi)
Bijapur	sorghum, safflower, setaria (Rabi)
Bellary	coriander, setaria, sorghum (Rabi)
Coimbatore	gram, sorghum (Rabi)

Management-Based Criteria

The management levels are indirect factors to be considered as criteria for selection. These mainly reflect the socioeconomic conditions of the farming communities and their attitude towards improved technologies. The information collected by scientists from the Bureau of Soil Survey and Land Use Planning in case studies indicates that the management levels are low in the dry farming tracts. For example in the Bellary region the field size is 5 ha or more; but there are no bunds, which results in high runoff and soil loss. Only a few farmers apply fertilizers and pesticides. In contrast, the situation in Nagpur is encouraging. The farmers' level of management, in most cases, is higher than that which prevails in the Bellary region. Therefore, besides soil data, information on management levels should also be included in the list of criteria.

General Criteria

There are certain general criteria to be considered for site selection, the most notable being the following:

- availability of agronomic history;
- easy accessibility and communications for routine observations and sampling; and
- availability of weather records.

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SITE SELECTION FOR AGRONOMIC EXPERIMENTS: KENYAN SITUATION

N.N. Nyandat*

Abstract

Research must involve the quantification of constraints to agricultural production. Sites must be typical as regards soils, climate and land use of the areas they are designed to represent, so that results can later be extrapolated from the site to those areas. Other considerations involved in site selection include the socioeconomic circumstances and technological level of the farmers of the area, the availability of land and facilities, security of tenure at the site, and site accessibility. Inputs and implements to be tested should be easily available and within the reach of target farmer groups.

Introduction

Kenyan agriculture is quite varied. Ecologically it varies from tropical on the coast to arid and semi-arid as well as temperate agriculture in the interior. The production structure is also vastly different for small landholders and large farms in terms of the technology and the crops grown. The extent to which the land can produce crops is undoubtedly very limited. The limits of production are set by soil and climatic conditions as well as by the specific inputs and management applied.

It is essential that research should attempt to identify and quantify the different constraints which face agricultural production. On-site verification studies over a wide range of environmental and socioeconomic conditions are required to test the applicability of technologies for crop production. Such on-site verification studies need to be conducted through a network of trials which are sited on appropriately selected locations.

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* National Council for Science and Technology, P.O. Box 30623, Nairobi, Kenya.

Factors to Consider in Site Selection

Agronomic experiments have often been done without due consideration of the environmental and socioeconomic characteristics of the test site, leading to difficulties in adopting the results of the experiments. The ultimate usefulness of the results of agronomic research requires a recognition of the following site characteristics at the time of selecting the site for the experiment:

– the representativeness of soil, climate, land use, and the cropping system at the location of the experiment;
– the capability of the farmers who are expected to use the results of the experiment;
– the availability of the tested materials within the region;
– the availability of sufficient land and appropriate facilities at the site to conduct the experiment properly;
– security at the site;
– accessibility of the site;
– the extent of the variables at the site.

The above site characteristics are briefly elaborated on below, especially with regard to the Kenyan situation.

Representativeness of soils, climate, land use and the cropping systems

Some of the fundamental factors that should be considered in the selection of a site for field agronomic experiments is the representativeness of the soils, climate, land use, and the cropping systems at the site of the experiment. In Kenya, there are diverse soils and agroclimatic zones (Sombroek *et al.*, 1982). The Vertisols of the semi-arid zones (Agroclimatic Zones IV and V: Sombroek, 1982) occur in different regions of Kenya (Muchena *et al.*, 1986) where there are also different land uses and cropping systems.

Past agronomic experiments in Kenya have been carried out at sites that are not representative of the general region. It has consequently been difficult to extrapolate the results, and even when the extrapolation is done the outcome is often disappointing to the farmers. For ultimate adoption of the results of an experiment, the first requirement is to determine representative soils and agroclimatic zones so that the agronomic experiment can be located at a site which represents adequately the general features of the region. With the present availability of fairly detailed soil maps and agroclimatic maps (scale 1:1 million) in Kenya, there is now more scope to improve agronomic research by carrying out appropriately focused and sited agronomic experiments.

Capability of the farmers

In Kenya, four sets of socioeconomic circumstances pertaining to farmers may be recognized (Collinson, 1983). They are as follows:

1. Wholly subsistence production for basic food requirements with surpluses locally exchanged or used for social activities.

2. Dominantly subsistence production for basic food requirements with deliberately produced surpluses for sale locally or elsewhere.
3. Dominantly cash enterprises but with basic food requirements still produced on the farm; food shortfalls or special preferences are supplemented by purchases.
4. Wholly cash enterprises and most family food purchased.

Most of Kenya's small-scale farmers fall under the second category. Therefore in Kenya, for the technology tested to be relevant and acceptable, it has to be site-specific and should be focused on one of the four categories of farmers – whichever one prevails in the area of the experiment.

Availability of the tested materials within the region

The materials concern the inputs as well as the implements used in conducting an experiment. The inputs determine the anticipated output. It is therefore unrealistic to test inputs which will be unobtainable to the user of the results of the experiment, since under such circumstances the results of the experiment cannot be adopted. Testing of materials that cannot be easily secured within a region or carrying out experimental treatments at rates which are not economically feasible for the farmers of the region is not uncommon. Often lower rates of treatment have been ignored.

In Kenya, cases are known where certain materials for mulching have been tested when the material cannot easily be secured, even if it was found to be effective. Similarly, cases are known where the manure to be tested is imported to the experiment site when it is obvious that the manure is not available in the region and cannot be economically imported for routine use. Certainly agronomic experiments that do not consider the availability of the test materials within the region cannot provide practical results.

It is necessary to consider right from the beginning the supply of inputs being tested. It is especially important to identify the constraints that may be operating on the availability of the inputs within the region and test only those inputs which can be easily obtained in quantity, quality, and at a reasonable price. Emphasis should also be placed on the selection and development of simple implements appropriate to the conditions experienced by the target farmers. These site-specific approaches will enhance a faster adoption rate of new research technology.

Availability of land and facilities

In order to carry out a field experiment properly, there is need for adequate land. Where adequate land is available it is possible to lay out a satisfactory design for the experiment and also to install the essential supporting facilities. In Kenya, however, the majority of landholders have small tracts of land, so they cannot spare large plots for experiments. This implies that the required land for an experiment should be the minimum for conducting a particular experiment properly and also should be acquired where the landholder cannot be inconvenienced.

Security at the site

Security involves both the convenience of the landholder and the safety of the experiment. The establishment of the experiment should not become a hindrance to the normal use of land by the owner. Also the experiment should not be sited within easy reach of the general public, as for instance at the side of a major public road. Furthermore, the experiment should not be sited in an isolated area, away from the cultivated plots of the farmer, where it stands the risk of being destroyed by wild animals and birds.

As part of the security, the land for the experiment should be acquired under a lease agreement. This will give the landholder a feeling of security with regard to the future of his land, and by virtue of receiving some income from the lease he will not feel he is losing by allowing part of his land to be used for experiments. This is an aspect which has been given little attention in Kenya, where land for field experiments has often been obtained on a rent-free basis. It is therefore not uncommon to find that the farmer will refuse continued use of his land for an experiment before the experiment is concluded.

Accessibility to the site

An experiment can only be properly installed and managed if there is easy access to the site of the experiment. It is essential that vehicles and implements should be able to reach the site without difficulty. Furthermore, the experiment should not be sited where servicing of the equipment being used is not possible. Delays in servicing broken-down equipment can be detrimental to the success of the experiment.

Extent of variables at the site

When the site of the experiment has too many variables to be controlled, the experiment may be difficult to handle. For this reason it would be advisable to site an experiment only where the number of variables do not create difficulties.

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Third session: Site characterization

Chairmen: Dr. A. Osman

Dr. M. Rasheed

THE PHYSICAL AND MECHANICAL CHARACTERIZATION OF VERTISOLS

K.J. Coughlan[1], D. McGarry[2] and G.D. Smith[3]

Abstract

Soil characterization is required for management decision making in agriculture, for determining the effects of management practices on soil properties, for the location of field experiments, and for technology transfer. Characterization may range from visual assessment of selected soil profile properties to complex field and laboratory measurements. The choice of the variables to be characterized is dependent on the reasons for the characterization, as well as on the availability of facilities and expertise.

A range of physicochemical properties which influence soil physical behaviour are considered. We also consider certain direct measures of the physical properties of Vertisols which affect, or are affected by, management practices.

It is stressed that there are certain problems associated with the measurement and interpretation of the physical properties of Vertisols, due particularly to the effect of soil water content. A prime example is the difficulty of comparing bulk density measurements between soils, or over time for one soil.

Introduction

The characterization of soil at a site is vital – principally to provide a datum for technology transfer. Only with such a datum can a field trial be optimally located, the results of the trial be meaningfully related to data from other sites, management decision making be soundly founded, and the effect of management practices be fully assessed. The varia-

[1] Queensland Department of Primary Industries, Meiers Road, Indooroopilly, QLD 4068, Australia.
[2] CSIRO Division of Soils, 306 Carmody Road, St. Lucia, QLD 4067, Australia.
[3] Queensland Wheat Research Institute, P.O. Box 5282, Toowoomba, QLD 4350, Australia.

bles characterized at a given site will be determined not only by the reasons behind the characterization but also by the availability of facilities and expertise. The level of characterization can range from simple to complex field observation. With Vertisols, soil physical and mechanical properties are important in affecting crop growth and are greatly affected by management practices, but because of the difficulties of interpreting the measurements adequate characterization is rarely done.

The majority of the physical properties of soils are controlled by the arrangement of soil solids and pores. This arrangement determines the movement of water and air, and these affect root growth and nutrient availability. With Vertisols in particular, no one measure provides a complete picture of their physical and mechanical nature, since their physics changes as their water content changes. As a result, their physical identity is multifacet and best documented by a set of techniques, each giving further insight into their nature under different water content conditions. With Vertisols, physical measurements are no more difficult to collect than with most soils. However, care is needed both to collect representative samples and in the interpretation of the measurements.

The prime objective of this paper is to describe our experience with selected measures of the physical and mechanical properties of Vertisols to characterize sites. Associated problems will also be documented. Some physicochemical attributes that are related to these physical properties will also be presented. To this end there are two subsidiary objectives: (i) to present either sufficient detail on these techniques, or provide references to published sources, to help a potential user decide on which methods and equipment would be best suited to his needs, and (ii) to illustrate problems encountered in making physical measurements on Vertisols.

The experiences that we report here are not all drawn from Vertisols as defined by *Soil Taxonomy* (Soil Survey Staff, 1975), though all the soils concerned, the Ug soils as defined by Northcote (1979), can be termed 'vertic' as they have > 30% clay throughout and show seasonal cracking. Our experiences are also drawn from limited climatic conditions, mainly semi-arid with a summer rainfall maximum (500-700 mm/year). This latter point is important as it helps explain our perception of the relative importance of various physical measurements.

Site and Soil Profile Description

In terms of site characterization, the importance of site and soil profile descriptions cannot be overemphasized. Soil morphological description can be a most useful guide to soil physical behaviour, and is the very basis for technology transfer since it provides most of the data for soil classification. In addition, morphological properties are relatively permanent and most do not vary seasonally. Data recorded for general soil profile description are principally concerned with the kind, thickness and arrangement of soil horizons and in particular their colour, texture, structure, consistence, segregations, depth of soil to hard layers, and parent material. These data, together with landform, slope, aspect, microrelief, and regional climatic information, can be used to devise land-use decisions and management strategies.

Of prime importance in site and soil description is the standardization of terms and subjectively-named size classes that are used, normally achieved by standardizing the field handbook used. The authors use the *Australian Soil and Land Survey* (McDonald *et al.*, 1984). Others available are: *The Soil Survey Manual* (Soil Survey Staff, 1951) and *Guidelines for Soil Description* (FAO, 1968).

Physicochemical Properties

Excluding field observations, the simplest methods of inferring a soil's physical and mechanical properties are based on laboratory measurements of physicochemical properties. In Queensland we have done a considerable amount of research (Smith *et al.*, 1984; Coughlan and Loch, 1984; Shaw and Thorburn, 1985) relating physicochemical properties to the physical behaviour of field soils. Information on plant-available water capacity (PAWC), hydraulic conductivity, shrinkage and surface aggregation has been obtained from these studies.

Our experience with Vertisols indicates that soil salt profiles, cation-exchange capacity (CEC), clay percentage and exchangeable sodium data are the most useful in predicting soil physical behaviour. Soil organic matter seems to be of secondary importance in these soils because of the strong forces of both bonding and aggregate disruption associated with swelling clay minerals.

Coughland *et al.* (in press) have listed the major constraints to crop production on Vertisols. These are: surface sealing and crusting, excessive cloddiness, low PAWC, restrictions to root growth (including subsoil salinity), and surface waterlogging. They suggested that these properties often occur in combination and appear to be related to hydraulic conductivity. The model explaining these relationships is given by Coughlan (1984). Our hypothesis is that the amount and distribution of soluble salts in the soil profile (and particularly of mobile anions such as chloride) is a good indicator of the amount of water movement through the profile. Evidence for this hypothesis is the effect of rainfall, irrigation and soil management on the salt profile (Coughlan *et al.*, in press).

For a given environment, increased profile salinity is taken as an indicator of reduced profile hydraulic conductivity. According to the model proposed by Coughlan (1984), low hydraulic conductivity leads to:—

- o surface water logging, runoff and erosion;
- o crusting or excessive cloddiness on drying;
- o limited water penetration and reduced PAWC.

In some cases, resultant subsoil salinity may be sufficient to limit root growth.

From the studies of Shaw and Thorburn (1985) and Coughlan and Loch (1984), CEC, clay percentage and exchangeable sodium percentage (ESP) appear to be the major properties determining at least unsaturated hydraulic conductivity. Shaw and Thorburn examined physicochemical data on 766 Queensland soils. After removing the variability associated with rainfall, they made the following conclusions regarding the effect of soil properties on "relative permeability". The variables used were clay percentage, the ratio of CEC:clay percentage (CCR), and ESP. The effect of these variables is shown in Figure 1.

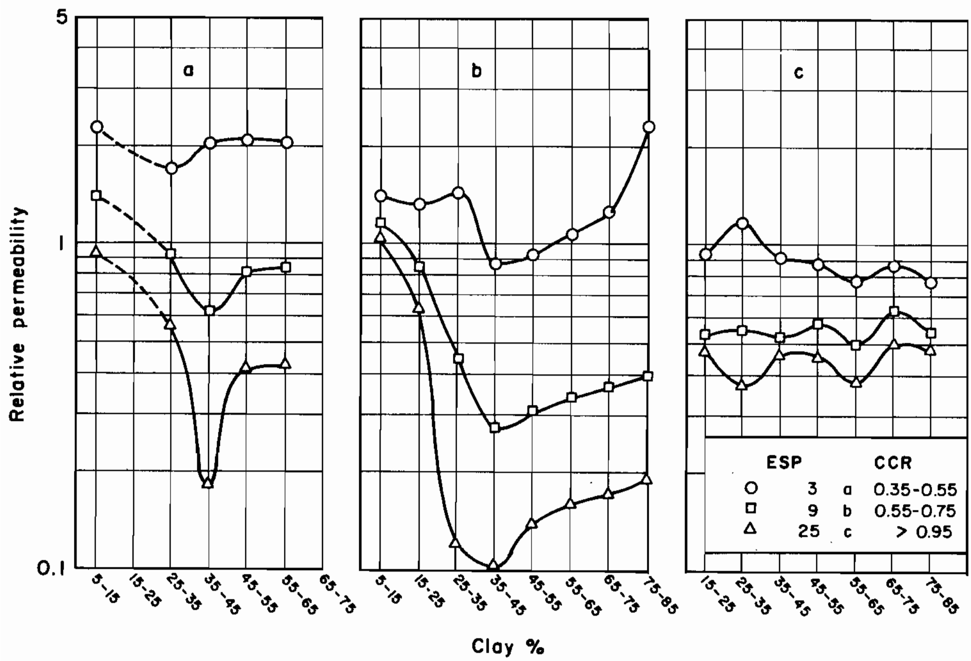

Figure 1. The relationship between "relative permeability" and clay percentage for different clay types and a range of ESP.

Conclusions were:

- The lowest permeabilities occurred at 35-45% clay and the effect of ESP is greatest in this clay percentage range.
- The lowest permeabilities were for soils in the CCR range 0.75-0.95. The range closest to this (Figure 1) is 0.55-0.75. In Queensland Vertisols, smectites (with an average CCR of about 1) are the dominant clay minerals, with kaolinite (CCR < 0.2) normally the subdominant mineral. The above result suggests that relatively small amounts of kaolinite in a smectite-dominant soil can markedly reduce its stability and hydraulic conductivity.
- Soils with active smectite clays (CCR > 0.95) have a permeability which is relatively insensitive to variations in clay percentage or ESP.

Measurements of clay percentage, CEC and ESP are relatively time-consuming, and we have been investigating simpler ways of predicting these properties. Results for prediction of CEC and clay percentage from water absorption measurements are encouraging. However, no simple method of predicting ESP is yet available.

Plant-Available Water Capacity

Charaterization of plant-available water capacity (PAWC) is important because PAWC is a measure of the soil's capability of storing water that will be available for use by crops. PAWC influences the potential for dry-season cropping (e.g. the ICRISAT broadbed and furrow system depends on soils having a PAWC of 200 mm (Swindale and Miranda, 1984) and irrigation frequency under irrigation. Our concept of PAWC involves two factors: the soil water storage and plant water extraction. PAWC is defined (Gardner *et al.*, 1984):

$$\mathrm{PAWC} = \sum_{z=O}^{z=RD} (W_{max} - W_{dry})\, BD\, \Delta z / DW$$

where W_{max} = the gravimetric water content at the upper storage limit in the field soil (g/g),
W_{dry} = the final gravimetric water content after plant water extraction in the field (g/g),
RD = rooting depth,
BD = field bulk density at W_{max} (measured or estimated).
Δz = depth increment
DW = density of water

PAWC may vary with crop, stage of growth, level of stress, root development restrictions, extent of soil water recharge, etc., but when measured using management appropriate for the intended application it has proved an extremely useful concept for comparisons among soils (Shaw and Yule, 1978; Gardner and Coughlan, 1982).

W_{max} should be measured by sampling the fully wet profile (i.e. two to three days after profile recharge) and W_{dry} by sampling when the crop shows a specific stress symptom. If suitable equipment is available, field bulk density can be measured in conjunction with W_{max} sampling. However, Shaw and Yule (1978), Gardner *et al.* (1984) and Gardner (1985) have shown that BD at depths > 20-30 cm can be estimated from the measured W_{max} value using the following equation:

$$BD = \frac{1 - e}{\dfrac{1}{AD} + \dfrac{W_{max}}{DW}}$$

where e = air content (cm^3/cm^3)
AD = particle density (g/cm^3)

Assuming the soil has 5% air by volume and a particle density of 2.65 g/cm³ the above equation reduces to

$$BD = \frac{0.95}{0.377 + W_{max}}$$

If no land under the crop of interest is available it may be necessary to set up small, protected plots (minibays) to grow the crop under simulated conditions to provide the range of wetting and drying required. This approach has been used to assess the PAWC of potentially irrigable soils in Queensland (Shaw and Yule, 1978; Gardner and Coughlan, 1982). The minibay approach is slow, expensive and inconvenient, but it has generated equations that can be used to estimate PAWC for soils in other regions. These equations were derived for a range of Vertisols by growing a crop of sorghum in minibays. Both W_{max} and W_{dry} were significantly correlated with CEC and the regression equations varied slightly with depth (Shaw and Yule, 1978). The −15 bar water content is related to CEC and can be used in the prediction of W_{max} and W_{dry}. The following equations are given by Shaw and Yule:

$$W_{max} = 0.124 - 0.265\,D + 0.160\,D^2 + 1.284\,(-15\text{ bar W}) \qquad R^2 = 0.959$$
$$W_{dry} = -0.176 + 0.022\,D + 1.0054\,(-15\text{ bar W}) \qquad R^2 = 0.922$$

where D = depth in metres, i.e. 0–10 cm = 0.1 m $(0 < D \leqslant 1)$

Of course, W_{dry} can be equated directly with the −15 bar water content for each depth interval, but it must be remembered that in the deeper subsoil crops might not remove water from the soil even though it is wetter than −15 bar (because of restrictions to root distribution and to osmotic effects of salinity). It has been common to estimate W_{max} from laboratory measurements of water content at a particular potential (e.g. −0.1 or −0.3 bar). However, our results (Gardner *et al.*, 1984) show this approach may be seriously misleading.

These equations have been found reliable on a range of Queensland Vertisols and vertic soils (with −15 bar water content > 0.10 g/g), but caution is needed where soil wetting or plant water extraction is atypical. In soils with restricted internal drainage (wetting), the approach of McCown *et al.* (1976) based on the soluble salt profile, may be useful. It is difficult to arrive at the depth of rooting by any indirect method, although it may be estimated from the age of the crop. Subsoil structure affects root growth but we are uncertain as to the specific soil properties that best indicate potential rooting depth.

Dry Bulk Density and Air-Filled Porosity

The measure of dry bulk density is central to derivations of soil porosity and PAWC.

It is also commonly accepted as a direct measure of soil compaction, but it is only one index of this complex phenomenon. Defined as the weight of solids per unit of total soil volume, bulk density provides a basis for comparing the compactness of soil particle packing between two samples. Soil porosity is an alternative way of expressing a soil's structural condition. Air-filled porosity is the volume of air-filled pore space in a soil at a given moisture content, and as such provides a guide to a soil's aeration status, which may be related to air diffusion and the potential for plant root respiration.

Values of bulk density and air-filled porosity can be derived from the one sample. Samples collected should be undisturbed and of known value. A common technique uses an integral sampler where a sharpened cylindrical metal sleeve of known dimensions is driven into the soil (Loveday, 1974, ch. 3). The trimmed, 'wet' soil core is weighed, dried at 105° to constant weight, and reweighed after cooling. The calculation (after Loveday, 1974, chs. 3 and 8) of dry bulk density and air-filled pore space (as well as the gravimetric and volumetric water contents of the sample) requires:

M = 'wet' mass of the core (g),
Ms = mass of solids (i.e. the oven-dry mass of the soil in the sleeve) (g),
Vb = bulk volume (i.e. the volume of the metal sleeve) (cm^3),
AD = particle density, usually taken as 2.65 (g/cm^3);

to give:

- o Dry bulk density, $Db = Ms/Vb$ g/cm^3
- o Gravimetric water content, $W = (M\text{-}Ms)/Ms$ g/g
- o Volumetric water content, $Wv = W.Db$ cm^3/cm^3
- o Air-filled porosity, $f = (1-(Db/AD) - Wv$ cm^3/cm^3

In all soils it is vital that samples taken for determination of bulk density and air-filled porosity contain representative proportions of the volumes of solid, liquid and air. This is particularly difficult in Vertisols due to cracking. Doubt has been expressed about the efficacy of 7.5 cm and 10.9 cm (internal diameter) cores for sampling Vertisols, (McGarry, in press; Berndt and Coughlan, 1976, respectively) but no author has demonstrated an optimal size for all conditions.

If bulk density is required for expression of water content and/or nutrients in volumetric terms, it may be sufficient and preferable to estimate Db from more easily measured soil variables (see 'plant-available water capacity' section and Figure 2).

When using bulk density as a measure of soil compaction, two things should be remembered:

- When comparing soils, the minimum bulk density will depend on the maximum field water content. The latter is determined in Vertisols by the amount and swelling capacity of the soil clay fraction. For these reasons, it may not be reasonable to conclude that Soil TS1 (Figure 2) is 'more compacted' than Soil B8.
- When comparing treatments on a single soil (or where Db measurements are made over a period of time), it is important to remember that the Db-water content plot has a negative trend similar to that shown in Figure 2, particularly if cracks are not representatively sampled. Therefore, to compare different treatments or times it is

important to sample at the same water content, or over a similar range of water contents.

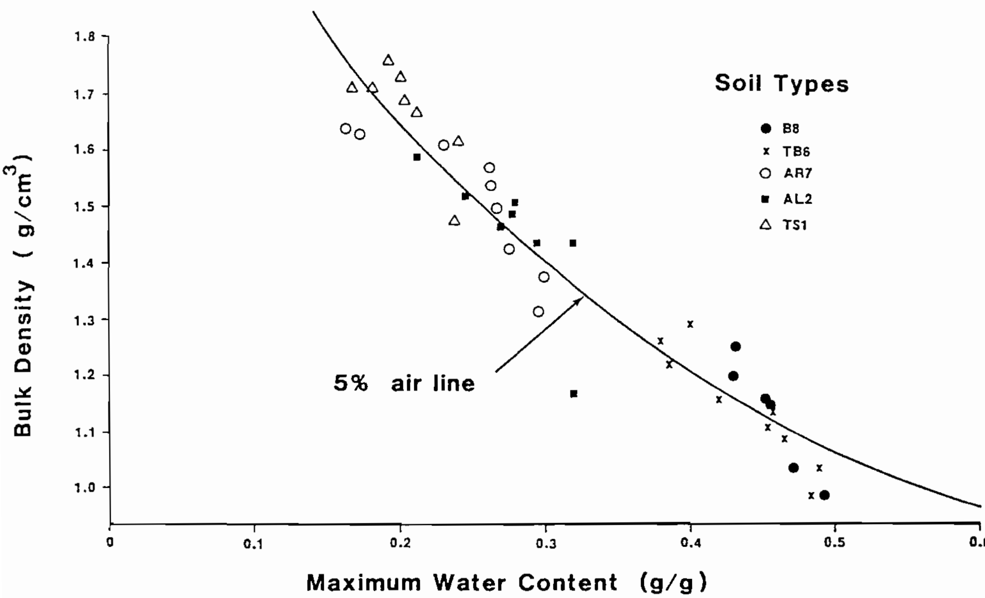

Figure 2. The relationship between bulk density and water content (both measured at maximum field water content) for a range of Vertisol subsoils.

Air-filled porosity can be a more meaningful way of presenting soil structural status or compaction than bulk density. To illustrate differences, plot the increase in the percentage of air-filled pores on subsequent days after an irrigation or heavy rainfall. A commonly accepted critical value of air-filled porosity below which a soil is waterlogged is 10%, though it is somewhat arbitrary, being both soil type- and crop-dependent. The rapidity with which a soil achieves an air-filled porosity value of 10% following an irrigation or heavy rainfall may be related to the soil's structural status, a more compacted soil remaining at low air-filled porosities longer. An example illustrates recovery rates of air-filled porosity for a Vertisol after irrigation (McGarry and Chan, 1984) (Figure 3). The site (where a cotton crop was growing at the height of summer) was sampled on each of 2, 5 and 10 days after an irrigation. For five days after the irrigation, air-filled porosity was < 10% below 20 cm, and it took 10 days before this extended to 40 cm. Even after 10 days, below 40 cm did not achieve a value greater than 10%. At this site, therefore, if you accept that 10% air-filled pores is a critical value, then plant root respiration beneath 20 cm was impaired for 5 days after an irrigation, and to 40 cm for 10 days.

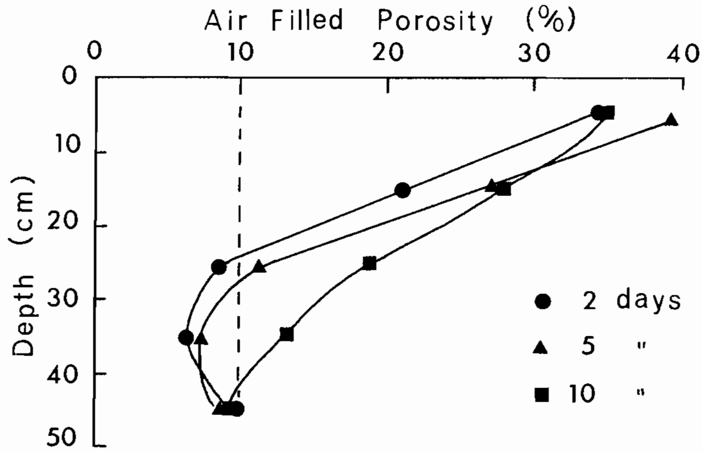

Figure 3. Air-filled porosity vs. depth in a Vertisol sampled 2, 5, and 10 days after irrigation of a cotton crop.

Penetration Resistance

Soil resistance to the insertion of a penetrometer is a commonly accepted measure of soil strength which many authors have attempted to relate to root exploration and expansion into soil. The ease and rapidity of data collecting have ensured its popularity. However, uncertainty exists about the meaningfulness of the measure, both due to its interdependency with other soil factors, and to its interpretation as regards plant root exploration of a soil. Measurement is commonly made by means of a hand-powered penetrometer, though electric-powered recording penetrometers are becoming more widely used. The range of penetrometers available in terms of size, shape of tip, strength of internal spring, etc., is very large, but the uncertainties associated with interpretation of the values are common to all.

If soil water content is not taken into account when penetration resistance is measured, misleading interpretations can be made. For example, in one study six sites on Vertisols were sampled, each over a different range of soil water content (McGarry, unpublished data) (Figure 4). If associated water content had not been measured, then it could have been concluded (wrongly) that site 5 had higher penetration resistance (soil strength was greater) than the other sites. When viewed in association with water content it can be seen that all sites quite closely fit one line – a negative exponential. As with bulk density, between-site comparisons of penetration resistance should be restricted to one water content or the same range of water content. Measurement at maximum field water content is one option.

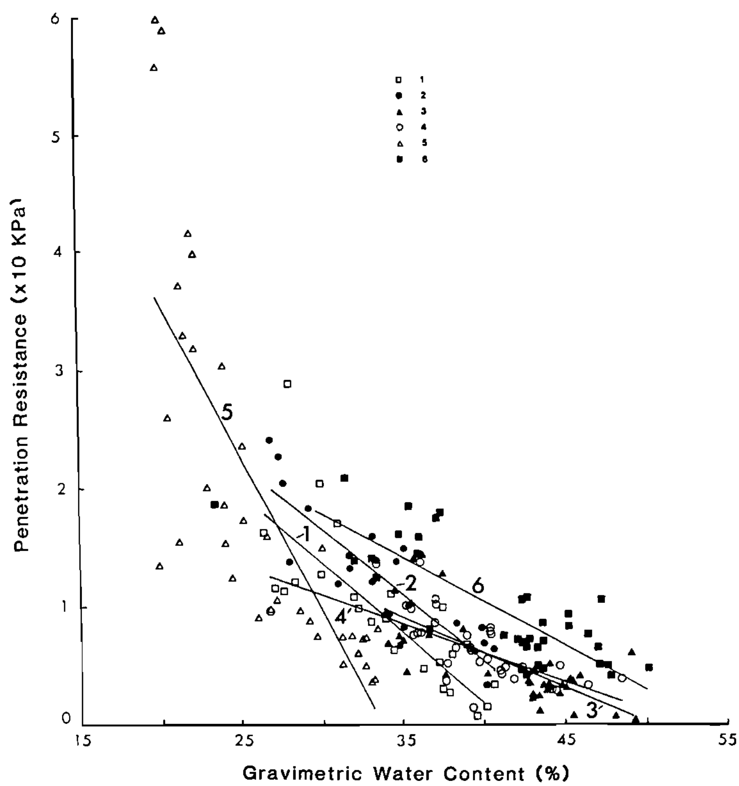

Figure 4. Soil penetration resistance plotted against water content for six Vertisol sites.

Critical values of penetration resistance above which root growth stops may be found in the literature; a range of 2000 to 2500 kPa is common. However, such values cannot be directly related to root penetration as they cannot account for factors such as the lubrication of the soil by plant root exudates or the ability of a plant to seek out the path of least resistance, especially in a structured soil such as a Vertisol (Taylor, 1974).

Water Stability

The structure of Vertisols largely depends on how the soil reacts to wetting and drying. The stability of aggregates to wetting is important because the degree of breakdown influences the size and arrangement of aggregates and pores, which in turn influences the processes of infiltration, runoff and erosion in the wet soil, and crusting, cloddiness and ease of tillage of the dry soil. The processes that cause aggregate breakdown in wet soil are:

- *Slaking,* i.e. aggregates break into smaller aggregates due to swelling stress when dry soil is wetted quickly.
- *Dispersion,* i.e. the individual clay particles that make up aggregates are no longer bonded together and to other soil particles and may move apart due to electrokinetic repulsion.

Slaking only occurs when dry soils are wetted rapidly. The degree of breakdown is a function of the rate water is applied and the rate at which aggregates take up water (Collis-George and Laryea, 1971; Coughlan, 1979). Dispersion can occur spontaneously, but it more commonly occurs after mechanical energy is applied, e.g. raindrop impact, tillage, or livestock trending. Coughlan (1984) proposed a model for stability to rainfall wetting of aggregates in the immediate surface soil. The mean elements of this model were that surface tension forces maintain aggregate stability until the soil reaches the disruptive moisture content (DMC); at or above the DMC the aggregates are very easily broken down into individual particles. Coughlan also proposed that aggregates of some soils have an inherently slower rate of wetting. These slow-wetting aggregates might not break apart on wetting (e.g. immersion followed by wet sieving), but are susceptible to dispersion under raindrop impact.

Thus the degree of breakdown undergone by aggregates is a function of several factors – rainfall rate and energy, and soil wetting rate and strength characteristics. No single test for aggregate stability can fully assess stability under the range of conditions that may be experienced in the field. Any chosen test gives results directly relevant only to the standard conditions applied. Thus test results are a guide to field response and become more reliable (or may be applied with greater confidence) if they can be correlated with field responses under a range of conditions.

The choice of a test should be based on the soil physical factors and the soil management processes that are of most interest in the field. Wet sieving (after immersion of dry aggregates) has been used extensively for nonswelling soils, but is not appropriate for vertic soils (Coughlan, 1984). This is because the aggregates when immersion-wet are not exposed to the same energy as occurs under rainfall and may be wet more rapidly than occurs in the field.

The simplest approach is to note soil behaviour in the field. In the dry state note whether aggregates are coarse or fine, whether there is crusting on the surface, sand separation and clay 'curls' in depressions. If the soil can be observed when wet, it is useful to know under what rainfall conditions ponding occurs, and if ponded water is turbid. Soils showing ponding under light rain or having turbid surface water are more likely to have physical problems.

Simple tests may provide a guide to soil behaviour. The aggregate coherence (Emerson) test (Emerson, 1967) is a very simple test that separates soils on the basis of slaking, spontaneous dispersion, and dispersion after remoulding. The dispersion tendencies can be rated numerically to give a dispersion index (Loveday and Pyle, 1971), but our general experience for Vertisols has been that this test may not separate soils that show differing behaviour in the field. Our results (Coughlan, 1984) suggest that the dispersion ratio

(Middleton, 1930) is a better guide to field soil aggregate behaviour.

Of the many other stability tests available, most require complex equipment and sophisticated laboratory conditions. Tests that may be of value if relationships can be developed include those based on aggregate wetting rate (Coughlan, 1984; Quirk and Panabokke, 1962) and using simulated rain. Some results with Vertisols (Glanville and Smith, unpublished) suggest that the proportion of water-stable aggregates < 0.125 mm is closely linked with infiltration under simulated rainfall (Figure 5).

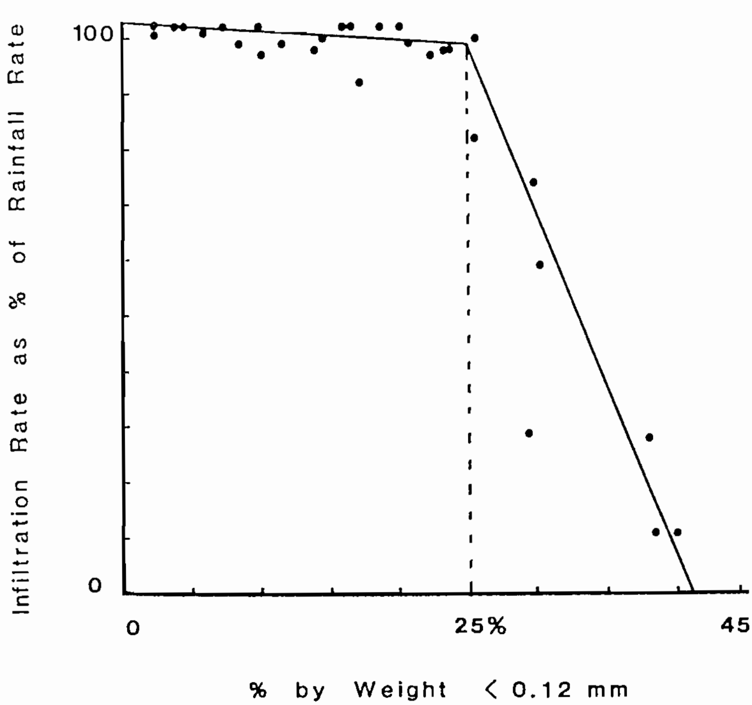

Figure 5. The relationship between infiltration of simulated rainfall and percentage of water-stable aggregates < 0.125 mm.

Self-Mulching

Dry aggregate size of the surface of self-mulching Vertisols is a distinctive morphological feature which can be subjectively rated in the field. Beckmann and Thompson (1960) used the fineness of aggregation in the surface as a criterion for classifying Vertisols. Such a classification relates to land use, since fineness of aggregation is related to surface tilth and ease of seedbed preparation. It must be remembered, however, that aggregate size in the self-mulched layer is influenced by the number and the nature (rate and intensity) of wetting and drying cycles (Coughlan *et al.*, 1973) as well as inherent soil properties (Smith, 1984) and the water content at the time of observation. Because the moisture regime varies over short distances, there is a need for a standardized test to note soil capability for regeneration of structure (self-mulching ability). In preliminary work we have used aggregate size after three standardized wetting and drying cycles as a guide to self-mulching ability. Soils that self-mulch usually slake but do not disperse on rapid wetting, and have a high shrink-swell capacity.

Water Movement

Three aspects of water movement are considered of importance in the productivity and management of Vertisols:

o water intake into a dry soil;
o drainage of a waterlogged profile; and
o rate of evaporate drying of the surface.

In relation to the first aspect, water intake into a dry soil, two questions can be asked:

- Will the profile fill before significant surface ponding/runoff occurs? Stability of surface aggregates to rainfall may be relevant to this question (see Figure 5), as may the occurrence of cracks and rainfall intensity.
- Will the rain infiltrate below the surface layer where evaporative losses are rapid? Information on water content of the surface after a prolonged drying period and maximum water content may be used to calculate 'ineffective rainfall'. It can take up to 50 mm of rain to wet the top 100 mm of soil from a dry condition.

As regards the second aspect, the drainage of a waterlogged profile, it should be noted that waterlogging may seriously affect crops if saturated hydraulic conductivity is low. However, measurement of this parameter is difficult in Vertisols for two reasons. Firstly, measurements must be taken over a long period, because in Vertisols (in contrast to nonswelling, lower clay soils) hydraulic conductivity changes markedly with time of ponding. Over the period 5-24 hours, the average saturated hydraulic conductivity of a group of Vertisols was 3.8 cm/day. For the period 3-7 days, it had fallen to 0.5 cm/day (Gardner and Coughlan, 1982). Secondly, the ponded area must be large to representatively sample the macrovoids which make such a large contribution to saturated hydraulic conductivity. For the same reason, the retaining ring must not be driven too far into the soils.

However, we do have a number of measurements in large bays over long periods, and Shaw *et al.* (1986) have developed a relationship between saturated hydraulic conductivity and soil salinity at 90 cm (Figure 6). This type of relationship may be sufficient for the grouping of soils in accordance with the waterlogging hazard, particularly considering the great variability of this parameter over short distances.

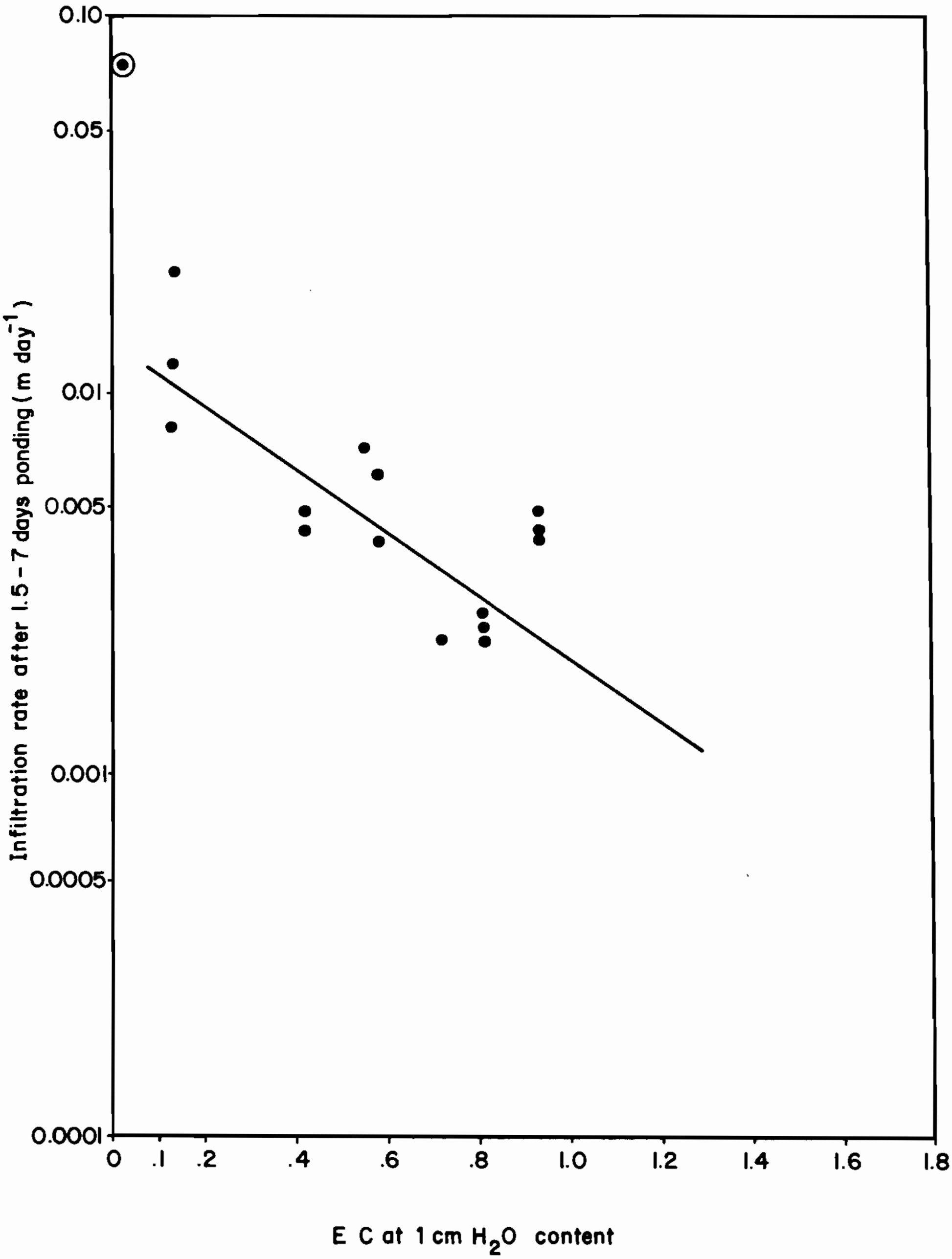

Figure 6. The relationship between saturated hydraulic conductivity and soil salinity at 90 cm for a range of Vertisols.

In relation to the third aspect, the rate of evaporative drying of the surface, it will be appreciated that the rate of drying is relevant to both seedling emergence and long-term profile evaporative losses. Measurements of both water content and water potential may be useful.

Conclusions

On the basis of our experience, the following measurements are recommended for physical and mechanical characterization of Vertisols. Both field and laboratory measurements are listed in the order simple to complex and/or necessary to less necessary. As the range of measurements made increases, the confidence of prediction of soil behaviour also increases.

Field profile description:

- aggregate size and crusting tendency of surface soil
- aggregate consistence, depth of self-mulching
- size and type of subsurface structural units
- presence/absence of polished faces on peds
- distribution and nature of segregations
- mottling
- field pH profile

Field measurements:

- profile description (structure, concretions, pH)
- maximum field water content
- wet penetration resistance
- permeability
- rate of drying of seedbed (water content, potential)

Laboratory measurements:

- salinity and pH profiles
- water contents at −15 bar and lower water potentials
- CEC, exchangeable cations
- clay
- dispersion
- aggregate size after simulated rainfall
- self-mulching of clods
- aggregate porosity
- liquid and plastic limit
- high energy moisture characteristics
- clod shrinkage curve

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WATER MANAGEMENT OF VERTISOLS IN THE SEMI-ARID TROPICS

D.F. Yule*

Abstract

Water management for cropping in semi-arid environments must aim to maximize transpiration and minimize evaporation, runoff and drainage. The soil water balance is used to consider these processes and their interactions. Data applicable to Vertisols are limited.

Our research on Vertisols in Queensland indicates that infiltration (rainfall-runoff) depends on rainfall, soil surface and soil profile conditions. On an annual basis, runoff will generally be small. Soil evaporation is the major exter-loss mechanism, often accounting for more than 50% of rainfall. Rainfall < 30 mm is readily lost to evaporation. Drainage may be significant in water-balance terms. Tillage management and its effects on cover, weed growth and surface roughness can increase infiltration and/or decrease evaporation.

Transpiration can be maximized by managing crop, planting, and agronomic options. Crops develop in a high-stress environment in semi-arid regions and few applicable crop water-use data are available.

Options for soil water measurement are discussed.

Introduction

Water management must aim to maximize the productive use of water by minimizing the unproductive losses. Simplistically this means maximizing the transpiration component of the water balance. This will achieve maximum annual dry-matter production. However, to achieve acceptable grain production it may be necessary to accept greater

* Queensland Department of Primary Industries, Rockhampton 4700, Australia.

losses during a fallow period.

This discussion is based on a consideration of the soil water balance and its application to relatively dry environments where soil evaporation is the major loss mechanism and crop growth is extremely restricted by water stress. Most of the examples used are from Queensland, Australia.

The Soil Water Balance

Infiltration = Precipitation – Runoff = Evaporation + Transpiration + Drainage + Soil Water Change.

Components and processes within the soil water balance

Rainfall

Rainfall amount, frequency, reliability and intensity are all important considerations. Specific requirements include rain for planting and crop establishment, rain during the growing season, rain for fallow water accumulation, start and end of wet season, etc. Matching crop requirements to rainfall expectations and stored soil water becomes more important and more difficult with decreasing rainfall.

Runoff

Runoff is a loss that should be minimized to increase soil water available to crops and to decrease erosion and off-site effects. The amount of runoff can be influenced by soil surface conditions (roughness and cover), rainfall characteristics (amount, intensity) and antecedent soil water content (surface, subsurface). Surface roughness is useful at the start of a fallow but is difficult to maintain during seedbed preparation and during wetting and drying cycles. Cover can decrease runoff markedly, particularly when the soil is dry (Figure 1) (Freebairn and Wockner, 1986). Similar effects have been measured near Emerald (Table 1). Cover prevents degradation of the surface soil structure and therefore maintains a higher infiltration rate. When the soil is fully wet, the infiltration rate is determined by the hydraulic conductivity of the soil, and cover has a small effect (Figure 1).

Infiltration

Infiltration is far more important than runoff from a soil water management perspective. On an annual basis, infiltration can be more than 90% of rainfall, and factors which markedly affect runoff will have only a small effect on infiltration. The dominant effect on infiltration is soil water content (Figure 1). Annual infiltration will be increased by maintaining higher soil water deficits. The soil hydraulic conductivity, soil cracks, rainfall intensity, and cover can also influence infiltration. Infiltration into Vertisols is not well understood and is being studied by our group in Queensland using rainfall simulators and small catchments (1 to 15 ha). Currently attempts are being made to estimate

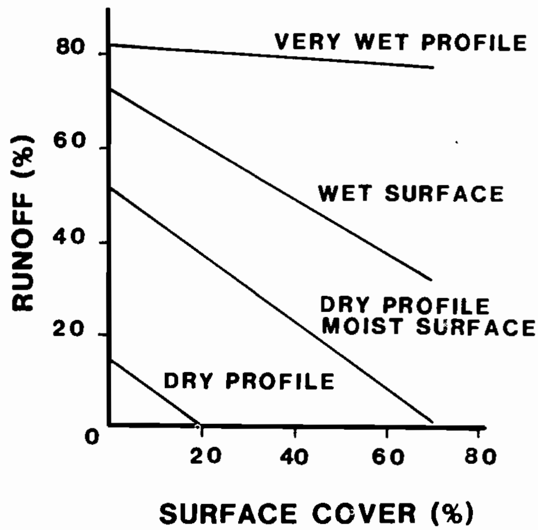

Figure 1. The effect of surface cover on runoff: Greenwood Grey Clay (Freebairn and Wockner, 1986).

Table 1. Effect of stubble cover from three crops on runoff from a single event (P = 23 mm) at Emerald.

Crop	Cover (%)	Runoff (mm)
Sunflower	9	10.0
	16	4.3
	42	1.6
Sorghum	29	3.8
	43	1.4
	44	1.0
Wheat	78	0.2
	84	0.3
	90	0

Source: M.M. Sallaway, QDPI, Emerald.

the time course of infiltration from runoff data by solving the surface hydrological responses of the catchments.

Many infiltration equations have been developed for noncracking soils. Both the Green and Ampt and Philip equations arise from mathematical solutions of a defined physical infiltration problem. The Horton, Kostiakov and more recent Collis-George (1980) equations are empirical expressions (with some physical basis) selected to have the correct qualitative shape. The application of these equations to both small catchments and Vertisols is complicated. Soil properties (within the physical equations) are difficult to measure due to soil heterogeneity produced by soil shrinkage. Curve fitting of empirical equations may not produce parameters with physical meaning or broad applicability. Additionally the infiltration process in Vertisols may combine one-dimensional flow through the surface and preferential flow down cracks.

The Green and Ampt equation has been applied to catchments with noncracking soils by Aston and Dunin (1979). The Horton equation, via the Boughton (1966) model, has been used for cracking clay catchments (e.g. Freebairn and Boughton, 1985). The curve number approach is similarly useful, but extrapolation beyond measured catchments seems difficult. The pragmatic equation of Collis-George (1980) warrants testing. We have used a simplified version to describe infiltration in Vertisols during flood irrigation. In this application the parameters were related to soil properties, but extrapolation to other areas has not been tested.

Soil water redistribution

The distribution of infiltrated water with soil depth influences both crop water use and water loss by other mechanisms. Important factors will include total infiltration, antecedent soil water content, water-holding capacity of the soil, and soil hydraulic properties.

Evaporation

Soil evaporation is the major loss mechanism for soil water. During a drying cycle, evaporation will be influenced by evaporative demand, soil water content, soil surface condition and cover, tillage, and soil properties such as hydraulic conductivity. Since the evaporation rate decreases rapidly as the soil dries (Figure 2), the annual evaporation depends strongly on the number of wetting and drying cycles.

Evaporation losses usually decrease rapidly with soil depth and are small below 30 cm depth (Figure 3). Large soil cracks, produced by crop growth, can facilitate losses from greater depths, but usually both the rate and amount of evaporation will be small. Stubble cover can reduce the evaporation rate (Figure 2). The effects of tillage on soil evaporation have not been quantified. While process-based models exist, I am not aware of any applications to Vertisols. The empirical model of Ritchie (1972) was developed on Vertisols but possibly without the extreme drying conditions typical of the semi-arid tropics.

Vertisols have high plant-available water per unit depth and also have a large water storage between air-dry water content (the end result of soil evaporation) and −15 bar

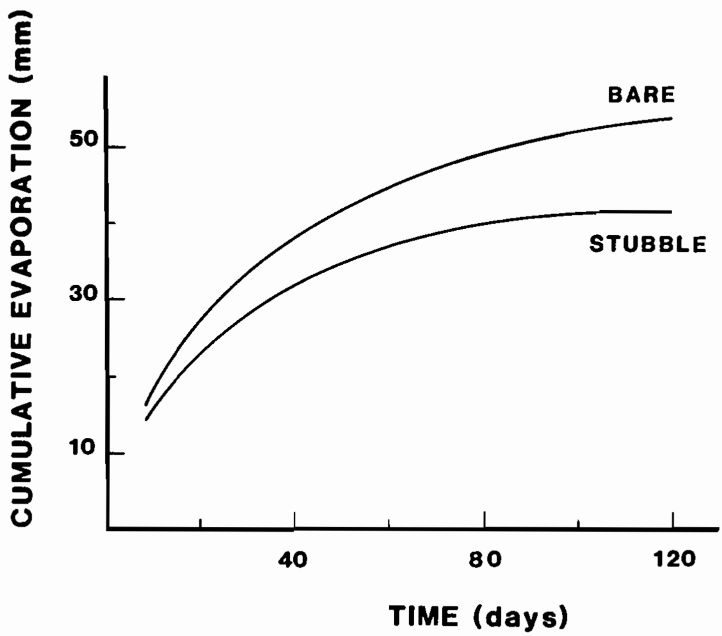

Figure 2. Soil evaporation during a long drying cycle for bare and stubble-covered plots (Yule, unpublished data).

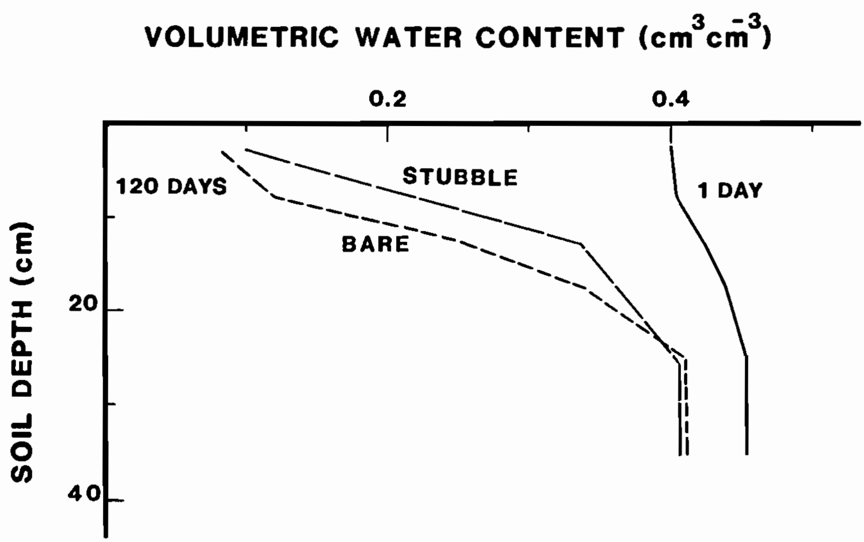

Figure 3. Volumetric water content profiles one day and 120 days after rainfall for bare and stubble-covered plots (Yule, unpublished data).

water content. Consequently, after a long dry period, very large deficits develop in the surface soil (e.g. the deficit of 30 mm at 0 to 10 cm in Figure 3) and large falls of rain are needed to penetrate to the subsoil. Rainfalls of 20 mm or less are held in the 0 to 10 cm zone and rapidly evaporate (12 days in Figure 2).

Transpiration

Transpiration rate is a function of soil water supply and evaporative demand. Other influences include leaf area index and depth, and activity of rooting. Models developed elsewhere should be generally applicable. Difficulties may arise due to high plant water-stress conditions associated with semi-arid environments. Reasonably successful models have been developed in Queensland for sunflower (Hammer *et al.,* 1982), wheat (Hammer and Woodruff, 1984) and sorghum (in progress) (Wade, pers. comm.).

Drainage

Few direct measurements of drainage in Vertisols are available from dry semi-arid tropical environments. Soluble salt profiles can be used to indicate the likelihood of significant drainage (Shaw and Thorburn, 1985). In our black basaltic cracking clays (Typic Pellusterts) salt bulges do not occur if the solum is shallower than 150 cm. If soil depth > 150 cm, it is usual to find salt accumulation in the profile. Therefore significant leaching could be expected in the shallow Pellusterts. In grey Vertisols (Entic Chromusterts) with lower hydraulic conductivity, salt bulges occur at shallow depths (50 to 80 cm). Application of water-balance models such as SPAW may allow a better definition of drainage. At Emerald on Pellusterts, indications of drainage greater than 50 mm from single-rainfall events have been obtained. These have occurred during unusually large winter rainfalls of low intensity when drainage appears to exceed runoff on most occasions. These findings suggest that hydraulic conductivity is an important soil property.

Soil water storage

Change in the soil water storage are the net results of the rainfall inputs and the loss mechanisms described. Measurement of the soil water content is a fundamental part of soil water-balance studies and will be discussed later.

Summary of soil water balance

The components of the soil water balance that are most dominant are rainfall, infiltration, transpiration, evaporation and drainage. Soil water content is used to monitor changes. The factors involved are meteorological (rainfall, evaporative demand), soil properties (PAWC, hydraulic conductivity, air-dry water content, cracking), historical (as indicated by antecedent soil water content) and soil surface management (cover, roughness).

Implications for Management

This discussion will consider the interactions of the soil and crop processes with the environment and some possible management options which may be exploited. The intent is to produce regular crops rather than irregular, large crops.

Interpretation and extrapolation of these responses is highly dependent on environmental conditions. Table 2 presents some monthly mean data for two sites in the semi-arid cropping regions of Queensland and, for comparison, Niamey and Bulawayo (Source: ICRISAT's *Agroclimatic Environment, ICRISAT Annual Report, 1984*). These centres have similar annual rainfalls. Table 2 supports the comment "as in most semi-arid areas, rainfall during the rainy season accounts for over 90% of the annual rainfall" *(ICRISAT Information Bulletin no. 19)* for Niamey and Bulawayo. By comparison, Emerald has 57% and Roma 49% of annual rainfall in the four wettest months. As a consequence the "rainy season" is comparatively more arid and less reliable for crop growth.

Table 2 shows that mean evaporation greatly exceeds mean rainfall in all months at Emerald and Roma, and that significant rain can fall in each month. These factors combine to decrease the amount of effective rainfall, and our research results may be applicable to areas with much lower annual rainfall. Additionally, successful crop production is dependent on fallow soil water storage.

Fallow water accumulation

Factors that affect fallow water accumulation are antecedent water content (deficit at harvest), rainfall, and surface management. At Emerald, fallow water storage (FS) is linearly related to soil water deficit at harvest (SWD) by the equation:

$FS = 0.55\ SWD - 13\ (n = 26, r^2 = 0.71)$ (units are mm).

Data were taken from three cropping monocultures (wheat, sorghum, sunflower) during 1982-1986. This relationship indicates that the deficit is reduced by about half during an average fallow. However a fallow following a wet harvest may produce negative storage. The high r^2 value shows that soil water deficit has the major effect on fallow water accumulation.

The effect of rainfall on the physical processes occurring has been discussed. High-intensity rain can produce runoff, rain on a wet profile can produce drainage, and frequent small rainfalls can produce high evaporation losses. This last effect is demonstrated in Table 3. If rainfall events do not exceed 30 to 40 mm, evaporation losses can reduce soil water accumulation to very small amounts.

In our studies at Emerald, surface management has had some effect on fallow soil water accumulation (Table 4). The total effect appears to be a combination of reduced runoff (in 1983/84 and 1985/86) and reduced evaporation (1982/83). Fallow efficiencies are very low ($< 35\%$) and, as expected, depend strongly on soil water deficit at harvest. The achievement of high fallow efficiency is further complicated by feedback mechanisms within the water balance. Clearly a treatment that increases infiltration during one rainfall event may produce higher evaporation or greater runoff from subsequent

Table 2. Monthly mean values of rainfall, class A pan evaporation and maximum temperature for four sites.

		JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	TOTAL
Emerald	R*	106	100	74	36	28	40	29	21	26	39	57	81	638
	E	232	188	177	153	118	93	108	133	180	232	252	260	2126
	T	35	34	33	30	26	23	23	25	28	32	34	35	
Roma	R	81	76	65	31	34	36	38	26	34	49	55	68	593
	E	235	199	186	141	93	63	71	99	138	186	222	248	1881
Niamey	R	0	0	0	0	35	85	150	205	95	10	0	0	580
	E	160	170	215	210	220	200	160	130	130	175	160	135	2050
	T	34	36	40	41	40	37	33	31	33	37	37	33	
Bulawayo	R	140	120	70	25	10	0	0	0	10	30	90	130	625
	T	31	30	27	25	24	20	22	25	27	30	27	29	

* R = Rain (mm)
E = Class A pan evaporation (mm)
T = Maximum temperature (°C)

Table 3. Soil water accumulation during fallows as related to rainfall amounts.

Stubble	Date	Soil water deficit (mm)	Soil water change (mm)	Total rain (mm)	Rainfalls > 30 mm (mm)
Wheat	29.2.84	105			
	21.6.84	112	− 7	80	Nil
Wheat	21.6.84	112			
	8.8.84	37	+75	123	75,38
Sunflower	28.6.84	161			
	25.1.85	78	+83	310	75,45,39 37,38
Sunflower	25.1.85	78			
	2.5.85	67	+11	126	Nil

Table 4. Soil water balances during sunflower fallows for reduced tillage (RT) (blade plough, tyned cultivators) and zero tillage (ZT) systems.

	1982/83		1983/84		1984/85		1985/86	
	ZT	RT	ZT	RT	ZT	RT	ZT	RT
Rainfall (mm)	246	246	272	272	459	459	164	164
SWD at harvest (mm)	155	174	72	40	161	186	121	153
Runoff (mm)	27	25	13	23	8	8	11	27
Soil water accumulation (mm)	73	44	21	−6	107	114	57	53
Fallow efficiency (%)	30	18	8	−2	23	25	35	32

rainfall. The net result is generally conservative responses to soil management, particularly over longer times or several rainfalls. Therefore stored soil water should be used productively (for transpiration) as soon as possible.

Surface management

Surface management and soil physical amelioration techniques can influence the soil water balance. Our emphasis has been on tillage and cover effects, and the responses within the soil water balance have been discussed. The implications for management by our farmers using heavy machinery include a longer time after rain before planting can commence, a longer time when planting conditions are optimum, and the need for new equipment to handle high stubble levels. Herbicide technology is well advanced, though generally too expensive to be economic for complete zero till. Opportune herbicide spraying can be highly effective, for example, to control weed growth when the soil is too wet to cultivate, or to allow rapid weed control postharvest prior to double-cropping.

Cultivation methods have changed dramatically. Disc ploughs have been replaced by tyned ploughs with sweeps. This has increased stubble retention and decreased soil disturbance. The number of cultivations needed to prepare a seedbed can be reduced. While tillage for weed control requires subsequent tillage to prepare a seedbed, direct drilling following chemical weed control is possible. The self-mulching characteristic of Vertisols produces adequate seedbed properties for seedling establishment. The implications are that tillage should be reduced and should aim for minimum soil disturbance while achieving the main aim of weed control.

Cultivation for surface water retention can be effective. Soils with a rough surface can absorb high-intensity rainfalls, particularly when dry. No-till treatments may seal and run off. However the conditions when such rough cultivation can be effective have not been defined. Additionally, the rough surface degrades naturally during wetting and drying cycles, and a seedbed must be prepared. The use of furrow dykes, basin listing, etc. may have potential as appropriate machinery is developed. Research at Emerald in the 1960s found no advantage from basin listing for fallow water accumulation. However, this was an extremely dry period with little runoff (D. Younger, pers. comm.).

The most common manipulation of surface configuration used on Vertisols in Queensland is contour banks. About 850 000 ha of cropped land have been contoured. Contour banks are installed to decrease soil erosion, to prevent gully formation and to control runoff. While no direct effect on the soil water balance has been measured, the opportunity exists for increased infiltration (and possible deep drainage) in the channel of the contour bank. Soil erosion is such a major concern that any proposed management system must consider the implications for runoff and soil erosion control.

Gypsum can be effective in reducing runoff, increasing soil water storage, and increasing crop yields (So and McKenzie, 1984). However these responses are not achieved consistently. In a number of experiments on the Darling Downs, Queensland, yield increases have been recorded, but without an increase in fallow-soil water storage (G.D. Smith *et al.*, 1986). The seasons were wetter than normal and possibly did not allow expression of a gypsum response. The explanation of gypsum responses, and therefore the situations where a response can be expected, requires further clarification.

Vertical mulching at intervals of 4 m and 8 m has increased soil water recharge and crop yields in India (Rama Mohan Rao *et al.*, 1977). Gypsum enriched slots (mixing high rates of gypsum into a trench) are being tested in Australia (Jayawardane and Blackwell, 1985). Deep ripping on the contour has increased infiltration into a dry soil during heavy storms. These developments in the management of Vertisols indicate considerable potential, but the circumstances needed for successful implementation must be defined. Presumably they function by intercepting runoff.

In summary, a wide range of options exist to manage the soil surface so as to manipulate the soil water balance. It is now opportune to develop management systems incorporating these options. These systems should be based on the philosophy of zonal tillage (Larson, 1963), i.e. managing zones of the field for their intended use: for example, zones for seedbed, traffic, infiltration, root growth, runoff, etc. Such systems have been developed for Vertisols in India (El-Swaify *et al.*, 1984) and for Red-Brown Earths in Australia (Adem and Tisdall, 1984). These systems are designed around permanent beds and consequently provide excellent control of machine operations. Therefore contour banks or furrows, vertical mulching, tie ridging, etc. could be incorporated. Using this approach, systems can be designed to optimize the soil water balance for crop production.

Crop water use

Cropping requirements include rain for crop establishment and rain or stored soil water for crop growth. In Queensland, it is usual to plant after rain. A "planting rain" must wet the soil to the depth of stored soil water, that is the zone of soil evaporation. As stated previously, this may require 30 to 40 mm of rain. Planting dry in the expectation of rain is very uncommon. However this management option should be evaluated for summer crops in relation to rainfall probabilities. Manipulation of surface configuration may also be useful (Coughlan *et al.*, in press). Furrows could decrease the depth of dry soil and allow localized runoff to concentrate. A zonal tillage system would allow subsequent planting in the furrows.

Water for crop growth will be supplied by rainfall and stored soil water. The principles have been discussed in relation to fallow water accumulation. Due to the large inefficiencies in soil water storage, rainfall on crops must be potentially more efficient. Therefore, if water for cropping is limited, some crops should be grown during the rainy season.

Many aspects of crop agronomy offer options for soil water management. A range of crops and planting dates are needed to take advantage of soil water when it is available. This is more important in regions without discrete rainy seasons such as Queensland. Satisfactory planting conditions can occur in virtually every month of the year. However planting at Emerald is generally confined to the periods from December to May and from August to September, and the crops grown are sorghum, sunflower, wheat and maize with smaller areas of pigeonpea and chickpea. At Roma, summer crops are less successful due to the lower rainfall expectation, and wheat is the most common crop. Sorghum, sunflower and chickpea may be grown if conditions are favourable.

A range of crops and a range of varietal maturity can provide a large spread of possible planting dates. The decision to plant must, then, be based on an assessment of stored soil water and the probability of sufficient rain on the crop. These assessments can be carried out using appropriate crop and water-balance models and historical meteorological records. We are currently developing these models by combining our research work with available models (Freebairn *et al.*, 1986). As indicated previously, modelling the soil water balance during the crop cycle is probably more advanced than during the fallow, but a major limitation relates to the definition of suitable conditions for planting – how much stored soil water is needed? what constitutes a planting rain? These questions can be addressed using models, and the results expressed in terms of a yield probability curve.

Plant population can be based on available soil water at planting, although under Queensland conditions benefits from low populations and wide row spacing (2 to 4 m) occur only at yield levels below 900 kg ha (Thomas *et al.*, 1981). In intensively farmed areas, it may be possible to respond to improved seasonal conditions by intercropping. The previously described zonal tillage system would facilitate this possibility. For extensively farmed areas, strip-cropping may have potential. The minimum width of strip would be determined by tillage, planting and harvesting machinery.

While crop growth and yield are limited by water stress, soil fertility must be adequate for the expected yields. Despite low soil nutrient levels in many central Queensland Vertisols (bicarbonate phosphorus 6-10 ppm and total nitrogen $< 1\%$), fertilizer responses are rarely measured. The adequate phosphorus nutrition is apparently due to mycorrhizal associations (Hunter and McCosker, 1982; Hibberd *et al.*, 1986).

Adequate weed control is necessary to maximize crop water use. In particular, large or perennial weeds can use water from below the evaporation zone. A particular problem in our zero-till experiments is grain sorghum regrowth, because it is difficult to kill postharvest and has a well-developed root system.

In our environment, flexible crop rotations are essential to maximize crop water use. A system of opportunity cropping has developed. Cropping systems are particularly difficult to research and few specific data are available. Our assessment will be based on long-term simulations using crop models developed from experiments with monocultures. Consequently synergistic effects tend to be neglected.

In summary, crop water use can be maximized by using a wide range of planting-time options and by controlling weeds. High soil water deficit at harvest will increase fallow efficiency. The most important decision is "When to plant?", and further research is needed to define planting conditions based on stored soil water and rainfall probabilities. Every planting opportunity must be taken if efficient water management is to be achieved.

Measurement of the soil water balance

Gravimetric water content

The vast majority of our work has involved gravimetric sampling with thin-walled tubes and machined cutting tips. Tubes are driven hydraulically or by jack hammer. All weighing is now automated so that gravimetric water content calculations involve only internal computer manipulations. This has decreased the time involved and prevents transcription and data entry errors.

Bulk density

Bulk density is needed to convert gravimetric values to a volumetric basis. Bulk density is not constant in Vertisols due to the shrink-swell property. Possible approaches to these problems have been discussed by Yule (1984b), Bridge and Ross (1984), and Ross (1985). The soil shrinkage curve, which relates bulk density or shrinkage to soil water content, can be obtained by slowly drying undisturbed cores in the laboratory (Yule and Ritchie; 1980; Yule, 1984a). The shrinkage curve defines the swelling limit and allows accurate bulk density calculation at all water contents.

An approximate bulk density that is sufficiently accurate for many applications was calculated by Yule (1984b) from

$$BD = \frac{1 - E}{\frac{1}{PD} + \sigma_{gl}}$$

where BD = bulk density
E = air content
PD = particle density (usually assumed 2.65 g cm^{-3})
σ_{gl} = gravimetric water content at the swelling limit (approximated by sampling 2 to 3 days after rain)

The assumed density of water is 1 g cm^{-3}. The air content of fully wet soil varies with soil depth (Table 5). The values at 0 to 20 cm depth are based on few data and may change with further sampling. Additionally, these values can be influenced by tillage, self-mulching, crusting, etc. This approximate bulk density can be used at all water contents with errors in profile water-content change of less than 4% (Yule, 1984b). This method accounts for soil shrinkage but does not account for sampling errors associated with soil shrinkage.

Table 5. The effect of soil depth on the air content of fully wet soil (approximately the swelling limit).

Depth (cm)	Air content (cm^3 cm^{-3})
0-10	0.2
10-20	0.1
20-100	0.07

Soil shrinkage

Soil shrinkage can be used to estimate profile water-content change (Yule, 1984a). Since shrinkage is equidimensional, profile water-content change will be approximately three times the change in the soil surface elevation. This method could also be calibrated in the field. I am not aware of any reports where this method has been attempted, although it would provide a quick estimate of profile water-content change for irrigation scheduling or to support a planting decision.

Neutron moisture meter

The neutron moisture meter has been widely used in Vertisols, but few calibration curves have been published. It is unclear if the problems associated with soil shrinkage around the access tube have been addressed. We are currently evaluating a field calibration experiment (Greacen *et al.*, 1981) in which we used soil shrinkage curves to calculate bulk density (S.E. Ockerby and D.F. Yule, unpublished). Preliminary results suggest that the calibration equations vary with both depth and soil type (two Vertisols were examined). The correlation coefficients of linear regression equations for each depth were generally greater than 0.9. These results suggest that the neutron meter is useful in Vertisols provided field calibrations are used.

Runoff

While runoff is generally a small portion of the soil water balance, its measurement allows an independent check of the other estimates. Even estimates of runoff or observations of occurrence of runoff are often helpful in interpretation of other data. Additionally it is usual to calculate some factors (for example, drainage) in the water balance by difference. Runoff measurement is not difficult and measurements over time may allow estimates of soil infiltration parameters.

Plant-available water capacity (PAWC)

A measurement or estimate of PAWC is needed for water-balance interpretation or modelling. Details are discussed by Coughlan *et al.* (these proceedings).

Modelling

The end result of most of our research will be the development of appropriate models of the soil water balance, erosion and crop production. As Smith *et al.* (1984) have stated, modelling is seen as a tool to extend and extrapolate research results. Estimation of the soil water balance over large areas or many fields can be most efficiently achieved by models. Our development of models is proceeding by (a) testing available models with our data sets and (b) process research to define relationships within the models. A number of models are currently being used with considerable success (Freebairn *et al.*, 1986), but weaknesses within the soil water balance (as previously outlined) remain a limitation.

Conclusion

This paper has provided a broad outline of the processes and principles involved in soil water management based on the soil water balance. The soil water balance has been discussed for Vertisols in the semi-arid cropping regions of Queensland. While a solid base of knowledge exists, much research is still needed to better define the processes within the soil water balance on Vertisols. Major emphasis should be placed on infiltration under rainfall and soil evaporation during fallows and when crop cover is small. Since the soil/crop/environment interaction dominates these responses, integrated research across a range of Vertisols and environments must produce highly robust solutions to these problems.

Similarly a vast amount of knowledge exists about crop water use, but its applicability to the high-stress environments of the semi-arid tropics must be rigorously tested across soils and environments. This research should culminate in the development of robust models which can then provide a basis for the development of soil management systems specifically for Vertisols in the semi-arid tropics.

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CHEMICAL FERTILITY CHARACTERISTICS OF VERTISOLS

P.H. Le Mare*

Abstract

Most Vertisols are neutral to alkaline; their dominant clay minerals are smectites; they often contain little organic matter and organic nitrogen, and they may have a large C:N ratio. The most important nutrient deficiency is usually nitrogen. Urea and ammonium fertilizers may lose ammonium ions, which associate with the smectite clay minerals. In general, responses to phosphate have been small, but some large responses have been reported. Response to phosphate is sometimes related to water supply: ferric hydrous oxides may absorb phosphate when Vertisols are dry, but some is released when they are flooded and iron is reduced. There has been little investigation of the nature and behaviour of phosphate in Vertisols, but work on Greek and Asian soils has indicated that sorption of phosphate is less than in many acid soils of the tropics. There are few reports of responses to potassium; although Vertisols fix potassium, the concentrations maintained in solution are generally adequate for most crops. The micronutrients most often deficient are iron and zinc. Harmful amounts of exchangeable sodium occur in some Vertisols.

Introduction

The principle areas of Vertisols are in Australia, India, and Africa, but they are also found in many smaller areas elsewhere in the tropics and subtropics. This paper collates reports from India, Africa and the Middle East; it includes reports on soils that were referred to as regurs, grumusols, black cotton soil, and other terms which were used before Vertisol became the generally accepted name for black cracking clay soil. Vertisols are almost identical in different classification systems and include most black tropical clays

* Department of Soil Science, University of Reading, London Road, Reading RG1 5AQ, England.

(D'Hoore, 1968). McGarity *et al.* (1984) edited a good review of Australian Vertisols so they are not considered in detail here. Other reviews of Vertisols, mainly Indian and African, have been made by Finck and Venkateswarlu (1982) and Virmani *et al.* (1982).

In the areas considered here, two large zones of Vertisols occur, in the Deccan plateau of India, reviewed by Landey *et al.* (1982), and in southern Sudan. Elsewhere in Africa, large areas occur in Chad and Ethiopia; there are smaller areas of Vertisols in many other countries, but for these there are few reports of investigations.

Effects of fertilizers in Vertisols

Investigations of the chemical fertility of Vertisols have a long history in Sudan, based on the Gezira irrigated agricultural project established in 1911. Nitrogen deficiency was recognized from the start (Crowther, 1948; Snow, 1948; Ferguson, 1953) and there have been many experimental investigations since 1919. Burhan and Mansi (1970) reported the results of an eighteen-year experiment which confirmed response to nitrogen; phosphate deficiency was less critical but response was related to soil moisture. Effects of potassium and micronutrients have been negligible. Elsewhere in Africa, Hagenzieker (1963) reported large responses to nitrogen and phosphorus in Ghana; smaller effects occurred on mbuga soils in western Tanzania (Scaife, 1968; Spence and Smithson, 1967) and at Kibos in the Kano Plain of Kenya (Hastie, 1966); on the Kafue Flats of Zambia, nitrogen increased yields of cotton and other crops, but there was little or no effect of phosphorus (Kerkhoven, 1963; 1964); these authors reported that potassium fertilizer did not affect yield.

Similar results were reported from Andhra Pradesh, India. Responses of cereals to nitrogen were very large; band placement of the fertilizer was better than broadcasting. Response to phosphate was small, which is especially interesting because the amount extracted by sodium bicarbonate solution (Olsen reagent) was also small, less than 2.5 μg P g^{-1} of soil (ICRISAT, 1981; 1984). However, Finck and Venkateswarlu (1982) quote results of a field experiment in India where there was a very large response to phosphate by sorghum.

Surface samples of two Vertisols in Syria (ICARDA, 1981) contained about 6 μg P g^{-1} of soil extractable in $NaHCO_3$. Wheat responded to phosphate, especially when it was band placed (Matar, 1985).

Clay mineralogy

The most common clay minerals are smectites, as the criterion of cracking in the definition of Vertisols implies. In the Deccan plateau of India, the Vertisols are the lower member of a catena, associated with red soils derived from the same or similar parent material. The Vertisol clay mineral is largely beidellite (Nagelschmidt *et al.*, 1940), montmorillonite (Chatterjee and Rathbone, 1976), or described more generally as montmorillonitic (Lotse *et al.*, 1974). Some kaolinite or other 1:1 layer silicate often occurs with the smectite mineral.

In the clay plains of the Gezira (Fadl, 1971) and the Fung (Bunting and Lea, 1962) in Sudan, montmorillonite is dominant, accompanied by some kaolinite; but in Khashm el Girba illite is present (Blockhuis *et al.,* 1964). In the Athi plains of Kenya (Stephen *et al.,* 1956) and the coastal area of Ghana (Stephen, 1953) the clay is largely montmorillonite in the Vertisols, whereas in Togo aluminous beidellite occurs (Konnetsron *et al.,* 1977). In Tanzania, the black cracking clays in the south (Muir *et al.,* 1957), the mbuga soil in the Ukiriguru catena (Calton, 1963), and the Vertisols of the West Lake region (Moburg, 1973), contain montmorillonite as the dominant mineral, with some kaolinite present, but in the Lubiri mbuga soil in central Tanzania illite is dominant, with accessory kaolinite (Anderson, 1957).

The common mineral characteristic of Vertisols, namely that they contain 2:1 layer silicates, usually smectites, is the basis of some chemical characteristics, especially cation behaviour, including ammonium and potassium fixation and cation-exchange capacity, that affect their fertility. The cation-exchange capacity is commonly in the range 30-60 me/100 g of soil (Jewitt, 1955; Landey *et al.,* 1982; Ahmad, 1983).

Chemical Characteristics

Vertisols are generally plains or valley soils, often the lowest member of a catena in which richer minerals were formed with ions received from higher members of the catena. The potential productivity of Vertisols is greater than soils above them, but their use and productivity may be limited by physical properties which make their management for arable cropping and grazing difficult during the wet season. Where these problems are overcome, some chemical characteristics may limit production.

pH

The Vertisols in Sudan have surface soil pH in water in the range 8 to 9.5 with little change below the surface (Robinson *et al.,* 1970; Bunting and Lea, 1962). Elsewhere in Africa the Vertisols are less alkaline or slightly acid (Anderson, 1957; Stephen, 1953; Stephen *et al.,* 1956; Muir *et al.,* 1957; Calton, 1963; Brammer and de Endredy, 1954). In India, Vertisols are alkaline, in the pH range 7.2-8.5 (Simonson, 1954; Landey *et al.,* 1982; ICRISAT, 1984). Acid Vertisols, pH 5.0-6.2, occur in the Caribbean area (Ahmad, 1983).

Organic carbon and nitrogen

The Vertisols of India have 0.3-0.9% organic carbon (Simonson, 1954; Singh, 1954; Landey *et al.,* 1982; ICRISAT, 1984) and similar amounts occur in the Gezira soil, in which there is little change with depth (Robinson *et al.,* 1970). In central, western and southern Tanzania (Anderson, 1957; Muir *et al.,* 1957; Mbourg, 1973) and in Ghana (Brammer and de Endredy, 1954) there is up to 4% organic carbon in Vertisols. In Syria, two samples contained about 0.45% organic carbon and 0.06% total nitrogen (ICARDA, 1981).

In general, Vertisols contain little organic carbon, especially when they are cultivated continuously. The dark colour of Vertisols, despite small amounts of organic matter in many of them, is caused by complexes of it with the smectite clay, probably with some contribution by sorption of Fe, Mn, Ca, and Mg (Singh, 1956).

Organic matter and crop production

Jones (1957; 1958a) investigated the complex effects of rotations involving cotton, sorghum, Dolichos lablab and bare fallow. During six years, rotational cropping did not increase organic nitrogen content beyond an equilibrium amount which was presumed to be a function of environmental conditions. Changes in nitrate nitrogen depended upon the nature of the rotation and on the time of year. Nitrate accumulated in the surface at the beginning of the rainy season but was rapidly leached. Organic nitrogen was independent of rotation phase; cotton yields were not limited by organic nitrogen but by physical conditions which improved with fallowing. Soil organic nitrogen and nitrate nitrogen did not seem to function interdependently.

Seasonal changes of organic carbon showed a phase of slow fluctuation when the soil was wet and carried a crop, and a phase of rapid fluctuation when the soil was bare, dried by insolation, and cracked (Jones, 1958b). Rotations did not affect the organic carbon:organic nitrogen ratio, which was 13:18, but it fluctuated between seasons: the ratio increased during senescence of the crop and decreased during the hot, dry period that followed, and during crop growth (Jones, 1958c).

In Tamil Nadu, India, farmyard manure and NPK fertilizers, applied to eight crops grown with irrigation during three years, increased organic carbon and organic nitrogen. This effect was caused by the extra crop residues which the manures and fertilizers produced (Mathau *et al.,* 1978).

At Nagpur, under annual dressings of NPK fertilizers and farmyard manure for eight years, organic nitrogen fractions, especially humin-N and amino acid N, predominated under all treatments. Farmyard manure increased total and organic nitrogen, and green manure increased nitrate nitrogen more than fertilizers (Purinak *et al.,* 1978).

Nitrogen transformations

Investigations of microbiological activity in Gezira soil (Musa and Mukhtar, 1969; Musa, 1971) showed that there was much activity in surface soil but it decreased down the profile. Moisture, from rain or irrigation, stimulated activity. Musa (1970) observed that the *Nitrosomonas* population increased more rapidly than *Nitrobacter* so that at the beginning of the crop season nitrite may accumulate for a short time. Nitrate accumulated later and moved down the profile; little nitrate was formed during hot, dry months. The effect of drying and wetting on biological activity and nitrate production may be especially important in Vertisols.

Nitrogen fertilizer is necessary for sustained large crop yields, so its reactions in Vertisols are important. Ammonia volatilization can cause serious waste of fertilizer.

Musa (1968a) reported that loss of ammonia was fastest during the first week after application; there was greater loss from ammonium sulphate than from urea. Loss was lessened by increasing the amount of irrigation water, but the loss was increased when the soil was alternately dried and wetted. Loss of ammonia was greater where fertilizer was more concentrated, so patchy distribution of fertilizer and frequent light showers may cause poor recovery of fertilizer nitrogen by crops (Musa, 1968b).

The Gezira soils contain up to 0.3 me of fixed ammonium per 100 g of soil, comprising 12 to 20% of total nitrogen (Said, 1973). The fixation capacity, which is associated with smectite minerals in the clay, increases with depth, but cropping and fertilizer practices have little effect on ammonium fixation.

Ayed and Wild (1983) reported that in three Gezira soils no nitrate accumulated except in the lower layers of a natural reserve plot. All samples contained about 12 ppm of NH_4^+; their large capacity to fix NH_4^+, and the amount of NH_4^+ fixed, was three times greater after drying and increased with depth, where it accounted for a larger proportion of total nitrogen. Long-term field treatments seemed to have no effect on the fractions of N that were measured.

Ayoub (1986) investigated uptake of nitrogen from urea using ^{15}N in the Gezira. The amount of N taken up by cotton from urea placed 10 to 20 cm deep was 45% more than when placed on the surface. Recovery of fertilizer applied to sorghum at sowing time was small, but improved when the fertilizer was given four weeks later.

Phosphorus

The responses to the fertilizers mentioned above indicate that lack of phosphate is not generally a major limitation to crop production; hence there has been little chemical investigation of the amount, nature and behaviour of phosphate in Vertisols.

Phosphate sorption

Nychas and Kosmas (1984) measured sorption of phosphate by three Greek soils: the amounts of phosphate adsorbed by surface and subsurface samples were similar to those adsorbed by many acid, kaolinitic soils. Unpublished sorption data from Vertisols of Andhra Pradesh by K.L. Sahrawat and G.P. Warren, and of Pakistan by A. Rashid (pers. comms.), showed that amounts of phosphate adsorbed were similar to those in the Greek soils. However, all these Vertisols adsorbed very much less phosphate than some acid Ultisols, Oxisols and Andepts from West Africa and South America (Le Mare, 1982). The few data available indicate that phosphate is probably weakly held in Vertisols, and that it maintains concentrations which are adequate to prevent severe deficiencies in many crops, as most field experiments indicated.

Phosphate and soil water

The effect of water on phosphate availability in Vertisols is important: phosphate responses tend to be smaller and less consistent in irrigated and flooded soils than in soils that grow crops under rainfall. In flooded Vertisols iron exists as Fe^{++}, but when soils dry the iron is oxidized and poorly crystalline ferric hydrous oxides form; these may adsorb phosphate so that its availability is diminished, but the phosphate may become available when the iron is reduced after the soil is wetted again. Willett and Muirhead (1984) indicated that this mechanism is important for phosphate availability in New South Wales Vertisols; they also found that phosphate sorption was less if fertilizer was placed rather than broadcast.

Turner and Gilliam (1976a, 1976b) recognized that rice in lowland flooded Vertisols responded less consistently to phosphate than crops on similar upland soils. They considered that reduction of ferric phosphate may not account wholly for the difference, and that in alkaline soils more phosphate was likely to be associated with calcium than with iron. Later, ICRISAT (1984) reported that in a Vertisol from Andhra Pradesh, about two-thirds of phosphate was associated with calcium, and about one-third with iron; there was very little aluminium phosphate. Turner and Gilliam measured a number of phosphate characteristics to investigate the effects of waterlogging on diffusion of phosphate in Vertisols in Andhra Pradesh and Tamil Nadu, India. More phosphate was adsorbed by an anion exchange resin from a saturated soil than from a moist soil; this effect occurred before reducing conditions were established in the saturated soil, so the extra phosphate sorbed by the resin was not from ferrous phosphate. Measurements of capacity, kinetic and intensity factors of phosphate were not consistently affected by saturation of the soils with water, but diffusion coefficients increased greatly as moisture increased, especially beyond one-third bar. In split-root experiments with rice, uptake of phosphate and growth of shoots increased with moisture level. Turner and Gilliam concluded that the better availability of phosphate in flooded soils was related to improved diffusivity, caused by decreased tortuosity.

Katyal and Venkatramayya (1983) reported that in a phosphate-deficient Vertisol in Andhra Pradesh, concentration of P was influenced only slightly by flooding, but the concentration was 2.5 times greater in the wet than in the dry season, irrespective of flooding. The effect was attributed to temperature, which was 10°C higher in the first two months of the wet season then in the corresponding dry season. Effects of iron were not investigated.

Sulphur

There are few reports of sulphur deficiency in Vertisols, despite their small organic-matter content. In most Vertisols, gypsum in the profile probably ensures adequate sulphur for crops.

Cations

Potassium

Forms of potassium in sixteen profiles in Karnataka, India, were investigated by Kalblade and Swamynatha (1976). The range of total K was 12-49 me/100 g; cation-exchange capacity was 33-62 me/100 g, and exchangeable K was 0.5-1.3 me/100 g. The content and distribution of potassium was not related to potassium in the parent materials, and various fractions were not related to total K. Potassium soluble in water, nitric and citric acids and exchangeable K were intercorrelated; exchangeable and citric acid soluble potassium were correlated with silt, clay, organic matter, cation-exchange capacity and pH. In 22 soils of Rajasthan, India, the range of fixation was 2.5 to 25 me/100 g, with mean 7.5 me K per 100 g of soil (Bhatnagar *et al.*, 1973).

The lack of response to potassium in Vertisols in Sudan led Finck (1962) to investigate whether fixation caused inefficient use of fertilizer potassium, or whether, despite fixation, an adequate supply of potassium was maintained by the soil. Despite much clay, the soils have only moderate K reserves, but exchangeable potassium was large: more than 400 $\mu g\ g^{-1}$ (I me/100 g) in most soils; fixed potassium was about 8 me K per 100 g of soil. The more productive areas have more clay and available potassium. Potassium in young cotton leaves was about 3% of dry matter, more than is normally adequate. Potassium fixation was independent of clay content but the amount fixed was positively correlated with potassium concentration round clay particles. Fixation increased as more potassium was given. Finck concluded that, despite fixation, the soils supplied adequate potassium for cotton production.

Said (1971) showed that drying the Gezira Vertisol increased exchangeable potassium, and the effect was greater as intensity of drying increased. Both exchangeable potassium content and the amount released on drying were positively correlated with clay content. The effects of drying were less in soils treated with potassium then in untreated samples. Some of the potassium released on drying was fixed when soil was moistened and incubated, but the amount fixed was less than the amount released when the moist field soil was dried.

Calcium and magnesium

Deficiencies of these nutrients are unlikely in most Vertisols because their exchange capacities are dominated by calcium and magnesium, whose relative amounts are related to the origin of the soil: calcium is dominant in soils derived from calcareous materials but magnesium may be as much as calcium, or more, in soils derived from basic igneous and metamorphic rocks, and from marine sediments (Ahmad, 1983). Imbalance of the magnesium:potassium ratio may occur in soils with little magnesium and much potassium.

Sodium

Exchangeable sodium is important in some Vertisols. Robinson *et al.* (1970) concluded that a satisfactory exchangeable sodium percentage in Gezira soils is between 6 and 25, with optimum about 10. The range is larger than is suitable in other kinds of soil. The importance of the exchangeable sodium percentage is largely physical: much water enters the soil through the surface cracks which develop between irrigations; exchangeable sodium enhances swelling and cracking so that water penetration is better.

The basis for land classification in Gezira for many years was the sodium value, which expressed soluble plus exchangeable sodium per 100 g of clay. However, Finck and Ochtman (1961) indicated that clay content was better, except that sodium measurements were necessary to exclude sodic soils. Nevertheless, Robinson (1971) reported that the best soils have 0-15% exchangeable sodium and poor soils more than 25% in the top 30 cm. More exchangeable sodium occurs below 30 cm in all soils.

Micronutrients

Deficiency of iron occurred in central Tanzania (Le Mare, 1959) and of zinc in the Fung of Sudan, where the interaction with phosphate was important (Bunting, 1957). Both elements were deficient in Madhya Pradesh (Rai *et al.*, 1970) and in Uttar Pradesh, where zinc and iron were antagonistic; concentration of iron in rice tissue was greatest when the crop was in waterlogged soil, whereas zinc concentration was greatest in soil at field capacity (Tiwari *et al.*, 1976). Sarkar and Deb (1985) reported that zinc becomes unavailable in alkaline soils with much clay that contains smectite minerals.

Chemical estimates of available copper indicated small concentrations in black soils in Madhya Pradesh, but although copper sulphate applied to wheat slightly increased copper concentration in the tissue, it caused very little effect on yield (Rai *et al.*, 1972b). Similar results occurred with barley seedlings (Chatterjee and Rathore, 1974). Copper, like zinc, is strongly held by smectite minerals in Vertisols.

Investigations in Madhya Pradesh indicated that Vertisols there generally contained adequate available boron, manganese and molybdenum (Rai *et al.*, 1970; Rai *et al.*, 1972a).

Soluble salts

These may affect plant growth by their effect on osmotic pressure and its influence on intake of water. Robinson (1971) reported that soluble salts are not excessive in most Gezira soils.

Discussion

The definition of the Vertisol order is based on physical properties and does not specify a chemical or mineralogical criterion as, for example, in the Ultisol order, for which a criterion of cation-exchange capacity is specified. Hence Vertisols do not have *a priori* chemical fertility characteristics: these must be investigated and described for soils already classified as Vertisols. However, many of the chemical fertility characteristics depend upon important properties of Vertisols, especially their large amount of smectitic clay that causes turning and inversion of the soil, as implied by the Latin root of their name. These properties lead to important effects of water and aeration, which affect nutrient supply. The smectites give Vertisols a large cation-exchange capacity which enables them to hold reserves of cations; this is especially important for ammonium, potassium and some micronutrient ions. The generally small organic carbon content and large C:N ratio cause nitrogen deficiency in most Vertisols.

Repeated seasonal wetting and drying occurs in the semi-arid climates in which Vertisols occur. The smectites cause Vertisols to swell upon wetting and to crack when the soil dries again. When the soils are cracked, surface materials, especially fertilizer and organic residues, fall into the cracks and reach deeper into the soil, so that lower levels are enriched more than in noncracking soil. Amounts of organic carbon are relatively small but they vary little with depth. In cracked soil good aeration occurs throughout the profile, so oxidation of organic matter and nitrification of ammonium can occur rapidly when the soil is rewetted; but subsequently when the soil swells, and aeration is limited, reducing conditions exist.

Good aeration also ensures that, when soil is dry, iron is in the ferric state; this may cause iron deficiency, especially early in the life of a crop; but when the soil is saturated, so that aeration is poor, iron is reduced and it becomes available to the crop.

Oxidation of iron may lead to the formation of slightly soluble iron phosphates; however the solubility of these increases with pH so that the concentration of iron phosphate in solution in Vertisols will be greater than in acid soils. Nevertheless, most phosphate in Vertisols exists as calcium phosphates and these have smaller solubility than ferric phosphates at the pH of most Vertisols, so if equilibrium exists between the different forms of phosphate, calcium phosphates will control the concentration in solution. However, the repeated sealing and cracking of Vertisols, and consequent mixing, may affect the equilibrium between phosphates so that ferric phosphates may be important. When reducing conditions exist, ferric phosphates release phosphate as the iron is reduced.

ICRISAT (1974) gave an example of the small response to phosphate although the estimate of available phosphate by Olsen's solution of sodium bicarbonate was small, less than 3 ppm P. In a phosphate sorption investigation the amount of phosphate necessary to bring the concentration to 0.2 μg P cm^{-3} was constant in samples taken down to 180 cm. The small response to phosphate in apparently deficient soils may occur because small amounts of phosphate are released throughout a large volume of soil, so that the total available to a deep rooting crop is adequate for it to achieve the yield potential set by the limitations of other factors.

Little is known about the state of phosphate in Vertisols. The mechanisms mentioned, and perhaps others, may ensure that phosphate is readily available to crops. The nature of the phosphates, and their kinetic behaviour, seem important topics for further investigation – although it may not be urgent for better crop production because large response to phosphate by crops is not common.

Effects of wetting and drying seem important for the fixation and release of cations, including some micronutrients. Although concentrations of these seem to be small in many Vertisols, responses by crops are often small. There may be processes which ensure intermittent or slow release of potassium and micronutrient cations from reserves to maintain an adequate concentration. As with phosphate, in deep Vertisols a small concentration in a large volume of soil may supply crops with their needs. Nevertheless, deficiencies of micronutrients occur in some Vertisols.

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OCCURRENCE AND MANAGEMENT OF VERTISOLS FOR THE PRODUCTION OF COTTON AND OTHER CROPS IN WESTERN TANZANIA

J.G. Mowo*

Abstract

The paper outlines the properties and distribution of Vertisols in Tanzania, and discusses their management for agricultural production. At Ukirigura Research Station in western Tanzania, cambered beds were found to drain away excess surface water effectively and good yields of cotton were obtained. Cotton responded to sulphate of ammonia. The establishment of other crops, including maize and sorghum, is often poor due to waterlogging, but chickpeas in the area grow well when planted at the end of the rain. At present large areas of Vertisols in the region are used for grazing.

Introduction

In Tanzania the majority of the Vertisols are calcareous, and the calcium in these soils has accumulated and preciptiated as calcium carbonate. A few, however, are non-calcareous, and in these the exchange complex is saturated but there is no excess calcium. Vertisols are basically soils with a high clay content (clayey soils) characterized by deep wide cracks at a certain time of the year brought about by their shrinking properties when dry. Through these cracks, their moisture reserves are replenished in depth at the onset of rains. On becoming wet, the soil swells and the cracks close. The mineralogy of Vertisols varies from place to place, but they are mostly montmorillonitic, kaolinitic or illitic. In Tanzania, the dominant clay minerals are montmorillonite and illite (Anderson,

* Tanzania Agricultural Research Organization, PO Box 1433, Mwanza, Tanzania.

1963). They accumulate sodium and some are saline. Table 1 shows some of the chemical properties of Vertisols.

Table 1. Some chemical characteristics of Vertisols*

Depth (cm)	pH 1:5 H_2O	$CaCO_3$ %	Conductivity (mm/hos/cm)	Exchangeable bases (me/100g)				Total base saturation %	N %	Organic carbon %	C/N
				Ca	Mg	Na	K				
0-30	8.4	2.3	0.06	35.6	3.6	0.49	0.13	100	0.07	0.90	12.9
50-75	9.0	3.0	0.13	36.1	3.9	2.16	0.17	100	–	0.56	–

*Source: Wengell *et al.* (undated).

In Tanzania, Vertisols occupy the broad open valleys or mbugas[1] of the western (Lake Victoria), central and northern regions (Anderson, 1963). The area covered by these soils in western Tanzania is approximately 2.5 million ha. Large areas of Vertisols can be found in the Mwanza and Shinyanga regions to the south of Lake Victoria, in the Mara region – mostly around Lake Victoria and extending as far as the initial part of the Seronera region – in the Serengeti region, and in the Tabora region. Figure 1 shows the main Vertisol areas in western Tanzania.

Management of Vertisols for Agricultural Production

The drainage problem

Vertisols are well known for their high fertility, despite the fact that they suffer from a number of drawbacks. Because of their swelling properties when wet, it becomes very difficult to work these soils after a good amount of rain has fallen; and during the dry season they are so hard that it is very difficult to till them. In western Tanzania, most Vertisols lie at the bottom of the catena, where they are subject to flooding by surface water coming from the soils further up. It is only through evaporation or by surface drainage that the water can escape.

The use of these soils for optimum agricultural production must therefore involve the removal of surplus surface water to allow the soils to dry out, crack, and restore aeration before the crop suffers from waterlogging. Studies carried out at Ukiriguru Research Institute in 1964 concentrated on how best to manage these soils for a good crop of cotton.

[1] Mbuga: A flat grassy plain with dark grey to black soils, impeded drainage, and calcareous concretions.

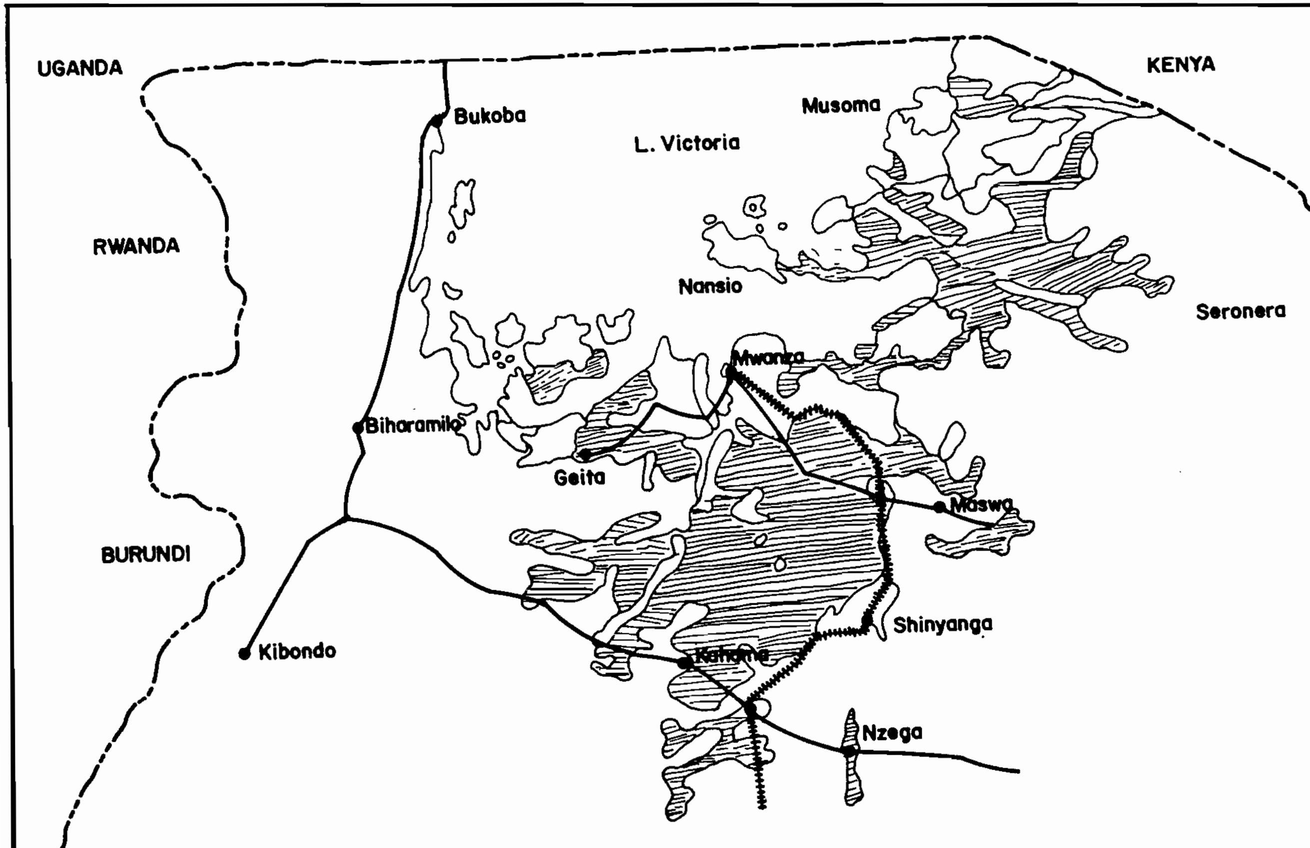

Figure 1. The main Vertisol areas in western Tanzania (Wangell *et al.*, undated).

Cambered beds for cotton production

The cambered-bed system was tried as a measure for improving drainage (Spence, 1967). These beds were prepared towards the end of the rains when it was not too wet or too dry. It was observed that the cambering of the beds enabled excess surface water to drain effectively, and the beds could be tilled within a day or two after heavy rains.

A yield of up to 2556 kg/ha of seed cotton was obtained from cotton sown at the end of December 1964 in a season when it was fairly dry (590 mm from December to May). In the following season, when it was relatively wetter (846 mm from December to May), the yield was 2778 kg/ha of seed cotton. A yield of up to 4078 kg/ha has been reported from these soils (Le Mare, 1965). It was observed at the end of the two very different seasons that the cambered beds had kept their shape, and no operations were needed for the third season. It was also found that cotton crops on these soils responded well to sulphate of ammonia, with yield increases of up to 15%. However, response to compost, phosphate, lime and gypsum were minimal or absent, while potassium depressed yields. Superimposing ridges on the beds gave similar yields to cotton sown flat on the beds.

Other crops on Vertisols

A few farmers in western Tanzania grow maize and sorghum on these soils. Some of them make ridges as a measure of improving drainage, while others provide simple waterways to remove excess water. However the establishment of plants is always poor and yields are very low. Paddy rice is commonly grown in these soils, and is planted on well-prepared bunded fields where rainwater from the hills collects. Normally this is not supplemented by irrigation, and in an abnormally dry season a substantial crop loss can be experienced. The Vertisols of western Tanzania are also well known for the production of chickpeas. These are normally grown at the end of the rainy season, since they can be established with the small amount of water available at that time.

Conclusion

Given the difficulties which have to be overcome in order to make use of these soils for agricultural production, it would appear that the commercial use of Vertisols for large-scale production of cotton – and other crops sensitive to poor drainage – is limited in western Tanzania, at least for the time being. Currently large areas under Vertisols in the region are used for grazing.

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CONSERVATION MEASURES IN VERTISOLS UNDER LARGE-SCALE WHEAT FARMING IN NORTHERN TANZANIA

R. Ngatoluwa, H. Mansoor, B.D. Majanga and J.A. McKeague*

Abstract

Wheat is produced in the highlands of northern Tanzania (latitude 4°20′ to 4° 35′S; longitude 35°0′ to 35°20′E) at elevations of 1650 to 1800 m on seven NAFCO (National Agricultural and Food Corporation) farms with a total area of 30 000 ha. Vertisols account for approximately half the area of the farms; associated soils are Mollisols, Alfisols and Inceptisols. During the early stage of development of the farms in the '70s, the land was cleared completely and farmed as fields of several hundred hectares. Sheetwash and gullying in Vertisols on slopes as gentle as 1% showed the need for conservation measures. On the established farms, strips 5 to 8 m wide and 75 to 150 m apart, depending on slope, were surveyed on the contour, and annual weeds and native grasses were allowed to become established. Shallow ditches within the contoured grass strips helped to trap water. On the new farms being developed, contoured strips of the natural grassy woodland were left at 75 to 100 m intervals. Runoff from fields and adjacent highlands was directed into natural waterways under native vegetation.

Conservation measures on new farms have been completely effective in preventing erosion. Vertisols on slopes of up to 5% are being farmed without problems of sheetwash and gullying. The contoured grass strips have been an effective conservation measure on many fields of the older farms. They enforce cultivation on the contour and provide a barrier to sheetwash. On some slopes, however, especially in areas of shallow Vertisols, runoff from intense storms has washed out recently established grass strips and formed shallow gullies. Other conservation measures are being tested in such fields.

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* Tanzania-Canada Wheat Project, Tanzania Agricultural Research Organization, Selian Agricultural Research Institute, Arusha, Tanzania.

Introduction

Wheat farming west of Hanang Mountain in the highlands of northern Tanzania (Figure 1) expanded from a few scattered farms in 1967 to a block of nearly 30 000 ha by 1986. Seven large farms (4000 ha) were developed by the government of Tanzania with Canadian aid (Nielsen, 1982). The methods used on these farms are those developed on the southern interior plains of Canada, with large implements operating in fields of several hundred hectares. Problems of erosion began to be of concern several years ago and conservation measures were applied. This paper will summarize the environmental conditions at the Hanang wheat complex, relate these conditions to erosion problems, explain the conservation measures used and assess the effectiveness of these measures. The focus of the paper is on Vertisols (Soil Survey Staff, 1975) because these soils and intergrades to Vertisols occupy nearly 50% of the area of the farms, and most of the erosion problems are associated with Vertisols and vertic intergrades.

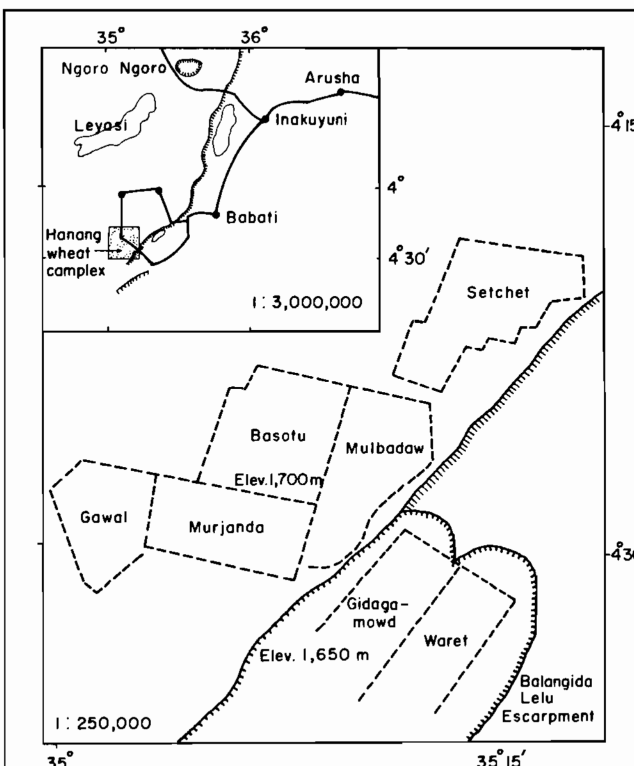

Figure 1. Map showing location of NAFCO Hanang wheat complex in northern Tanzania (inset), and of the seven farms.

Environment of the Hanang Farm Area

Location and landform

The Hanang wheat complex is located above and to the west of the main Gregorian rift escarpment in north central Tanzania (latitude 4°20′ to 4°35′S, longitude 35°0′ to 35°20′E) (Figure 1). Most of the farms are located on the long, gentle incline that forms the backslope of the rift escarpment (Figure 2). Long (1 to 4 km) gentle slopes, averaging 3% but ranging from 1 to 8%, account for most of the current and potential farmland in the area. Elevations of the farms range from approximately 1650 to 1800 m. The farms are approximately 280 km southwest of Arusha, site of the Selian Agricultural Research Institute that provides research support.

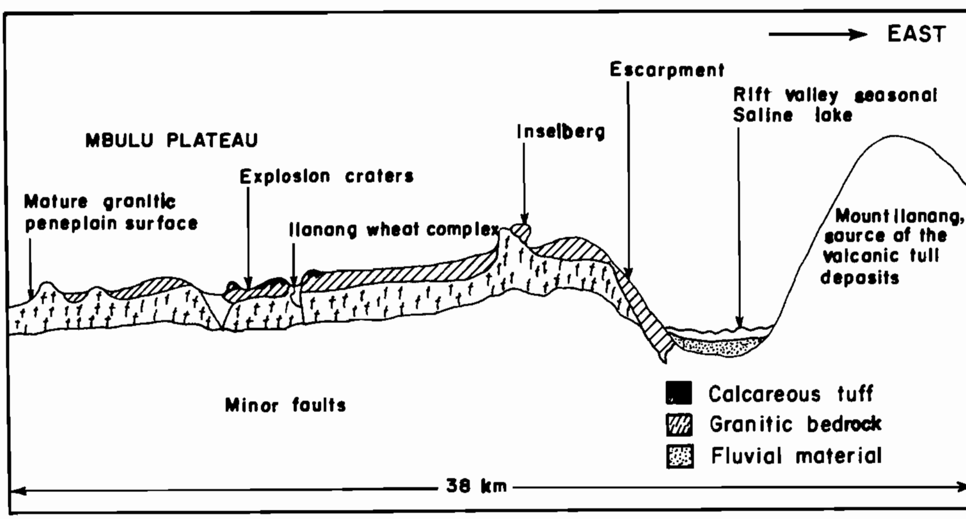

Figure 2. Geologic setting of Hanang wheat complex (Fenger *et al.*, in press).

Vegetation and land use

The native vegetation of the Hanang plateau is grasses: *Cynodon dactylon, Themeda triandra,* and *Pennisetum mexianum,* with scattered trees: *Acacia seyal, A. sonegal, A. garrardii* (Chatwin and Chatwin, in press). The area was formerly used as grazing land for cattle and goats by the Barbaig, a pastoral tribe that practices little agriculture. The Barbaig people continue to occupy the area surrounding the farms and uncultivated land within the Hanang wheat complex.

Climate

During the rainy season from November to May, rainfall ranges from approximately 400 to more than 800 mm and averages 617 mm (Figure 3; Moyer and Mmari, 1986). Potential evapotranspiration during the growing season is 800 to 900 mm; it exceeds rainfall in all months except December, January and February in some years. Rainfall distribution and intensity from year to year are highly variable (McMillan and Ngoma, 1983).

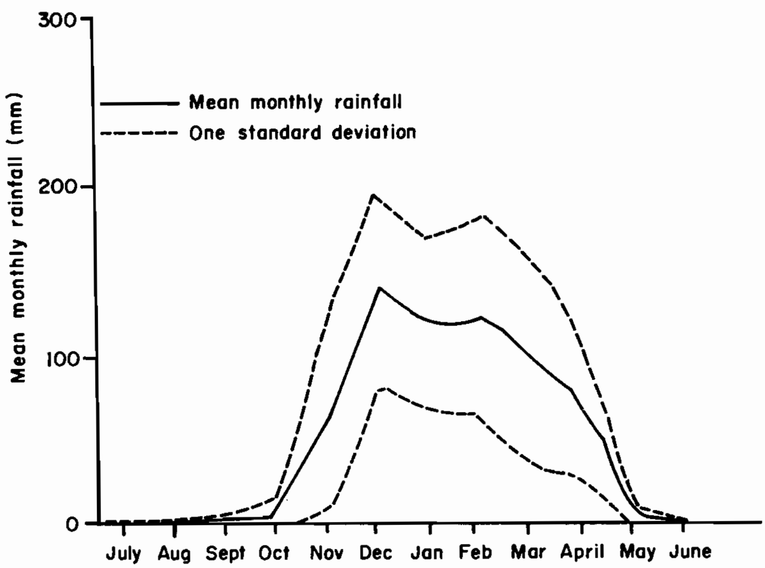

Figure 3. Mean rainfall (and mean ± 1 standard deviation), and distribution at the Hanang wheat complex (Hoyer and Mmari, 1986).

Mean temperature varies little from month to month. June and July mean temperatures are 19°C and those of the warmest months, October and November, are 22°C. The daily temperature range is from approximately 9°C during some nights in June and July to approximately 29°C during some afternoons in October and November (McMillan and Ngoma, 1983).

Soils

Soils of the Hanang wheat complex are related generally to their position in the landform (Figure 4), with Vertisols in depressions and on lower slopes, vertic intergrades to Mollisols, Alfisols or Inceptisols on midslope positions and deep to shallow soils of these

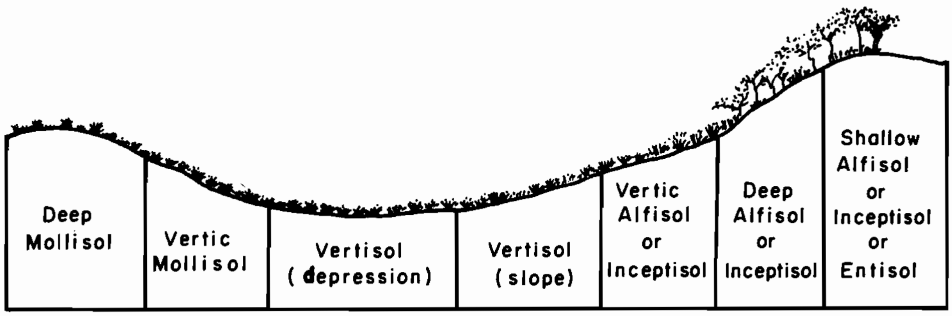

Figure 4. Schematic diagram showing the general relationship of soils to position in the landscape at the Hanang wheat complex.

three orders on upper slopes (Presant, 1973; Fenger *et al.*, in press; Chatwin and Chatwin, in press). Vertisols and vertic intergrades with more than 50% clay occupy approximately half of the area of the farms. A typical Vertisol (Table 1) consists of deep, black, heavy clay materials, and has pronounced cracking to form very coarse prisms, and a high pH. Slickensides are common at depths of 50 to 100 cm. Subdued gilgai microrelief occurs in areas of uncultivated Vertisols. The soils have most of the features of Vertisols (Soil Survey Staff, 1975; Ahmad, 1983) including expanding clay (Ross and Presant, 1976).

Table 1. Some properties of a Pellustert.

Depth (cm)	Colour (moist)	Bulk density (mg/m)	pH 0.01 M $CaCl_2$	Clay %	Crack width (cm)	Distances between cracks (cm)	Slickensides
0-30	$10YR^3/1$	1.0	6.1	63	5	25	–
30-60	$10YR^3/1$	1.0	6.3	63	1.5	25	x
60-84	$10YR^3/1$	1.0	6.9	68	0.5	25	x
84- +	cemented, calcareous tuff						

Note: Most of the data are for VAM-78-23 (Fenger *et al.*, in press). The bulk density data are those typical of Vertisols in the area. Mean crack widths were measured in a Vertisol on Gidagamowd farm, September 1986. Surface cracks ranged from 2 to 10 cm wide. Slickensides were noted below 50 cm at the Gidagamowd site.

Erosion Problems

Sheetwash and severe gullying on cultivated Vertisols on several of the Hanang farms was recognized as a significant problem in the early years of this decade. The factors contributing to the problem are summarized below.

Natural factors

Slope

Though slopes in the farmed area are relatively gentle (1 to 8%), the slopes are long, and large volumes of runoff water may move over the lower part of the slope during intense storms.

Soils

Vertisols swell markedly on wetting and are almost impermeable when nearly saturated with water (Ahmad, 1983). At the onset of the rainy season, water enters the soil readily through cracks; approximately 120 mm of water may be required just to fill the space occupied by cracks. By the middle of the rainy season, however, the soil has usually swelled sufficiently to close the cracks. Subsequently, only a small proportion of water from intense rainstorms will enter the soils; the rest will run downslope. If the slope is long, small channels will develop into gullies.

Rainfall

Rainfall intensity is highly variable but several downpours have been recorded with intensities greater than 50 mm/h (McMillan and Ngoma, 1983). If such storms occur when the Vertisols are nearly saturated, serious runoff occurs from Vertisols on slopes, and those in depressions are flooded and receive a deposit of sediment.

Gully development

Once a small gully forms in a Vertisol, its growth is assured unless countermeasures are taken. During the dry season, the walls of the gully crack, and soil material falls into the gully and is washed downslope during the rainy season. The gully becomes progressively wider.

Man-induced factors

Though erosion is a natural process, the activities of man on the Hanang plateau have accelerated the process in several ways:

- Pastoral people initiated some gully formation by destroying vegetation on trails leading to water for their cattle. But this is minor relative to the changes brought about by large-scale wheat farming.
- In the first 10 years of development at the Hanang wheat complex, the natural vegetation was removed completely from fields of several hundred hectares. No effort was made to till on the contour. Frequently the access roads ran up and down slopes, thus initiating gullies.

Conservation Measures

In 1983 measures were initiated to avoid erosion problems on new land being developed at the Hanang wheat complex and to fight the erosion problem on the older farms. Erosion was most serious on the older farms with high proportions of Vertisols: Basotu, Mulbadow, Murjanda and Gawal. Perhaps 5% of the area of these farms was affected by erosion to the extent that it made farming operations more difficult. Sheet-wash had reduced the depth of topsoil on another 20% of the land.

New farms

Clearing and development of the new farms (Waret and part of Gidagamowd) was organized so as to minimize erosion and maximize the storage of water in the soil (Figure 5). The methods were:

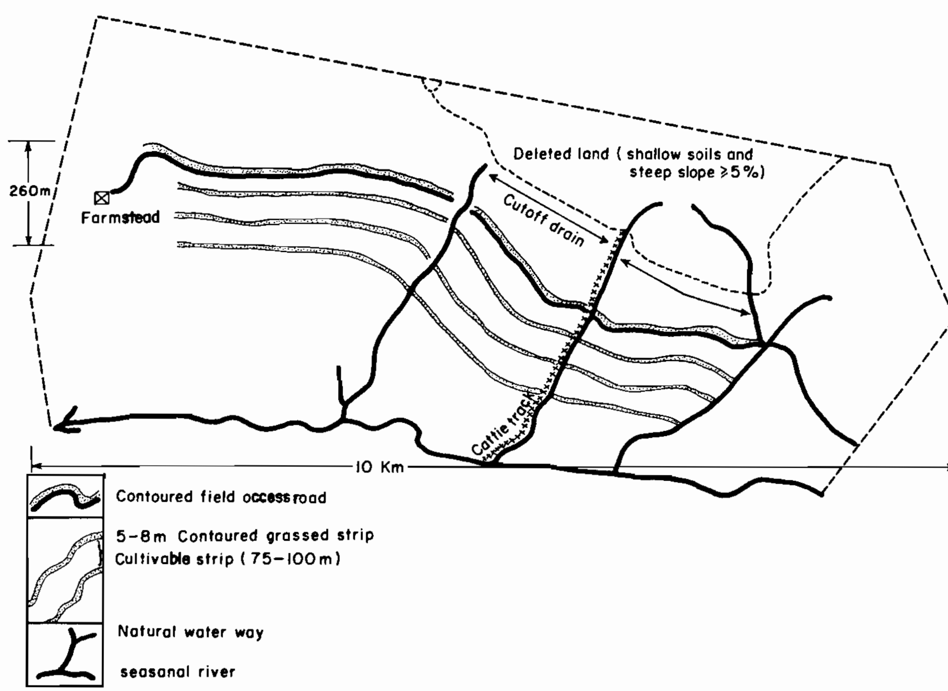

Figure 5. Schematic diagram showing conservation measures on Waret farm.

- The land was surveyed and strips of natural vegetation 5 m wide were marked on contours at intervals of 75 to 100 m. These strips were left intact during clearing, thus forcing cultivation on the contour.
- Roads were designed, when possible, along contours.
- Shallow soils and slopes greater than 5% were not cleared.
- Natural waterways were left intact.
- Diversion channels were constructed to guide water from hilly uncultivated areas to natural waterways.

Older farms

Conservation work began with a general survey to assess relationships between erosion and slope, soil and farm management, and to decide on procedures. Several conservation measures were tried:

- Contoured grass strips were planted on gently sloping areas. Strips 5 to 8 m apart were surveyed on the contour, and native grasses were allowed to become established.
- Absorption channel terraces (shallow, wide ditches) were installed on the contour 75 to 125 m apart on slopes of more than 3%. The purpose of the ditch is to intercept and store runoff.
- Graded channel terraces. These are similar to absorption channels except that they have a gentle slope (0.3%) to conduct water to a waterway. They are used on steeper slopes in areas of shallow soils where runoff is appreciable.

Installation of these conservation measures should be completed on the older farms in 1987. The next step will be to work on reclaiming the small areas of gullies.

Assessment of Conservation Measures

The conservation measures described for the farms have been effective to date. No erosion problems were noted on Waret in 1985-86 in spite of the higher-than-average rainfall and some storms of high intensity. The strips of natural vegetation were effective in absorbing any runoff water.

On the older farms, the enforced cultivation on the contour and the grass strips have been effective in most cases. Problems have occurred on some shallow, sloping Vertisols. In some cases, absorption channels have overflowed and shallow gullies have developed downslope. Some of these problems are due partly to the need to space contoured strips far enough apart to accommodate large machinery between the strips. Graded channel terraces appear to be effective if grass becomes established prior to the occurrence of intensive storms.

Perhaps the most convincing evidence of the effectiveness of the conservation measures applied is the fact that the farm managers are requesting aid for establishing conservation measures on their farms. Their recognition of the need for farming on the contour and of interrupting cultivated slopes with strips of natural vegetation or grass on the contour implies benefits that exceed the costs of installation, the loss of land (approximately 7% of the area), and the inconvenience of having to farm relatively narrow strips on sloping terrain. Indeed, preliminary results indicate that the yield of wheat from a given area under conservation farming exceeds that of an area of the same size under clear cultivation. The greatest benefits, however, are avoidance of gullying and reduction of sheetwash.

Conclusion

The conservation measures described have been particularly effective on the newest farm, Waret. The layout of the farm was designed with conservation in mind. The contoured strips of natural vegetation, natural waterways left intact, and roads following contours have been highly effective in avoiding serious erosion problems. This implies that the remaining 70 000 ha of potential wheatland in the area (Chatwin and Chatwin, in press) could be developed for large-scale wheat farming without incurring serious erosion.

Conservation measures applied to the older farms after the development of erosion problems have been successful in many areas. Some problems remain, however, in areas of shallow, sloping Vertisols. Establishment of grass on absorption channels, and graded channels prior to the onset of runoff is essential. In addition the problem of filling and preventing the spread of gullies remains. Clearly, the most effective conservation results from planning farm development with conservation as a priority. With such planning, large-scale wheat farming without incurring serious erosion problems is feasible on the Hanang plateau of northern Tanzania.

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MANAGEMENT OF VERTISOLS FOR IMPROVED CROP PRODUCTION IN THE SEMI-ARID TOPICS: A PLAN FOR A TECHNOLOGY TRANSFER NETWORK IN AFRICA

J.S. Kanwar and S.M. Virmani*

Abstract

In the Vertisols of semi-arid India (Usterts), ICRISAT has shown that by the application of efficient land, water and crop management techniques, crop yields of the order of over 3 tons per ha can be harvested successfully where traditional methods only yield 500-700 kg per ha. Some of the components of this technology can be progressively applied to the African Vertisols and vertic soils. Verification trials and additional experiments may be required to adapt the available improved technologies in Vertisols to the semi-arid tropical regions of Africa.

This paper also outlines the background leading to the proposal for the establishment of a Vertisol management network for increased crop production. A suggested list of activities for collaborative research and the institutions that are comparatively strong in various activity areas has been compiled. Finally some items towards an agenda for developing a workshop network proposal are identified.

The Semi-Arid Tropics

Semi-arid climates[1] cover much of the tropical areas of the African continent stretching in a broad band from west to east in the sub-Saharan region, and including much of eastern and south-central Africa. In Asia they cover much of India and parts of Burma

* International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru P.O., Andhra Pradesh 502 324, India.

[1] Following Troll's classification, the semi-arid tropics have been defined as areas where monthly rainfall exceeds potential evapotranspiration for 2-7 months. In these areas the mean monthly temperature is above 18°C.

and Thailand. The northern territories of Australia, several countries in southern Africa, including Mexico, Venezuela, Brazil, Paraguay, and Bolivia lie within this region.

The tropical regions are characterized by high evapotranspirational demand. Temperatures are fairly high for most of the year, usually exceeding a mean of 18°C in all months. The semi-arid areas have a short rainy season. Most of the rainfall is received within 2 to 5 months – from June to October in the northern hemisphere and from October to April in the southern hemisphere.

Of the different climatic elements which are important for crop production in the semi-arid tropics (SAT), rainfall is the most variable. The total annual rainfall varies considerably, ranging from 400 to 2000 mm. The coefficient of variation of annual rainfall is 20-30%. In most years the rainy season in the SAT is long enough for annual crops to grow. Indeed, there is often excess water in the rainy season, a part of which can be stored in the soil, but most of it runs off and causes soil erosion. In the SAT, the management of land, crops, and livestock is intimately associated with the water resource availability.

Distribution and Properties of Vertisols

Vertisols occur in many climates. There are approximately 310 million ha of these soils in Asia (mostly in India), in America (mostly in the United States of America, Venezuela, and Argentina), in Australia, and in the continent of Africa.

Vertisols occur extensively in several countries in Africa under arid, semi-arid, and humid climates, and have an agroecological potential for food production well above their present level of use. According to Swindale (1982), there are approximately 104 million ha of Vertisols and vertic soils in Burkina Faso, Niger, Nigeria, Chad, Sudan, Ethiopia, Somalia, Kenya, Burundi, Malawi, Zambia, Zimbabwe, and Botswana (Figure 1). Some small areas occur in other countries of Africa, and altogether about 30% of the world's Vertisols are located in Africa.

Vertisols are a highly productive group of soils. They contain at least 30% clay, and the dominant clay mineral is usually one of the smectite group. These soils are generally 60 cm deep or more. Vertisols are therefore able to retain considerable amounts of available water in the soil profile. Due to the nature of the dominant clay mineral, they exhibit shrinking and swelling properties, and are highly erodable. Their physical properties make them difficult to handle. For example, they are heavy soils and are difficult to cultivate; further, some exhibit a 'gilgai' formation, and therefore the preparation of the seedbed on these soils presents many difficulties. Due to their low terminal water intake rates, they easily get waterlogged during the rainy season.

In Africa, three suborders of Vertisols (as defined in *Soil Taxonomy*) are found:

- **Torrerts**: Vertisols of deserts or very low rainfall areas of the arid tropics, generally having less than 2 humid months annually.
- **Usterts**: Vertisols in summer-rainfall areas of the SAT, generally having 2-7 humid months annually.

– **Uderts:** Vertisols in the humid tropics, generally having more than 7 humid months annually.

Figure 1 shows the distribution of Vertisols and vertic soils in the African continent. Sudan, Ethiopia, Chad, Nigeria, Somalia, Zimbabwe are some of the countries which have a large proportion of their land in the Vertisol and vertic soils group. Table 1 lists some of the countries reported to have Vertisols and vertic subgroups by climatic regions. This is based on the information furnished by the participants of the IBSRAM workshop (IBSRAM, 1985) and the FAO report (FAO, 1965). The data are generalized and need review and updating.

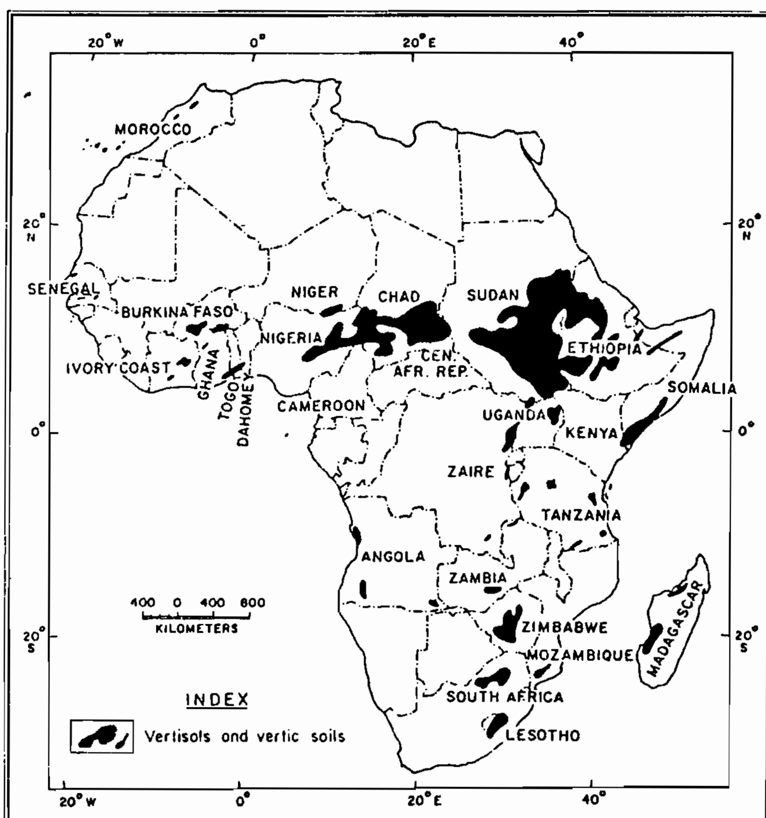

Figure 1. Areas of major distribution of Vertisols and vertic soils in tropical and subtropical Africa (FAO, 1965).

Table 1. A tentative list of countries in Africa with Vertisols and vertic soil groups by climatic zones*

Humid and subhumid	Semi-arid	Arid
Cameroon	Botswana	Chad
Ethiopia	Burkina Faso	Somalia
Sudan	Burundi	Sudan
Zaire	Chad	
Mozambique	Ethiopia	
Angola	Kenya	
Uganda	Malawi	
Dahomey	Niger	
Togo	Nigeria	
Shana	Sudan	
Ivory Coast	South Africa	
	Zambia	
	Zimbabwe	
	Senegal	
	Tanzania	
	Uganda	
	Ghana	

*Source: FAO (1965) and IBSRAM (1985).

Current Management of Vertisols in Semi-Arid Africa

Since Vertisols and vertic soils occur in diverse agroecological environments in Africa, they are used for a variety of purposes. The Torrerts, Vertisols of the arid areas, are generally under natural grassland and associated vegetation and are used for extensive agriculture, mainly cattle raising. Where irrigated, these soils are highly productive, and are used to grow a variety of tropical crops. The management of irrigated Vertisols poses many problems: they become waterlogged, and soil salinity can also develop if water management is inefficient. In Sudan, Torric Vertisols are used mainly for growing cotton. In the semi-arid areas of Africa which have a ustic moisture regime, Vertisols and vertic soils are sometimes used for raising crops like sorghum, millet and maize in the uplands, and rice, teff, etc. in the lowlands. In some areas of southern Africa, wheat is also grown in these soils. However, in most instances the intensity of cultivation is very low. Their common current land use is pasture-livestock production systems. The lowland Vertisols of the humid tropics have a udic moisture regime. Generally these are not cultivated, but in some cases they are used for growing rice and teff.

To summarize, the current land use of Vertisols and vertic soils in Africa is limited to livestock farming, grazing, and related animal farming activities. These soils are not extensively used for raising food crops, and they primarily sustain subsistence-level animal production systems. Where crop production activity is prevalent, the per ha yield of crops is quite low. On an average, in rainfed agriculture grain yields of 250-500 kg/ha of most crops are commonly reported. The components of improved agriculture do not seem to have touched the Vertisol areas of Africa.

We have calculated the length of the crop-growing season for a few locations of Vertisols in Africa to illustrate their agroecological potential, and have also included data from the ICRISAT Center in Hyderabad (India) for comparison. The data (Table 2) show that except for the Torric Vertisols, the Usterts exhibit a crop-growing season with a length of 130-240 days. The thermal environment of the locations studied is also suitable for growing tropical and subtropical crops. We believe that through the application of appropriate land and water management and crop production technologies, the Vertisols and vertic soils of Africa can be efficiently harnessed for increased crop production. Based on the experience gained at ICRISAT, the agricultural production on these soils can be significantly increased. Under soil and climatic conditions which are somewhat similar to those found in Africa, ICRISAT has shown that through the scientific management of Vertisols and vertic soils in a semi-arid environment, a sustained and high crop production can be achieved in dryland farming conditions.

IBSRAM's Proposal for Launching a Vertisol Soil Management Network

In February 1985, IBSRAM – the International Board for Soil Research and Management, in cooperation with several other institutions, organized a workshop on the Management of Vertisols for Improved Agricultural Production at the ICRISAT Center in India. At this meeting it reviewed the important principles of improved Vertisol management technology and its application for increasing production under diverse farming systems. The workshop discussed research priorities for the improved management of Vertisols for sustained agricultural production. In the dryland semi-arid areas, it noted that soil-related problems associated with improved Vertisol management are: surface drainage during the rainy season, lack of water in the dry season, and inadequate plant nutrients. In the irrigated use of Vertisols important research priority areas were also identified. Some of these are: drainage, salinization, irrigation scheduling, crops and cropping systems, soil and water management, weed control, soil testing for available nutrients, and standardization of methods for evaluating nutrient deficiencies.

The IBSRAM workshop (IBSRAM, 1985) also discussed the verification, testing, and validation of improved technologies developed by different institutions. It was considered essential to select components suitable for local needs, and it was suggested that a Vertisol soil management network should be organized without delay. A set of principles for a successful Vertisols network were listed.

- o Establish a common objective and then set priorities.
- o Allocate resources by the national research programmes for the network.
- o Identify the comparative advantages and leadership capabilities of the various research organizations with improved technologies.

Table 2. Rainfall, temperature, and length of the growing season at some selected locations in Vertisol areas of Africa, and Hyderabad, India.

Moisture climatic environment	Location/ country		1	2	3	4	5	6	7	8	9	10	11	12	Annual
Torrerts	Khartoum/ Sudan	Rainfall (mm)	0	0	0	1	5	7	48	72	27	4	0	0	164
		Temperature (°C)	22	24	27	31	33	33	31	29	31	31	27	24	29
		Growing period	Undefined – July-September												
Usterts	Maiduguri/ Nigeria	Rainfall (mm)	0	0.3	1	4	34	78	180	227	112	23	0.3	0	659
		Temperature (°C)	22	24	29	31	32	30	27	26	27	28	25	22	27
		Growing period													135
Ustarts	Moundou/ Chad	Rainfall (mm)	0	< 0.3	2	40	118	171	244	303	250	96	4	0	1228
		Temperature (°C)	25	27	30	31	29	27	26	25	25	27	27	25	27
		Growing period													210
Uderts	Addis Ababa/ Ethiopia	Rainfall (mm)	24	25	68	93	50	105	228	263	174	41	3	15	1089
		Temperature (°C)	16	18	19	19	20	18	15	15	15	15	15	15	17
		Growing period													240
Usterts	Hyderabad/ India	Rainfall (mm)	2	11	13	24	30	107	105	147	163	71	25	6	704
		Temperature (°C)	21	24	27	30	34	29	26	26	26	25	23	21	26
		Growing period													210

- o Supply coordination and logistics.
- o Look at the levels of interaction required.
- o Link national cells (units) with other agencies.
- o Establish principles for the selection of areas of activity.

Management of Vertisols in the SAT: ICRISAT's Work in India*

In the Indian subcontinent, about 70 million ha of Vertisols and vertic soils occur, mostly in the ustic moisture regime in peninsular India. In this region the farmers are small landholders who operate 2-4 ha farms and own a pair of oxen for draught. These small farmers of limited means are generally not able to cultivate their farms in time for the planting of rainy-season crops. Their land is often exposed to short-term waterlogging. Most farmers can raise only one crop a year on these soils, even in relatively assured rainfall areas.

ICRISAT has now assembled a technology for improved management of Vertisols suitable for the SAT. It facilitates growing two crops, one in the rainy season and another in the postrainy season. Adoption of this improved Vertisols management technology has resulted in considerable increases in crop production. Where a farmer harvested about half a ton of sorghum or chickpea by using his traditional system, a total yield of some three tons of grain per ha has been consistently harvested through a two-crop combination under the improved Vertisols management system at ICRISAT during the past nine years of experimentation (Table 3). Further, in the vertic soils several intercrop combinations, e.g. sorghum-pigeonpea or millet-pigeonpea, have produced yields of 2-3 tons/ha under medium-fertility treatment (60-12-0), as shown in Table 4. The introduction of the new system has also resulted in (i) a considerable reduction in soil erosion; (ii) a much higher *in-situ* moisture conservation, and therefore in higher rainfall-use efficiency (Table 5); and (iii) much more dependable harvests year after year (Table 3).

The improved Vertisols management technology

The technology for improved management of Vertisols is a framework. It consists of several interrelated components, each of which consists of several options. The components of the improved technology are:

Land and water management

Improved land and water management practices are applied for alleviating the constraints, such as waterlogging, which arise due to the physical properties of Vertisols.

* A detailed explanation of the technology may be found in Kanwar *et al.* (1982) and Virmani *et al.* (in press). Ryan *et al.* (1982) have given details on the economic aspects of the improved Vertisols management technology and indicated some constraints to its adoption in the Indian semi-arid tropics.

Table 3. Grain yields under improved and traditional technologies on deep Vertisols* at ICRISAT Center in 9 successive years.

Year	Cropping period rainfall (mm)	Grain yield (kg ha^{-1}) Improved system: double cropping: Sorghum/ maize and	Sequential chickpea/ intercropped pigeonpea	Traditional system: single crop: Sorghum	or chickpea
1976/77	708	3204	717	436	543
1977/78	616	3076	1223	377	865
1978/79	1089	2145	1256	555	532
1979/80	715	2295	1195	500	450
1980/81	751	3587	920	596	563
1981/82	1073	3194	1047	635	1046
1982/83	667	3269	1095	630	1235
1983/84	1045	3051	1766	838	477
1984/85	546	3355	1014	687	1232
Mean	801	3020	1137	587	771
SD	209	482	289	138	327
CV (%)	26	16	25	24	42

Average rainfall for Hyderabad (29 km away from ICRISAT Center) based on 1901-84 data is 784 mm with a CV of 27%.

*Available water-holding capacity of 180 cm deep soil profile is 240 mm.

Table 4. Grain yields of some cropping systems grown on vertic soils* under low (0-0-0) and medium (60-12-0) fertility at ICRISAT Center in operational-scale experiments.**

Year	Cropping period rainfall (mm)	Soil fertility	Grain yield (kg ha^{-1}): Sole pigeonpea	Sorghum/ pigeonpea	Millet/ pigeonpea	Groundnut/ pigeonpea	Sole sorghum
1981/82	1073	Low	700	937	1201	1387	516
		Medium	868	2175	3581	1423	3234
1982/83	667	Low	1041	2219	2190	2214	1170
		Medium	1217	4291	3178	2917	2869

* Available water-holding capacity of 50 cm soil profile is 80 mm.
** Source: ICRISAT (1983, 1984).

Table 5. Annual water balance and soil loss (t/ha) for traditional and improved technologies in Vertisol watersheds, ICRISAT Center, 1976/77 to 1983/84.

	Water-balance component				
Farming systems technology	Annual rainfall (mm)	Water used by crops (mm)	Water lost as surface runoff (mm)	Water lost as bare-soil evaporation and deep percolation (mm)	Soil loss (t/ha)
Improved system: double-cropped on broadbed and furrows	904	602(67)*	130(14)	172(19)	1.5
Traditional system: single crop in postrainy season, and cultivation on flat	904	271(30)	227(25)	406(45)	6.4

*Figures in parentheses are amounts of water used or lost expressed as percentage of total rainfall.

Vertisols have very poor internal drainage when they are wet. Under the improved system of management, microwatersheds of 3-15 ha size were taken as units for land and water management and agronomic practices. Surface drainage is improved through the provision of surface drains and land smoothing. The *in-situ* water conservation improvements are brought about by laying out the bed-furrow (ridge-furrow) cultivation systems along the contour. Since the surface runoff water is discharged in a controlled manner, the loss of soil is considerably reduced and water-use efficiency is increased considerably (Table 4). At the ICRISAT Center, the main features of this system are that a slope of 0.4 to 0.6% graded broadbeds and furrows (50 cm apart) are made which lead into grassed waterways and finally lead to a dug tank or a drain (Figure 2). By following this system the soil moisture storage is increased and the drainage of excess water is facilitated.

Primary tillage to prepare a rough seedbed is best carried out soon after the harvest of the postrainy-seaon or rainy-season crops. Land should be harrowed whenever 20-25 mm of rain is received over a period of one-two days. When blade-harrowing is done, the clods easily shatter and a satisfactory seedbed is attained.

Dry sowing ahead of onset of rainy season

Since the preparation of the seedbed and the sowing of crops present serious problems in Vertisols, we find that the planting of crops in dry soils ahead of the commencement of rains ensures their establishment early, and avoids the difficulty of planting in

Figure 2. Some important layout features of a small agricultural watershed on a Vertisol at the ICRISAT Center.

a set, sticky soil. We have noted that dry seeding is successful where the early season rainfall is fairly dependable and seeds are placed at a depth of 7-10 cm. At the ICRISAT Center, good stands were established by dry seeding of crops such as mung, sunflower, maize, sorghum, and pigeonpea (Figure 3).

Improved cropping systems

The introduction and adoption of improved cropping systems provide a continuum of crop growth from the commencement of the rainy season until most of the available moisture is utilized by the crop. At ICRISAT we have found that this can be achieved by:

* intercropping of long-duration crops (e.g. pigeonpea) with short-duration crops (e.g. maize or sorghum or soybean).
* sequential cropping of crops (e.g. sorghum or maize followed by chickpea or safflower).

Figure 3. A two-week-old stand of dry-sown maize intercropped with pigéonpea combination tested on a Vertisol watershed at the ICRISAT Center.

Fertility management

In the tropics the management of soil fertility is very important for realizing the full potential of improved cropping systems. At the ICRISAT Center we have found that the management of soil and fertilizer nitrogen is necessary in Vertisols. We have also observed that the application of phosphates and zinc is also required. Our studies have shown that the inclusion of legumes in the crop rotations or in intercrop systems has substantially reduced the fertilizer nitrogen needs (by about 40 kg N ha) of the subsequent cereal crops.

Efficient farm machinery

For a successful implementation of the improved Vertisols management system, we have observed that it is necessary to carry out all the operations thoroughly and in good time. Since animal draught is the main source of energy available to small farm operators of semi-arid areas in Asia and Africa, much of ICRISAT's work is related to animal-drawn equipment. We have found that the use of a wheeled tool carrier (e.g. Tropicultor or Nikart) is a most efficient technique for managing Vertisols in India.

Appropriate crop management

In order to realize the full potential of improved land and water management and cropping systems, it is essential that an appropriate set of crop management practices be adopted. Weed control, integrated pest management, the placement of fertilizers at an appropriate depth and their application at critical stages of crop growth are some of the crop management factors which could lead to the realization of high and sustained yields on Vertisols.

Since most SAT soils are deficient in nutrients like N, P, and Zn, we get good responses to applied fertilizers. The application of fertilizers in the right doses and at the right time, and the adoption of appropriate methods in their application, is the way to obtain good results from fertilizer application in Vertisols (Kanwar and Rego, 1983).

One important aspect of the improved Vertisol technology is the synergistic effect of various components when applied together, as compared with their individual effect. This point has been brought out convincingly after ten years of watershed-based experimental results from ICRISAT (Table 3). Kanwar and Rego (1983) and Kanwar *et al.* (1984) noted during the steps taken to improve Vertisols technology conducted at ICRISAT that though the contribution of fertilizers was highest, the response to fertilizers was most highly marked when they were applied in combination with improved land and water management treatments and the adoption of improved agronomic practices. This observation has great relevance in the African continent. Here fertilizers are costly and in most instances have to be imported. All efforts therefore must be made to realize maximum fertilizer-use efficiency by applying the principles of improved Vertisol technology.

Suggested Agenda for a Vertisol Management Network in Africa

Purpose

We believe that in the African context the main purpose of a Vertisols management network is to tackle successfully issues related to increased agricultural productivity, sustainability, and the introduction of appropriate technologies in the Vertisol and vertic soil areas. We further believe that such research should receive priority because of the vast underutilized potential of Vertisols for crop production. As a first step, we suggest that improved technologies that are already available should be screened and tested both in Usterts and Uderts. Issues concerning the improvement of productivity of irrigated Vertisols should receive priority where soil-related problems are major constraints to increased crop yield.

Main problems to be solved

In terms of the adoption and testing of new technologies, the major problems to be tackled are likely to be in the following three areas: soil management, cropping systems, and land and water management. A partial listing of some researcheable issues is given in Table 6.

Table 6. Major areas of adoptive research in the Vertisols and vertic soils of Africa.

Area	Problems and issues
1. Soil management	o Tillage-cultivation, seedbed preparation, timing of operations
	o Agricultural machinery – kind, draught, availability
	o Nutrient management – N, P, micronutrients
2. Cropping systems	o Intensification of cropping where crops are already grown
	o Introduction of new crops
	o Socioeconomic considerations
3. Land and water management	o Drainage
	o Irrigation water management
	o Scheduling of irrigation
	o Soil/water quality
4. Other location-specific problems, e.g. management of acid Vertisols, effective soil conservation tillage/cultivation methods for Vertisols located in areas with >.4% slope, may be investigated.	

Training needs

Training will be an important part of the agenda of a successful Vertisols network. Training will be required for creating an awareness of the need for the introduction of improved technologies for increasing crop production, and will need to be undertaken by collaborators for the implementation of the network programme, by those responsible for the testing and adoption of new technologies, and those contributing to the development of a data base and its management.

Expected outputs

Over a period of 5 years of operation, the project is expected to achieve some of the following objectives through the application of improved Vertisols management technology:

* locally adaptable technology packages for increasing crop production of Vertisol and vertic soil areas;
* improved cropping systems options for adoption by farmers of different areas;
* a few diversified agricultural systems for alternate management of Vertisols;
* a cadre of trained staff; and
* a substantial strengthening of institutional linkages.

Collaborating institutions

A suggested list of institutions where there are opportunities for training and collaborative research, and where research results are available for evaluation with a view to adoption in the Vertisols and vertic areas of Africa, is given in Table 7. We propose that IBSRAM provide the necessary backup support for coordination of the network activities, and for organizing financial support.

Table 7. A suggested list of institutions for developing collaborative activities of the network.

	Soil suborder		
	Torrerts	Usterts	Uderts
o Soil characterization	National Res. – SMSS – IRAT/Gerdat		
o Agroclimatic evaluation	ICRISAT Agrhymet	ICRISAT Agrhymet	ICRISAT
o Cropping systems	National Res.	ICRISAT	IRRI for rice-based systems, ICRISAT for postrice cropping
o Land and water management	National Res.	ICRISAT	IRRI/ICRISAT/IITA
o Crop management	To be identified	ICRISAT	IRRI/ICRISAT + other institutions
o Soil management	US Soil Salinity Lab. SMSS	ICRISAT	IRRI
o Tillage equipment and related research			
Animal-drawn equipment	ICRISAT/IRAT/NIAE/National Res.		
Powered machines	NIAE Tillage Lab. Netherlands	NIAE Tillage Lab. Netherlands ICRISAT	IRRI Tillage Lab. Netherlands NIAE
o Fertility/nutrient	National Res. IFDC IRAT	ICRISAT IFDC IRAT National Res.	IRRI IITA IFDC IRAT National Res.

Issues Needing Immediate Attention for Formulating Network Plans

1. A complete inventory of soils (at the suborder level) and of climate (rainfall, evaporation, temperature, radiation) is necessary to characterize the agroecological potential of the Vertisols and vertic soils in the region concerned. These base data would be required both for the design of improved technologies and for their transfer.
2. Assembly of information on improved land-use and cropping systems suitable for Vertisols and vertic soils of the semi-arid humid-subhumid tropics of Africa.
3. Assessment of research needs, identification of locations where research could be carried out, and promotion of cooperation for interchange of information.
4. Exchange of germ plasm of improved cultivars amongst institutions for testing new cropping systems.
5. Identification of locations for training staff.
6. Establishment of a Vertisols soil management unit (SMU).
7. Location of an SMU network coordinator.

Conclusion

The Vertisols of Africa, which are situated mostly in ustic (Usterts) moisture regimes, have fairly long growing seasons, and consequently can be used to harvest successfully one or two crops per year. On such soils improved dryland agricultural practices for increased crop production could be adopted. For bringing about improvements in agriculture in Vertisols in the ustic moisture regimes, the major soil problems to be overcome are related to tillage, land preparation, water management, and the identification of suitable cropping systems. In the case of Uderts, issues related to drainage, preparation of land for planting of postrainy-season crops, and soil fertility management are the priority areas for research. In the Vertisols of the highland regions, some of the important agenda of adoptive research would be to fit crops into the available growing season, and to determine the management, water control, fertilizer application, and land preparation which they require. Some of the priority areas of research for a Vertisols and vertic soils management network for Africa would be the characterization of soil, and the study of climatic and biotic constraints to increased crop production.

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IMPROVED AGRICULTURAL UTILIZATION OF VERTISOLS IN THE ETHIOPIAN HIGHLANDS – AN INTERINSTITUTIONAL APPROACH

S. Jutzi[1] and M. Abebe[2]

Abstract

Vertisols cover 7.6 million ha of the Ethiopian highlands. One quarter of these soils is presently cropped, an acreage which in turn accounts for 24% of all highland soils cropped in Ethiopia. Vertisols account for about 70% of all highland soils with slopes between 0% and 8%. The high clay content (60-70%) of these Vertisols is responsible for their commonly heavy waterlogging. This characteristic is especially important in highland areas with good average rainfall and low evaporative demands due to moderate temperatures. Waterlogging imposes severe restrictions on the traditional agricultural use of these soils. If they are cultivated at all, the crops grown on Vertisols use mainly residual moisture. Much of the land under Vertisols is therefore left fallow and is subject to serious water erosion during the main part of the heavy rains.

There is much evidence for the possibility of producing substantial increases in crop yields on Vertisols if the excessive surface soil water is drained off and if appropriate cropping practices are used. Effective surface drainage enables farmers to use the full rainy season and the postrainy season for crop growth. A removal of the waterlogging stress also allows the utilization of higher-yielding crop species and cultivars and more effective preservation of the soil due to more important vegetation cover.

ILCA has initiated a research, training and outreach project on the improved management and utilization of highland Vertisols in conjunction with the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) and the Government of Ethiopia (Institute of Agricultural Research, Alemaya University of Agriculture, the Ministry of

[1] International Livestock Centre for Africa (ILCA), PO Box 5689, Addis Ababa, Ethiopia.
[2] Alemaya University of Agriculture, Dire Dawa, Ethiopia.

Agriculture, and Addis Ababa University). The main issues addressed in this joint inter-disciplinary operation are animal-powered devices for surface soil drainage, tillage and crop planting, the development of new cropping systems on drained Vertisols, crop protection, and improved management of plant nutrients with the use of low-cost phosphates and legumes as N sources.

Introduction

Twenty-four percent of Ethiopian highland soils presently cropped are deep black clay soils classified as Vertisols. These 2 million ha represent one quarter of the total Vertisol acreage in the Ethiopian highlands, the balance being uncultivated primarily because of physical constraints – especially the lack of sufficient drainage. Vertisols in Ethiopia account for about 70% of all highland soils on slopes between 0% and 8%. Heavy waterlogging of most highland Vertisols is common. This is due to their generally high contents (60-70%) of (montmorillonitic) clays, to the normally high rainfall of the Ethiopian highlands (above 900 mm/yr), and to low evaporative demands because of moderate temperatures.

This waterlogging during the main rains imposes severe restrictions on the traditional agricultural use of these soils. Much of the cropped land is left fallow and is subject to water erosion during the main part of the long rainy season. Crops are sown only as the rains diminish and then mature on residual moisture stored in the soil. Many Vertisols are left totally uncropped because of this excess surface water during the rains. The highland Vertisol crops in the Ethiopian highlands are generally low-yielding (Table 1) and have only a limited biological potential for incremental yield under improved chemical and physical conditions.

Table 1. Grain yields of food crops on Vertisols under traditional management in the central Ethiopian highlands.

Crop	Grain yields (kg/ha)
Teff	530
Barley	860
Emmer wheat	680
Durum wheat	610
Horsebean	750
Linseed	300
Lentil	500
Chickpea	600
Field pea	730
Noug (*Guizotia abyssinica*)	290
Vetch (*Vicia latyroides*)	690

Source: Berhanu Debele (1983)

By removing the main plant growth constraint on these soils – waterlogging – drastic changes can be brought about in their agricultural use so as to bridge the large gap between their low actual productivity and their high potential productivity.

Considering the need to address the improved utilization of these soils in a multidisciplinary mode, it has been agreed to set up a joint research, training and outreach operation with the participation of all interested institutions. A description of this joint operation is given below, after first outlining the main characteristics of Ethiopian highland Vertisols and alternative land-use techniques. Suggestions are then made for the discussion of programme perspectives beyond Ethiopian borders.

The Ethiopian Highland Vertisols

Vertisols, the fourth most important soil order in Ethiopia after Lithosols (16.2%), Cambisols (15.3%) and Nitosols (11.8%), cover 10.3% or 12.6 million ha of Ethiopia's land mass. It is suspected that more detailed surveys may reveal many more Vertisol areas than are reported here on the basis of an exploratory study. It has been estimated that 7.6 million ha of these Vertisols are located in the highlands above 1500 m asl, and that of these 1.93 million ha are currently cropped (H. Hurni, pers. comm.). The highland Vertisols are mainly on high-elevation plateaux (> 2500 m asl) in temperate ecosystems.

The general slope range of the landscapes on which Vertisols occur is 0-8% (Debele, 1983). They occur throughout this range but are more frequent in the 0-2% range, and are prevalent in landscapes of restricted drainage such as seasonally inundated depressions, basins, deltas, alluvial/colluvial plains, pyroclastic plains, undulated plateaux, valleys and undulating sideslopes (Debele, 1983).

In Vertisol areas it is generally rare to find extended tree vegetation. The predominant natural vegetation is grassland. Where they occur, trees are normally found scattered on better-drained terrain. *Andropogon, Sporobolus, Festuca, Eleusine, Hyparrhenia, Agrostis, Cynodon* and *Digitaria* are common grass species. Common weed species are *Pennisetum, Plantago* and *Guizotia.*

Debele (1983) reports that where Vertisols are cultivated the common crops grown under rainfed conditions include teff, durum wheat, chickpea, lentils, *Vicia latyroides,* linseed, *Guizotia abyssinica,* fenugreek, and Emmer wheat. In relatively better-drained conditions, horsebean, field peas and barley are also grown.

Debele (1983) also reports on a number of features of Ethiopian highland Vertisols. On the basis of the limited studies available, it can be concluded that they are generally dark, deep, heavy-textured (> 50% clay), with strongly developed prismatic structures and wide deep cracks, strongly developed slickensides, and pH in the acid range (61% between 5.5 and 6.7), and with a CEC between 35 and 70 me/100 g soil. The predominant exchangeable cation is Ca, which accounts for 80% of the exchange complex, and this is followed by Mg. In the highlands, base saturation, even in the presence of calcium carbonate nodules, is rarely greater than 80-90%. Calcium carbonate nodules occurring in the highland Vertisols are crystalline, hard, and chemically inactive. This carbonate has practically no effect either on the pH or the base-saturation status of the soil.

It is noteworthy that, thanks to the large proportion of Vertisols in the total agricultural land in Ethiopia, the soils of this country present above average CEC when compared with a large number of other countries (Sillanpaa, 1982).

In the surface horizon (0-30 cm) most of the Vertisols contain 3-10% organic matter. This percentage decreases with depth but is still about 1% at one metre depth – an indication of the self-cultivating characteristic of many Vertisols.

In 70% of the cases analyzed by Debele (1983), available phosphate (P_2O_5, Olsen) was below 5 ppm. The remaining samples all had less than 15 ppm. In ILCA's experience (unpublished) high-plateau Vertisols invariably had phosphate contents of less than 2 ppm in the top 30 cm. P deficiency, together with N deficiency, is therefore a general feature of these Vertisols (Jutzi and Haque, 1984).

Debele's statement on the proneness to erosion of the Vertisols is corroborated by Virgo and Munro (1978) who have indicated 400 t/ha × yr soil loss on a Vertisol in northern Ethiopia. These high soil-loss figures are commonly linked to the rainy-season fallow practice with several cultivation passes during that period. Loch and Freebairn (1984) have recorded drastic reductions of soil losses when a surface cover was introduced.

The Ethiopian highland Vertisol areas are generally characterized by smallholder mixed cereal-livestock farming systems with marked subsistence orientation. Land cultivation is almost exclusively done using animal power (oxen). These areas are also characterized by generally high rainfall (> 900 mm per annum) and low evaporative demands due to moderate temperatures, which vary widely with altitude but might average 15° annually. This results in severe waterlogging of most of these soils, and also of considerable acreages of other soils with vertic properties (an estimated 2.5 million ha, especially land with Vertic Cambisols and Vertic Luvisols).

It is therefore not surprising that many farming communities on these soils have developed techniques to drain cropped fields and even native pasture areas. The most widely used, although not very effective, system is the construction of drainage furrows across the contour at varying distances (3 m to 6 m). These furrows are opened using the traditional ox-drawn plough ("maresha"). Another widely used system is the ridge-and-furrow practice, whereby crops are grown on narrow ridges between furrows made with the "maresha". Very rarely, handmade raised beds-and-furrows are found similar to the ones proposed by ICRISAT (Kanwar *et al.,* 1982), and notably on the Inewari plateau, Selate, and the Fogera plains.

In high elevation locations on lighter-textured Vertisols with high organic-matter content and on other soils with vertic properties, soil burning (called "guie") is a quite widely used and most labour-intensive practice. It consists of intensively ploughing fallowed plots, of heaping up the topsoil into heaps of about 60 cm in height and 120 cm in diameter, and of burning them after they have been lit with drained dungcakes introduced while burning into the heaps. The soil is then left burning for several days, and after cooling down the burnt soil is distributed over the field which is reploughed before planting. Besides accelerating the mineralization of plant nutrients, especially P (Roorda, 1984), this soil burning also contributes to a temporary change in soil texture, in the sense that the high temperatures developed in the heap (600°C) can bake clay into sand-like particles which contribute to better *in-situ* drainage and soil aeration (Abebe, 1981: Debele, 1983). The combined effects of accelerated nutrient mineralization and textural changes on crop growth are quite impressive (plus 300-400%) but very short-lived (one season).

Experiences with Improved Management of Vertisols

There is much evidence that substantial increases in crop yields can be obtained on Vertisols if excessive surface soil water is drained off and if appropriate cropping and soil fertility practices are used.

During the past twelve years, ICRISAT has been developing a management technology for Vertisols in India with 100 million ha of Vertisols. The technological package developed at ICRISAT is designed to make optimum use for crop production of both the rainy-season and the postrainy-season growing periods. The package – essentially a double-cropping system – includes elements such as land shaping for surface drainage, tillage innovations, new crop and soil fertility management options, and improved crop protection. Results obtained at the ICRISAT Center (Hyderabad, Andhra Pradesh) with this technology consistently showed superior production and profits as compared with the traditional rainy-season fallow system. It allows two crops per year, which both are more productive than the traditional postrainy-season crop (Ryan and von Oppen, 1983).

The practical nature of all elements of improved Vertisol management and their relative importance are a function of the cultural, socioeconomic and ecological circumstances of the envisaged target areas. The Ethiopian highlands differ in all these aspects from those of the semi-arid tropics of India and of most other extended Vertisol areas. Special efforts for each particular setting are therefore warranted.

The Ethiopian Institute of Agricultural Research (IAR), which has three major research stations on Vertisols, proposed (among other projects) the construction of cambered beds of varying width (7-11 m) for Vertisol drainage. Results have been reported by Debele (1983). More than threefold yields of wheat and barley were obtained when using this technique as compared with the traditional land preparation practice. The IAR results not only revealed these large drainage effects but also stringent nitrogen and phosphorus deficiencies.

When analyzing the effects of soil burning ("guie"), Abebe (1981) recognized that they dealt importantly with *in-situ* drainage, effects which could just as well be attained by camber bedding, while also preserving organic matter. The construction of cambered beds, however, involves considerable earth movement, which is too expensive an operation for local resources.

It was mentioned earlier in connection with examples of traditional Vertisol drainage practices that the farmers realize that waterlogging is a major crop growth constraint. Substantial impacts of more systematic and more effective drainage systems are thus not only likely to be expected, but their acceptance by the farmers can be taken for granted.

Considering the subsistence character of the target farming systems, the Joint Vertisol Management Project in Ethiopia adopted a strict low-external-cost approach in the development of technological elements for the improved management of Vertisols.

An extremely low-cost device was developed for an animal-powered construction of broadbeds-and-furrows (BBFs) (Jutzi *et al.*, 1986). This broadbed maker (BBM) is built on the basis of two interconnected traditional ploughs with shortened beams, as shown in Figure 1. The two flat wooden wings of the traditional plough are replaced by two wooden mouldboard-shaped wings on either side of each beam. The two central wings of the BBM throw earth towards the centre, thus building up a raised bed, and the two outside wings throw soil to the outside. The implement thus leaves behind a raised bed about 1.2 m across and two drainage furrows about 20 cm deep. The implement can be pulled by a pair of local Zebu oxen, weighs about 28 kg (8 kg more than the "maresha"), and can be handled by one operator. It can cover up to 1 ha per working day (7 hours), depending on the moisture and tilth status of the soil. Its cost, in addition to the two "mareshas" used, is about US$15, and it can be made and maintained by village craftsmen. The BBM can be used as a seed-covering device while making the BBFs. Attachments for row-planting of crops and for harrowing (blade-harrow) are also available at an approximate cost of US$60 and US$10 respectively.

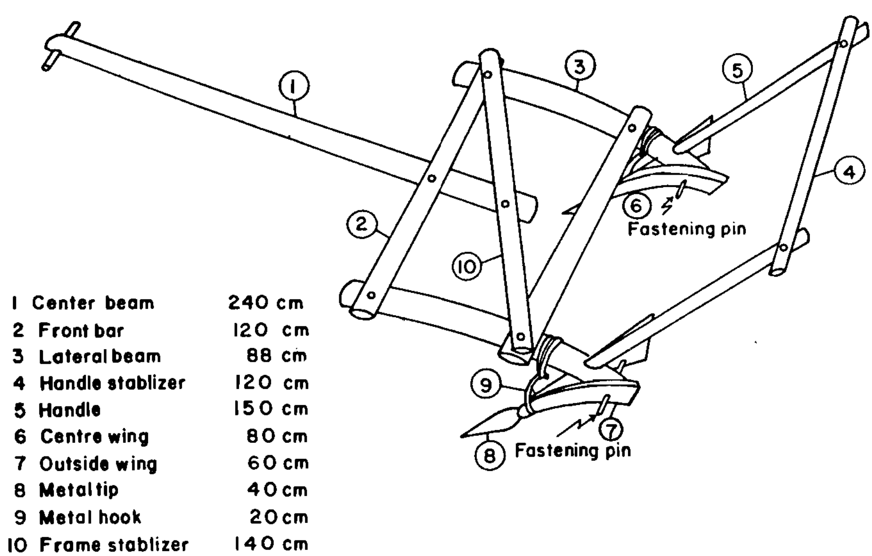

Figure 1. Broadbed makers – BBM (not to scale).

In an on-farm verification test in Debre Zeit in 1985 with 15 participating farmers, wheat yields increased by 78% and 56% for grain and straw respectively when using BBFs, with all other inputs being identical for drained and undrained plot pairs.

The implement is currently (1986) under on-farm verification in four different highland Vertisol areas (Debre Zeit – 1800 m asl, 800 mm annual rainfall, a teff-growing area; the Wereta and Fogera plains – 1800 m asl, 1500 mm annual rainfall, a finger millet-, teff-, and noug-growing area with traditional double-cropping systems; Were Ilu and S-Wello – 2600 m asl, 1100 mm annual rainfall, a wheat- and horsebean-growing area; the Inewari plateau and N-Shewa – 2600 m asl, 1100 mm annual rainfall, a wheat-, horsebean-, teff-, and fenugreek-growing area, with traditionally handmade BBFs). Some initial experiences are given below for the two high-elevation plateaux – Were Ilu and Inewari.

The heavy rainfall in Were Ilu during the 1986 cropping season resulted in extreme waterlogging which caused severe damage to the crops. In August 1986, thirty rainy days were recorded with an average rainfall of 9 mm per day. Tensiometer readings averaged 1.3 cbar suction on the BBF and 0.6 cbar on flat plots, with both readings taken at 15 cm soil depth. Horsebean *(Vicia faba minor)* has been entirely eliminated on many traditionally managed plots without adequate drainage. The results of a scoring of the crops for comparative treatment effects carried out in the second week of October (pod-setting in horsebean, heading in wheat) are given in Table 2.

Table 2. Crop scoring for expected drainage effect on yields at Were Ilu (October 1986)

Crop	Frequency, using pairs of plots of expected yield increase (see text) in the drained plots as compared with the traditionally managed plots.			
	equal	+50%	+100%	+ > 100%
Wheat	2	10	4	1
Horsebean	3	6	4	7
Teff			1	

On the Inewari plateau, a representative survey (45 farmers monitored) was undertaken to determine the human labour inputs into the traditional handmade construction of BBFs. With very little variation this operation requires about 60 h/ha. If the animal-drawn broadbed maker is used, the human labour input is reduced to about 16 h/ha. The total human labour input in land cultivation (average two ploughings before planting) and in BBF construction with seed covering can thus be reduced from 120 h/ha to about

75 h/ha. A socially interesting aspect of this substitution of human by animal labour is that the substituted labour is basically from children and women. Early indications are that the crops planted on BBFs made with the animal-drawn implement will outyield the ones made by hand, probably because of the greater uniformity of the BBFs.

There are strong indications of very serious soil fertility deficiencies (nitrogen, and especially phosphorus) in many highland Vertisols. Expected yield levels, even with improved surface drainage, are therefore still very low. Considerable soil fertility inputs are needed if higher levels of land productivity are to be obtained. Most of the highland Vertisols are in the acid range and can therefore make good use of cheap unrefined rock phosphates (Haque *et al.,* 1986). Nitrogen can be supplied to the soil by the farmer himself by strategically using leguminous plants in his cropping system (grain legumes, herbaceous forage legumes, leguminous browse plants). The nitrogen fixation of legumes can be considerable (Haque and Jutzi, 1984), and substantial nitrogen transfers from legume crops to the subsequent cereal crops grown on the same plots have been reported (Nnadi and Haque, in preparation).

The two key elements of low-external-cost soil fertility management on Vertisols are therefore cheap sources of phosphates and legumes for the generation of plant-available nitrogen.

An Interinstitutional Approach to Vertisol Management

A maximum impact on crop yields and soil and water preservation can only be expected if all relevant elements of improved Vertisol management are adequately combined and applied. The generation of these technological elements requires the input of specialists of many different disciplines in a coordinated mode of operation. It has therefore been decided to carry out the Vertisol management project for the Ethiopian highlands as a joint operation between the International Livestock Centre for Africa (ILCA), the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), the Institute of Agricultural Research (IAR), Alemaya University of Agriculture (AUA), the Ministry of Agriculture (MoA) and Addis Ababa University (AAU). Table 3 reflects the basic understanding between these participating agencies with respect to their contributions to the project.

An advisory committee has been established for the project whose members are the chief executives of all the participating agencies. This project governing committee has appointed a technical committee composed of specialists of all participating agencies. It is in charge of implementing the project as a joint operation, thereby utilizing all comparative advantages among the partner institutes.

Specific Vertisol activities in participating agencies are currently being identified for adequate budget allocation in order to ensure a concerted R&D effort for the improved utilization of the Ethiopian highland Vertisols for increased human food and animal feed production. The Joint Project on Improved Vertisol Management will participate as a main cell in the international network on Vertisol utilization organized by IBSRAM (In-

Table 3. Envisaged inputs into the joint Vertisol management project by participating agencies (*)

	ICRISAT	ILCA	AUA	IAR	MoA	AAU
1. Agrometeorology, soils and socioeconomics						
a. Agrometeorology						
Data analysis	x	x				
Training	x	x				
Crop modelling	x					
b. Soils						
Survey, characterization, classification	x				x	
Soil physics	x	x	x		x	
Soil microbilology	x	x	x			x
Soil chemistry	x	x	x	x	x	
c. Socioeconomics						
Baseline survey		x		x		
Monitoring		x				
2. Soil and water management, agronomy, animal husbandry						
a. Soil and water management	x		x	x	x	
b. Crop improvement, agronomy	x		x	x	x	
c. Animal husbandry		x		x	x	
3. Farm power (animal) and implements						
a. Animal power		x		x		
b. Farm implements	x	x		x		
4. On-farm verification, extension						
a. Verification		x	x	x		
b. Outreach, extension		x	x	x	x	

(*):
ICRISAT: International Crops Research Institute for the Semi-Arid Tropics, Hyderabad, Andhra Pradesh, India
ILCA: International Livestock Centre for Africa, Addis Ababa, Ethiopia
AUA: Alemaya University of Agriculture, Dire Dawa, Ethiopia
IAR: Institute of Agricultural Research, Addis Ababa, Ethiopia
MoA: Ministry of Agriculture, Addis Ababa, Ethiopia
AAU: Addis Ababa University, Addis Ababa, Ethiopia

ternational Board for Soil Research and Management). Project participants are currently organizing a major conference on the topic to be held in September 1987 in Addis Ababa. This conference will be a forum to review the state of the art and to discuss similar research and development activities in other areas of sub-Saharan Africa.

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THE POTENTIAL OF AGROFORESTRY FOR SOIL CONSERVATION – WITH SPECIAL REFERENCE TO VERTISOLS

A. Young*

Abstract

Soil conservation includes both control of erosion and maintenance of fertility. The principal adverse effect of erosion is reduction in fertility, through loss of soil organic matter and nutrients. Specific problems of Vertisols include the high erosion hazard on gentle slopes, low permeability, and N and P deficiencies. Six agroforestry practices can be effective in control of erosion, and eight in maintenance of fertility. At the same time, agroforestry contributes to other productive and service functions of farming systems. There has been very little agroforestry research conducted on Vertisols. The existence of a high apparent potential for soil conservation, coupled with the paucity of research results, calls for an internationally coordinated programme of soils research on Vertisols in semi-arid climates.

Introduction

ICRAF has recently carried out a review of the potential of agroforestry for soil conservation (Young, 1986b; Young, Cheatle and Muraya, in press). In this, soil conservation was interpreted in its broader sense, to include both control of erosion and maintenance of soil fertility. The present paper gives a summary of some results from this review, relating them when possible to the particular circumstances of Vertisols.

It should be said at the outset that there is relatively little recorded information about agroforestry on Vertisols. In the agroforestry systems inventory of the Interna-

* International Council for Research in Agroforestry, PO Box 30677, Nairobi, Kenya.

tional Council for Research in Agroforestry (ICRAF) there are only two such records, and in the multipurpose tree data base, seven. This review is therefore necessarily confined to the assessment of potential on general grounds.

Trends in Soil Conservation Research and their Implications

The traditional approach

Features for the earlier approach to soil conservation were:

- Soil conservation was regarded as synonymous with erosion control; the problem of decline in soil fertility, whether as a consequence of erosion or through other causes, received little consideration.
- Attention was concentrated on rate of soil loss, as tonnes per hectare or millimetres of soil thickness per year. Conservation measures were directed at reducing these rates to a (presumed) acceptable limit – "tolerable erosion"
- The requirements of arable cropping as regards soil cover were taken as unalterable. Hence conservation measures were directed at checking runoff by a barrier function, using bunds, terraces, etc.
- Assessment of the economic consequences of erosion were directed at the effects of reduction in soil depth, or total loss of land through gullying.
- Extension was carried out on the basis that erosion control should come first, as a prerequisite for good farming, applied in isolation from other agricultural improvements. Conservation extension was sometimes conducted on the basis of a prohibitive, legally enforced policy.

Some notable successes were achieved by this approach in its country of origin, the U.S., and in a few less developed countries (e.g. Zimbabwe). It ran into a number of problems, however. The costs (or equivalent labour requirements involved in structures such as bunds and terraces were high. Particularly when based on loss of soil depth, conservation works were frequently hard to justify in economic terms. Finally, in the present social context, conservation extension simply did not work: it was found impossible to enforce a prohibitive policy, and the cooperation of farmers could not be obtained unless they could see immediate benefits in the form of higher yields.

Recent trends

Recent findings from research (both scientific and socioeconomic), and resulting trends in policy, are as follows:

- Erosion is now treated as one of a number of forms of soil degradation. Fertility decline and its causes (physical, chemical and biological soil degradation) is of equal or greater importance. These aspects interact, both physically and economically, and conservation should address both jointly.
- Experimental work into the effects of erosion on crop yields has shown that the

earlier technique of artificial desurfacing underestimated yield reductions. Erosion reduces productivity not only by reduction in soil depth, but through effects on water-holding capacity, loss of nutrients, decline in soil organic matter and degradation of physical properties. The effects of a given rate of erosion on crop production are relatively greater in tropical than temperate zones, and are greatest on 'old', highly weathered tropical soils. Under high-input farming in the temperate zone, the consequences of erosion could be masked for a time by increasing fertilizers – an option not open to low-capital farmers of the tropics.

- It has been shown that soil cover (by including minimum-tillage agroforestry) can be a highly efficient means of controlling erosion, at least as effective as the runoff-barrier approach, and less costly.
- In extension, it is recognized that conservation must be achieved by the willing cooperation of farmers. It follows that farmers must be able to see tangible benefits, in the form of higher production, and associate these with conservation.

A schematic calculation illustrates the cost of loss of nutrients in soil erosion. Consider a tropical soil of moderately low fertility, containing 0.1% nitrogen in the top horizon. Assume a nitrogen enrichment factor in eroded sediment of 2.0 (it is often nearer 4.0) and a rate of soil loss under agriculture of 50 t/ha/yr. There will be a loss of 100 kg N/ha/yr, equivalent to removing 5 bags of 20-N fertilizer per hectare.

Policy implications

Once the full range of effects of erosion on soil properties and crop productivity are taken into account, conservation is more often found to be economically justifiable. Whilst problems of time preferences and pricing of externalities remain, there is less need for special pleading or manipulation of figures. Add to this the gains from maintenance of soil fertility, and analysis will often show good returns for investment in soil conservation, both to the farmer and to society.

From a technical aspect, further research is needed into land management practices which make use of methods of conservation based on soil cover. Such research should include how to reconcile maintenance of cover with other agricultural operations, and the ranges of physical environments and social conditions to which particular practices are applicable.

There should be no "soil conservation projects"! Conservation should be applied as an integral part of agricultural improvements, linked to increases in productivity.[1]

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[1] The principal sources used for this section were as follows: El-Swaify *et al.*, 1985; FAO, 1979, 1983; Follett and Stewart, 1985; Greenland and Lal, 1977; Morgan, 1981; National Soil Erosion, 1981; Rijsbermon and Wolman, 1985; Stocking, 1984; Stocking and Peake, 1986; Wiggins, 1981.

The Nature and Functions of Agroforestry

Definition and range

Agroforestry refers to land-use practices in which trees or shrubs are grown in association with herbaceous plants (crops or pastures) in a spatial arrangement or time sequence, and in which there are both economic and ecological interactions between the tree and nontree components of the system.

It is the ecological effects of the trees, for the most part acting through the microclimate and soil, that form the distinctive feature of agroforestry, and distinguish it from social forestry. All agroforestry practices except one, the establishment of timber plantations by the taungya system, are also social forestry; but the latter includes monopurpose wood production, such as the planting of eucalypt woodlots.

Nearly all agroforestry takes place on agricultural land. Indeed, with the single exception of the taungya practice, over 90% of agroforestry can be described in four words: "planting trees on farmland". It is thus the concern of departments of agriculture. However, 100% of it involves the raising, planting and tending of trees, a subject in which expertise lies with departments of forestry. There are real problems here in allocation of responsibilities, for which each country must work out its own solution.

In contrast to the situation five years ago, most people in the development field have some idea of what agroforestry is. Some, however, still view it mainly in terms of one or a few practices, often taungya or alley cropping. An agroforestry practice is an arrangement of components (trees, crops, pastures, livestock) in time and space. An agroforestry system is a specific local example of a practice, characterized by plant species, management, environment, and social and economic functioning. There are many thousands of agroforestry systems, but only some 20 distinctive practices (Nair, 1985; Young, in press). Table 1 is a classification intended to illustrate the range of practices. At the highest category it is based on components present, at the next on spatial and temporal arrangement, and at the lowest level on more detailed arrangement and on functions.

Functions

It is the function of trees in a land-use system which give agroforestry its distinctive nature. These are both productive functions, for fuelwood, domestic timber, fodder, food, oils, fibres, etc.; and service functions, such as shade, shelter (from wind), soil conservation, fencing and water management. Of the products, fuelwood is the most important on a world scale, perhaps matched in a few countries (e.g. India) by fodder. Of the service functions, without doubt soil conservation is that for which there is the greatest potential.

Table 1. Agroforestry practices.

MAINLY AGROSYLVICULTURAL (trees with crops)	
Rotational:	
1. Planted-tree fallow	
2. Taungya	
Spatial mixed:	
3. Trees on cropland	
4. Plantation crop combinations:	– with upper-storey trees
	– with lower-storey tree/shrub crops
	– with herbaceous crops (cf. also 12)
5. Tree gardens:	– multistorey tree gardens
	– home gardens
Spatial zoned:	
6. Alley cropping	
7. Boundary planting	
8. Trees for soil conservation:	– barrier hedges
	– grass barrier strips
	– on bunds etc.
	– on terraces
9. Windbreaks and shelterbelts	
10. Biomass transfer	
MAINLY OR PARTLY SYLVOPASTORAL (trees with pastures and livestock)	
Spatial mixed:	
11. Trees on rangeland or pastures	
12. Plantation crops with pastures	
Spatial zoned:	
13. Live fences	– mainly barrier function
	– multipurpose
14. Fodder banks	
TREE COMPONENT PREDOMINANT	
15. Woodlots with sultipurpose management	
16. Reclamation forestry leading to production	– on eroded land
	– salinized land
	– on moving sands
(cf. also 2)	
OTHER PRACTICES AND SPECIAL ASPECTS	
17. Apiculture with forestry	
18. Aquaforestry (trees with fisheries)	
19. Trees in water management	
20. Irrigated agroforestry.	

The Potential of Agroforestry for Soil Conservation

General

The broader interpretation of soil conservation, as set out above, will be taken as the basis for reviewing the actual and potential contribution of agroforestry. This may be summarized by the pseudoequation:

Soil conservation = Control of erosion + Maintenance of fertility

These two aspects will be taken in turn, notwithstanding the fact that one of the main messages is their interdependence, mainly through the effects of erosion on fertility decline.

Control of erosion

The distinctive problem presented by Vertisols is a high erosion hazard on gentle slopes, the result of their very low infiltration capacity when wet. Management systems designed to check erosion generally seek to reduce runoff or direct it into grassed waterways, as in the graded broadbed-and-furrow system developed by ICRISAT. It is also desirable to avoid decline in organic matter, leading to degradation of soil physical properties and still lower permeability (Dudal and Bramao, 1965; Young, 1976, ch. 9; Ahmed, 1984; Virmani and Swindale, 1984).

The tree component in agroforestry systems can assist in controlling the rate of soil loss through effects on four of the causative factors of erosion: rainfall erosivity, soil erodibility, runoff, and ground surface cover. Experimental evidence shows that the reduction in the impact energy of raindrops caused by a tree canopy is usually slight and may even be negative. Soil erodibility depends in part on organic-matter content, and the capacity of tree litter to maintain this can help to prevent decline in permeability and structural stability. For runoff reduction, the tree component can be designed so as to form a runoff barrier.

However, analysis of all of the major predictive equations (USLE, SLEMSA, FAO, Rose) shows that by far the greatest potential for controlling the rate of soil erosion lies in the cover factor. A ground surface litter cover of only 60%, maintained throughout the period of erosive rains, will normally reduce erosion to low and acceptable levels, even without additional structures of the barrier type. This effectiveness has been demonstrated specifically on Vertisols (Coughlan, 1987). In the design of agroforestry systems for control of water erosion, therefore, management practices that will lead to such a litter cover should be the primary aim, with runoff barriers secondary.

The functions of the tree component in the control of water erosion may include any of the following:

- To reduce erosion by increasing soil cover through tree litter, from both natural fall and prunings.

- To act as a runoff barrier, by means of closely planted hedgerows, coupled with the litter that accumulates against them.
- To strengthen and stabilize earth structures for erosion control (bunds, terrace risers, etc.) through the binding effect of roots.
- To make productive use of land taken up by earth structures, for fuelwood, fodder, fruit, etc.
- A function, partly psychological, of linking erosion control practices with production, and thus helping to make these practices an integral and permanent part of the farming system.

Evidence from controlled experiments on the effectiveness of agroforestry practices in controlling soil loss is scanty, but a number of countries have had sufficient confidence to include such practices in extension recommendations. Recent reviews have shown a capacity for erosion control in the following practices (with examples of countries in which they are found or recommended):

- Barrier hedges (e.g. Cameroon, Indonesia, Malawi, Philippines, Rwanda).
- Trees on soil conservation works – grass strips, bunds, terrace risers (e.g. Cameroon, Kenya, Nepal, Malawi, Philippines, Rwanda).
- Alley cropping: Trials that measure erosion rates are in progress (e.g. India, Nigeria, Tanzania), but available data are sparse. Through the capacity to combine litter cover with runoff barriers, the a *priori* potential for erosion control is high, and there is an urgent need for further experimental work.
- Tree gardens: Inherently highly effective (e.g. Sri Lanka, Tanzania, humid West Africa).
- Plantation crop combinations: Effective provided that they are managed for maintenance of ground cover (e.g. Costa Rica, Malaysia).
- Trees on pastures: In some countries, Vertisols are used as grazing land. Agroforestry is of little use in erosion control unless accompanied by standard measures of pasture management, control of livestock numbers, and rotational grazing. There is potential to assist in reducing the often serious erosion, but research is needed.[2]

Maintenance of soil fertility

Trees normally increase soil fertility. We know this from the high fertility of soils under natural forests, the restoration of fertility under fallow in shifting cultivation, and the effectiveness of reclamation forestry. The tree component in agroforestry systems possesses a capacity to improve soil fertility, whereas the crop component tends to decrease it. There is thus a *prima facie* potential to design agroforestry systems so that the effects of these two components balance each other, and soil fertility is maintained in a steady state.

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[2] The principal sources used for this section were as follows: Craswell *et al.*, 1985; Lundgren and Nair, 1985; Wiersum, 1984; Young, 1984, 1986b.

Some of the mechanisms by which trees improve soils are proven, others are hypotheses in need of testing. These processes are as follows:

- o Processes which augment additions to the soil:
  - o photosynthetic fixation of carbon and its transfer via litter and root decay to soil humus;
  - * nitrogen fixation;
  - * nutrient retrieval from deeper soil horizons;
  - * providing favourable conditions for input of nutrients by rainfall and dust.
- o Processes which reduce losses from the soil:
  - * control of erosion;
  - * root uptake of nutrients that would otherwise have been lost by leaching.
- o Improvement of soil physical properties:
  - * soils under trees tend to have favourable structural stability and water-holding capacity, as a result of organic-matter maintenance and the growth and decay of root systems.
- o Processes which affect the quality of plant residues and the timing of their transfer to the soil:
  - * provision of a range of qualities of plant litter, woody and herbaceous;
  - * growth-promoting substances in the rhizosphere;
  - * the potential, through management of pruning, to control the timing of nutrient release from decay of litter;
  - * effects of shading on microclimate, and thereby on rate of litter decay.

Vertisols are commonly deficient in N and P, particularly if continuously cropped. Problems of poor root development arise if the structure is degraded through reduction in organic matter.

Of the processes listed above, those which appear to have particular significance with respect to Vertisols are maintenance of organic matter, nitrogen fixation, and improvement of soil physical properties.

It can be presumed from the above that every agroforestry practice is likely to be more favourable for maintenance of soil fertility than arable agriculture. For some practices, the effects may be slight, e.g. boundary planting, live fences, and trees on soil conservation works. In the case of the taungya system, the comparison is with pure plantation forestry; such limited evidence as exists suggests that the cropping period will lead to some loss of fertility, although no substantial retardation in rates of subsequent tree growth has been demonstrated.

For eight agroforestry practices, there is a substantial and proven capacity for the tree component to augment soil fertility, and thus a potential for the design of land-use systems that will be sustainable. These are:

- o *Alley cropping:* Experimental evidence (including results from Nigeria, Philippines, and Malawi) has demonstrated the capacity of alley-cropping systems to lead to higher levels of soil organic matter and nutrients, and higher crop yields, than control plots under pure cropping, provided that leaf litter is returned to the soil. The system is most effective if the nitrogen- and carbon-fixation capacities of the trees are combined with modest levels of fertilizer addition, but zero-fertilizer systems are also possible. Quantitative data on amounts of biomass production and nitrogen fixation are available.

- *Tree gardens:* Multistorey tree gardens and home gardens (e.g. Sri Lanka, Tanzania, Vietnam) combine high litter production with dense ground cover. They exemplify in extreme form the three attributes commonly specified for good agroforestry design, being highly productive, fully sustainable, and practicable.
- *Plantation crop combinations:* The best documented example is the combination of coffee with *Erythrina poepiggiana* and/or *Cordia alliodora* in tropical America, the prunings from the *Erythrina* having a recognized function in fertility maintenance. Quantitative data on nutrient cycling exist for a few cases.
- *Windbreaks:* It should be possible to design windbreaks in such a way as to combine the architectural form necessary to fulfill their primary function with a capacity to enhance fertility on adjacent cropland. Research is needed.
- *Biomass transfer:* This refers to the practice, for example in Nepal, of carrying plant litter from communal forestland onto cropland. From the fact of its adoption, this clearly does improve fertility, although it may contribute to the degradation of communal forests.
- *Controlled or planted fallow:* Many years ago, work was conducted in Zaire to improve shifting cultivation through the corridor system. Some comparable methods have been tried in Amazonia. In part of the Philippines, a system of planting nitrogen-fixing trees in blocks in rotation exists. These systems are relatively demanding for land, but may have a potential in humid areas subject to rapid leaching and soil degradation under cropping.
- *Trees on cropland:* The beneficial effects of *Acaicia albida* on crops beneath them are known both to farmers of many countries and to scientists. Some other species with similar effects are known, e.g. *Prosopis cineraria,* in the drier regions of India, *Sesbania* spp. in moist subhumid western Kenya.
- *Trees and shrubs on pastures:* It is commonly found that pasture beneath trees is better than that on open ground, although to what extent this is due to livestock preferring to stand there is not known. An equal or greater contribution than pasture is made by the provision of tree fodder from deep-rooting woody perennials, particularly at a time when grasses are unpalatable or absent.

There is a potential for combining reclamation forestry with agroforestry in restoring degraded lands to productive use. The land is initially placed under pure forest cover. Once soil fertility has been found to be restored to some degree, selective clearance can be undertaken, along contour lines, with limited cropping or pasture production. The introduction of fruit trees is another possibility. Research is needed into the design and monitoring of such systems.

One substantial problem should be noted: the capacity of trees to maintain soil fertility is substantially reduced if a large part of the litter is not returned to the soil. An input-output model developed at ICRAF (Soil Changes Under Agroforestry, SCUAF) has shown that, whilst the contribution of root residues is substantial, it is much harder to design a sustainable system if aboveground tree biomass, particularly the leaf element, is removed (Young *et al.,* 1987). This is a serious difficulty in planning sustainable systems in countries, notably India, where fodder shortage has led to the practice of feeding all available herbaceous residues to livestock.

A second schematic calculation illustrates the orders of magnitude involved in the fertility-enhancement capacity of agroforestry. Alley cropping is most suitable as an example because the experimental evidence is best. In the humid and moist subhumid tropics, *Leucaena leucocephala* and certain other N-fixing trees have the capacity, in practical alley cropping designs, to yield 100-200 kg N/ha/yr; in the drier subhumid zone, the range is about 50-100 kg. A value of 100 kg N/ha/yr will be taken for illustration. In an N-deficient soil, it is common for each kilogramme of added N to raise cereal yields by something of the order of 10 kg/ha. Thus alley cropping with N-fixing trees has a potential either to raise cereal yields by 1 tonne per hectare, or to act as a substitute for 5 bags of 20-N fertilizer or 100 kg N. Substitution of money values for cereal crops for fertilizer gives the order of magnitude of the added production, or cost savings, involved. For farmers without access to fertilizer, there is an equivalent cost in lost production, either through being forced to leave land fallow in order to restore fertility, or in reduced yields.[3]

Discussion

There is a set of interactions and partial substitutions between soil erosion, other forms of soil degradation, decline in fertility, input of fertilizers, crop yields and production. The major adverse effect of erosion is through the annual loss of soil organic matter and nutrients, and consequent lowering of fertility. Reduced fertility can additionally or separately be caused by physical, chemical and biological soil degradation, basically the result of removing more organic matter and nutrients in crop production than is applied as inputs. Lowered fertility can be counteracted, by farmers with capital, through higher fertilizer inputs with consequent added costs. For many, it will mean reduced yields and crop production, leading towards a state of lower-level equilibrium, in which the agro-ecosystem is in a steady state but with very low productivity, a situation not uncommon on continuously cultivated Vertisols.

There is a known potential for agroforestry practices both to control erosion and to help maintain soil fertility. The proven experimental evidence is scanty, particularly as to the magnitude of effects and the applicability of specific practices to different environmental conditions. Moreover, by comparison with erosion control through earth struc-

[3] The principal sources used for this section were as follows: Nair, 1984; Prinsley and Swift, 1987; Swift, 1984, 1985; Young, 1986a, 1986c, and in preparation.

tures on the one hand, and fertilizer inputs on the other, soil conservation by means of agroforestry is a relatively lower-cost form of illustrated development. This compares with the very substantial benefits, as illustrated by the order-of-magnitude calculations above. The problem-solving approach normally adopted in agroforestry development is well suited to tackling problems in ways that are realistic for, and secure the cooperation of, the farmer.

It is necessary to repeat the qualification that many of the propositions put forward on the effects of agroforestry practices on soils, and thus their capacity to lead to sustainabe land use, rest on uncomfortably scanty evidence. Much information can be derived by analysis of data drawn from agricultural, soils, and forestry research, but there is still need for a much more substantial body of scientific information stemming from agroforestry itself.

Research is needed at two levels: understanding of the basic processes of tree-crop-soil interactions, through research on components and the tree/crop interface; and adaptive research leading to practical management systems. Substantial international and national effects are needed (not in planning networks but in actually doing research!) over the next 5-10 years if a body of knowledge comparable to that in other development disciplines is to be built up.

So far as is known, there are no published accounts of completed agroforestry research on Vertisols, other than their possible inclusion in accounts of the soil-improving capacity of *Acacia albida*. Work is in progress at the Dharwad (Karnataka) station of the Indian Council of Agricultural Research. Vertisols under semi-arid climates present a distinctive type of environment, in which it is highly desirable that agroforestry research should be conducted. A feature to which attention should particularly be directed is the combined roles of tree litter – in checking erosion, maintaining soil organic matter, and recycling nutrients. The potential for nitrogen fixation is also of significance.

It cannot yet be said that the potential of agroforestry systems for erosion control and maintenance of fertility is yet proven on Vertisols. However, the existence of a *prima facie* potential to achieve these aims, coupled with the relatively low input levels and costs required, is sufficiently great to call for an internationally coordinated programme of agroforestry research on Vertisols.

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VERTISOLS MANAGEMENT SYSTEMS IN SEMI-ARID MEDITERRANEAN AREAS

A. Osman*

Abstract

The paper reviews the properties, distribution and management of the over 10 million ha of Vertisols found in Arab countries. It discusses the major crops grown on these soils, the range of yields currently obtained, and land management problems, including surface drainage, tillage, cropping systems and fertilizer responses.

Introduction

Arab countries cover an area of 1400 million ha located in North Africa and the Middle East, and most of this area (about 90%) receives less than 150 mm rainfall per year. The remaining part is less dry, but rainfall occurs in a short time period and consists of heavy showers alternating with dry and sunny days.

Vertisols cover more than 10 million ha, located mainly in Sudan and partly in Morocco, Tunisia, Somalia and Syria. These soils produce numerous annual crops and fruit trees. Although they give relatively low yields, their potential production is considered to be very high, given appropriate soil and land management.

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* Arab Center for the Studies of Arid Zones and Dry Lands (ACSAD), PO Box 2440, Damascus, Syria.

Environmental Conditions

Climate

Two different climatic types are notable in Arab countries – the Mediterranean type and the monsoon type. A Mediterranean climate can be defined as having a wet, cold winter and a dry, hot summer. This is the situation in all North African countries and the Middle East. The monsoon type can be defined as having two rainy seasons, normally very short, when the rainfall exceeds the evapotranspiration.

Parent material and landscape

Vertisols are formed on different parent rocks and material. The most common ones originate from eruptive rocks, mainly basalt, or from alluvial material. The weathering of basalt gives a special kind of silicate clay that is not well crystallized and is very rich in iron oxides. These clays have high swelling/shrinking properties that characterize the soil order in the taxonomical systems.* Vertisols formed on alluvial material have a mixed clay composition, but consist predominantly of 2:1 silicate clays. They have different colours, generally light or dark brown, and sometimes red or reddish in the Munsell system. They may also show some textural changes or layering in the profile.

In both cases, Vertisols have a flat topography. They form very wide valleys (Orontes in Syria, Gezira in Sudan), but they might be found in rolling topography (Beja in Tunisia), mainly in the low-lying areas or depressions. Some Vertisols, however, are formed on colluvial clays on relatively steep slopes.

Vertisols are characterized by a texture with a high clay content. The clay fraction is dominated by 2:1 layer silicate clays that shrink and swell under alternating wet and dry conditions. This phenomenon is expressed by the formation of cracks that are over 1 cm wide and 50 cm deep. Most classification systems use these properties at least as the major criteria for determining the classification of Vertisols.

Most Vertisols in Arab countries have the same properties, but they show variations in colour, parent material, organic matter, calcium carbonate content, and landscape. All of them have a low water infiltration rate, low porosity, and a high water-retention capacity. These properties allow water to stagnate on the soil surface during the rainy season, and it takes a long time before any soil tillage or mechanized farming can take place. Soil fertility is generally very high, and weatherable mineral reserves in the soil are also very high, especially potash. These soils have a good response to nitrogen fertilizers, and a high potential for phosphorus accumulation.

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* These Vertisols are dark- or black-coloured and are generally homogeneous in the profile. Some of them have a high organic-matter content in the topsoil, and when this is associated with colour change between the dry and wet conditions, they are classified as Mollisols.

Geographic distribution

Vertisols cover over 10 million ha in the Arab countries, which is about 15% of the cultivated area under rainfed conditions. They are mainly located in Sudan (3.4 million ha), and are also located in Morocco (2.1 million ha), Algeria (1.8 million ha), Tunisia (1.3 million ha), Somalia (1.2 million ha), and Syria (1 million ha).

Land Use

Vertisols in the Arab countries produce a multitude of crops. Either under rainfed or irrigated conditions, they are used for field crops, legumes, vegetables, industrial crops, or fruit trees.

Wheat is the main annual crop cultivated on the rainfed Vertisols. This is the case in the North African countries (Tunisia, Algeria and Morocco) and the Middle East (Syria, Lebanon, Jordan and Iraq). Crop rotation is either biennial, where wheat is followed by legumes (e.g. vesces, lentils), or triennial, where the wheat-legume sequence is followed by fallow. The fallow system is applied under dry semi-arid conditions where rainfall is low and irregular. In Sudan and Somalia, sorghum replaces wheat. Other crops are also cultivated under rainfed conditions, such as chickpeas and faba beans as winter crops.

Under irrigation, the choice of crop is wider, and Vertisols can produce two crops per year. The winter crop might receive supplementary irrigation, giving a higher yield. Industrial crops are cultivated on a large scale: cotton and sugar beet in Syria, cotton and other fibre crops in Sudan. In neighbouring countries, vegetables are cultivated near the big cities under intensive cropping systems, receiving a high amount of fertilizer and manure. The coastal areas of the North African and the Middle East countries is cultivated by citrus trees and other subtropical fruit trees where frost or low temperatures are not to be expected.

Productivity

Vertisols have a very high potential capacity for production. Very often, the average yield is very low, and generally land management is responsible for this situation. Farmers do not care for these soils as they should. They apply traditional technologies in the farming system, or they do not receive the necessary technical and scientific assistance from extension services. This might explain the wide range in the level of yields obtained from these soils. Table 1 gives the range of yields obtained in the Arab countries from Vertisols.

Table 1. Crop yields from Vertisols in Arab countries.

Crop	Range of yields (tons/ha)	
	Low	High
Wheat	1	6
Sugar beets	15	100
Cotton	2	4.5
Citrus	10	40
Maize	2	6
Sorghum	1	4
Potatoes	5	20

Land Management

The variations of yields presented here might be even more extreme in some years, when it is either too wet or too dry. An integrated soil/land management system appropriate to each location and to individual conditions is the only way to increase the agricultural production of Vertisols.

Surface drainage

Even under severe drought conditions Vertisols may become waterlogged after heavy rain unless surface drainage is properly maintained. Irregular microtopography leads to irregularity in moisture distribution, and in this case it is necessary to use the grader blade or some other suitable technique to obtain a regular slope. This operation should be repeated whenever necessary, since this irregular microrelief forms normally even on a flat topography due to the swelling and shrinking of these soils every year in response to the sequence of the wet and dry seasons.

Tillage

Vertisols should receive particular care with regard to soil tillage. Cultivation should take place at the appropriate time and with the appropriate moisture content. In contrast with so many other soils, Vertisols are not easy to cultivate under very dry or very wet conditions. Ploughing should be as shallow as possible, and deep ploughing should only be applied for annual crops once every 3 to 4 years. Zero tillage is suitable in most cases, and is highly recommended in citrus orchards or other tree plantations where the rooting system is very shallow. Ploughing should be done immediately after harvesting the wheat – to conserve the remaining moisture in the soil on the one hand, and to avoid the hardening of the topsoil due to drought on the other.

Cropping systems

Vertisols should receive particular care with regard to the selection of a cropping system. For instance, suitable crop rotation is an important part of land management. Moreover, crop selection should take into consideration the provision of a good dense vegetation cover. The seeding rate also needs to be taken into account as an essential aspect of the technology. Further, it is important that plant residue should be incorporated in the soil to increase the organic-matter content and to allow better root penetration. One of the difficulties in the management of Vertisols is that the plant roots are not able to penetrate the soil and absorb the maximum amount of moisture and nutrients, even if the soil is very deep.

Fertilization

Vertisols generally give a good response to nitrogen fertilizer. Although the dissemination of the nutrients in the soil is relatively slow, it is recommended that the amount of nitrogen should be split into two or three applications to obtain the maximum benefit. Phosphorus also gives good results, but may only need to be applied once, either before or with seeding. Alternatively it might be applied once every two or three years, depending on its availability in the soil.

Most Vertisols are already rich in potash, so this element is not applied in most cases, unless its level decreases or the cropping system includes some potash-sensitive crop. Micronutrients might be needed in some cases, but deficiences can easily be detected and tests can be made accordingly.

Irrigation techniques

Wherever irrigation water is available, it should be applied according to the water infiltration rate, which is normally very low. Water application should be carefully calculated whatever irrigation method is used. Also, the amount of water should be calculated according to the depth of the roots.

Conclusion

These remarks are based solely on local and partial experience: only research can answer the many questions which arise concerning Vertisol management. Interdisciplinary investigation is highly recommended, and the results and experience gained should be exchanged and transferred at the regional and international level. Food security and starvation problems cannot be solved without increasing the production of the farmers' fields and without the efforts of the farmers themselves.

AVENUES FOR THE IMPROVEMENT OF CULTURAL PRACTICES ON VERTISOLS

T.J. Willcocks*

Abstract

Various ways of improving cultural practices on Vertisols are examined and the multidisciplinary nature of the work is emphasized. It is recommended that existing farming systems need to be carefully studied so that relevant research and development needs can be identified and effectively implemented. Examples of agricultural engineering projects for small- and large-scale rainfed and irrigated farming from countries like Sudan, Tanzania and Egypt are summarized.

Introduction

This paper outlines and gives examples of how agricultural engineers can assist in the multidisciplinary task of improving the management of Vertisols. The work of the ODA-funded Overseas Division at the AFRC Institute of Engineering Research (formerly the NIAE), Bedford, UK, has been concerned with the improvement of cultural practices in many developing countries. The information below is based on experience with Vertisols through field trials and/or observations in countries which include Egypt, India, Kenya, Sudan, Tanzania and the USA.

Vertisols cover about three million square kilometres of the earth's surface (i.e. 2% of the land area), and consequently represent vast crop production resources. Much of this potential has not been realized because of the difficult nature of these montmorillonitic clays which are very hard and cloddy when dry and extremely sticky when wet.

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* Overseas Division, AFRC Institute of Engineering Research, Silsoe, Bedford MK45 2BB, England.

The object of the agricultural engineering studies at AFRC has been to develop improved cultural practices that can be adopted readily by local farmers. The general criteria for an improved farming system has been that it shall conserve scarce inputs like energy and water and be more reliable than the one it is designed to replace.

The development and implementation of an appropriate methodology has been of paramount importance in this work, and it cannot be overstressed that it is necessary to approach the problem on a multidisciplinary basis. For the effective development of cultural practices it is essential that engineers work with local farmers, agriculturalists, agricultural economists (with farming systems experience), soil physicists and agroclimatologists.

Methodology Factors to Consider in Implementing R&D Programmes

Improved cultural practices should not only reduce the inputs necessary to produce a crop, but they should achieve it more reliably than with existing methods, and above all the new technology must be sustainable within a given environment. It is essential, therefore, that any research and development (R&D) work should take into account the primary and secondary constraints to efficient crop production. To achieve this adequately, the factors/resources discussed below must be considered carefully.

Farming systems management and energy resources

Resources are scarce in most developing countries and researchers need to ensure that their work is relevant to the realistic needs of local farmers. This is unlikely to happen unless scientists are quantitatively aware of the constraints within currently practiced farming systems. To achieve this the work must be done on a multidisciplinary basis, and economic, as well as agricultural, engineering and soil aspects play an important role in determining what level of technology is appropriate. In the past, agricultural economists have tended to concentrate on "constraints analyses" in postproject evaluations to establish the degree of technology adoption. This "post-mortem strategy" is of limited value in the management of R&D, and a new approach is needed so that economics can be used more effectively in the identification of variable R&D topics at the outset. Farming Systems Analysis (FSA) teams are therefore recommended to identify primary and secondary constraints to efficient and reliable crop production within current cultural practices. A typical team would consist of an agriculturalist, an agricultural engineer, a soil scientist and a farming systems economist. They should quantify the labour, time, financial, technical and economic constraints within farming systems so that R&D can be specifically targeted to meet priority needs.

The FSA team will need to conduct on-farm surveys with the advice and support of agricultural extension and research services. It is recommended that the work be conducted in four stages:

– Study the production environment of farmers so that their main management problems can be understood.

- Describe how farmers meet these problems, i.e. what they do and how they do it, and explain why they approach their priorities in these ways.
- Identify and describe the primary and secondary constraints that prevent farmers from achieving better or more reliable crop production, and consider the effect of constraint interaction.
- Provide the operational specifications for improved cultural practices that could be achieved with new or improved management or technology.

In the identification of agricultural engineering needs for the improvement of cultural practices the FSA team should have the following objectives:

- To identify primary and secondary constraints to effective crop production.
- To describe the mechanization systems used by the farmers and explain how these are determined by primary resources like climate, soil and energy (i.e. available inputs – labour, draught power, fertilizer, etc.), and agronomic and economic factors.
- Where improved mechanization is thought to be appropriate, to develop zero-option and managerially optimal models* in addition to the technically optimal models resulting from research-station experience. This type of analysis will provide evidence for the selection of relevant system and machinery designs.
- Where an improved implement is required, to provide:
  * a cost ceiling for viable implementation (the cost must be considered in terms of income-generating potential and also financial and economic costs, i.e. the effects of fuel subsidies, etc.), and
  * specifications for agronomic and/or soil requirements for optimum crop growth and the effect of reducing these specifications.
- To conduct a survey and literature search to establish whether the required equipment is already available elsewhere and whether such equipment could be produced locally.

The approach taken in these studies will depend on whether the farming system is rainfed, based on residual soil moisture, or irrigated.

With dryland farming, cultural practices are primarily determined by climate, soil type and available draught power – with timeliness of operations usually being of over-

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*Zero option	=	productivity of agricultural system without improved technology component
Technically optimal model	=	potential productivity of improved system or technologies operating under ideal conditions (e.g. as often found on research stations)
Managerially optimal model, i.e. on-farm conditions (frequently suboptimal technically)	=	potential productivity of improved technology when used under pre- and postoptimal conditions, in addition to optimal (e.g. tillage cannot always be conducted when soil is friable since soil can be hard early in the season and more weedy later). These considerations on system capability are particularly important for implements since they need to be used over sufficiently long periods to keep cost/ha or cost/t low).

riding importance. For investigations into tillage and planting practices, a soil physicist should be consulted, and for certain aspects the services of a soil and water engineer will be needed.

For irrigated agriculture, consideration must be given to water-use management, and multiple cropping aspects will warrant special attention to market analysis.

The studies will need to be ongoing to cover different seasons and crop regimes, and a diagnostic approach should be developed to indicate trends early on in the management of the R&D. It must be stressed that the introduction of more efficient crop-production systems is the primary goal of this work and any new farm implements or systems should only be developed within this context.

Soil (Vertisol)

The improvement of cultural or tillage practices can only be achieved when the difference between the physical condition of the undisturbed soil and the optional edaphic requirements of the crop are known. This can often be readily achieved by inspecting/comparing the root growth of crops grown in untilled soil and soil which has been cultivated to known depths.

The inherent bulk density of self-loosening Vertisols is not generally limiting to crop root growth (Willcocks, 1984a, 1984b), and any tillage can, therefore, be confined to shallow weed control operations. Knowledge of soil physical properties is therefore needed, and an example is given in Table 1 which compares a Vertisol with a Luvisol.

Background information on the properties of Vertisols is readily available (see bibliography by Willcocks and Browning, 1986). Helpful reference material includes De'Vos and Virgo (1969) on Sudan, Newman (1983) on Texas, Smith *et al.* (1984) on Australia, and Venkateswarlu (1983) on India.

Vertisols can be described as 'self-loosening' soils:

- During soil drying, shrinkage occurs, resulting in the formation of deep cracks (fissures) with rough cleavage faces. Continued dry-season desiccation of the soil results in the formation of a loose and dusty surface with the majority of Vertisols. Under the combined influence of livestock, wind, cultivation, rainfall, irrigation and gravity, much of this surface soil is dislodged and accumulates within the fissures. When water enters the cracks, through the onset of rains or irrigation, swelling of the accumulated soil at the bottom of the cracks occurs. This results in considerable stress at this level (typically 1 m depth) due to expansion of the montmorillonite clay through wetting. These pressures are relieved by an upward movement of some of the soil mass along slickensides (Newman, 1983). This process results in an intermixing of soil surface material with the lower horizons (homogenization).
- Because Vertisols shrink and fissure they are also referred to as 'clod-forming' soils. This can lead to severe management difficulties in countries where there are no frosts to break down clods lifted to the surface by inappropriate tillage operations. In addition to this, these soils are very sticky when wet, and on account of their physical properties Vertisols require very careful management.

Table 1. Soil characteristics of a Botswana Luvisol/Cambisol and a Vertisol from Sudan (soil samples taken from cultivated topsoil, e.g. 0-0.25 m).

Texture class	Particle size analysis, μm: 2000-500	500-250	250-100	100-50	50-2	< 2	Moisture retention %, w/w, held at -0.01 M Pa	-1.50 M Pa	Consistency limits, % water: Shrinkage limit	Plastic limit	Liquid limit	Proctor compaction value, mg/m at % water
	Coarse sand		Fine sand		Silt	Clay						
Luvisol (Botswana) Ferruginous sandy loam	18	16	29	13	12	12	13	5	10	14*	23*	2.05 at 8%
Vertisol (Sudan) Montmorillonitic clay "black-cotton soil"	4		13		23	60	36	28	–	28*	70*	1.5* at 16%

Soil moisture on gravimetric (w/w) percentage dry basis

Botswana Luvisols: Shrinkage limit.[3] Proctor compaction value.[4]

Field experience with Botswana Luvisols showed that they were in practice nonplastic; and nonplastic and unsieved (425 m) soil containing some very small stones had a liquid limit of 19%.

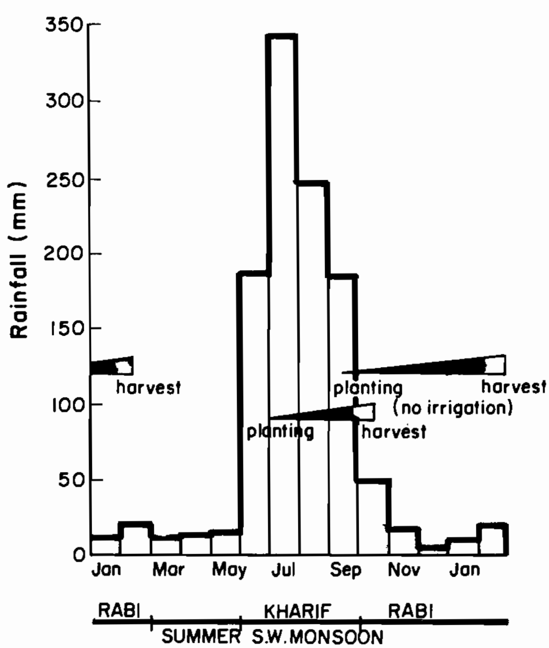
Sudan Vertisol was 30% m.c. at pF 3.3, which approximates to the plastic limit.[3]

*Overseas Division, NIAE and Silsoe College cooperative measurements. (Source: Willcocks, 1984).

– The suitability of the edaphic environment for effective crop production can best be estimated by excavating soil pits next to crop plants to a depth of about one metre so that the development of mature crop root systems can be inspected. Crop roots are a valuable and readily available dynamic "instrument" as they will clearly show if soil physical factors are seriously limiting to root elongation. Since the dry bulk density of these clay soils is rarely limiting to crop root growth (i.e. > 1.6 million g/m^3), and homogenization occurs naturally, it is necessary to consider carefully the question: "What is the purpose of tillage?"

Climate

The water and heat (temperature) resources of the crop-growing season(s) needs to be known so that cultural practices can be aimed at optimum climatic conditions for crop growth. Figure 1 depicts typical rainfed cropping systems in Maharastra, India, and Figure 2 shows how cotton yields are seriously depleted by late planting in Kordofan, Sudan. Timeliness of planting is critically important in rainfed agriculture, and climatic data is needed to develop optimum rainfed and irrigated systems.



Mean max temp	37°C	31.8°C	29.3°C
Mean min temp	22.5°C	23.6°C	16.4°C
Mean daily RH	36%	73%	54%
AV. monthly evaporation	393mm	162mm	151mm

Figure 1. Rainfed cropping in Vertisol region of India (Central Vidarbha Zone, Maharashtra).

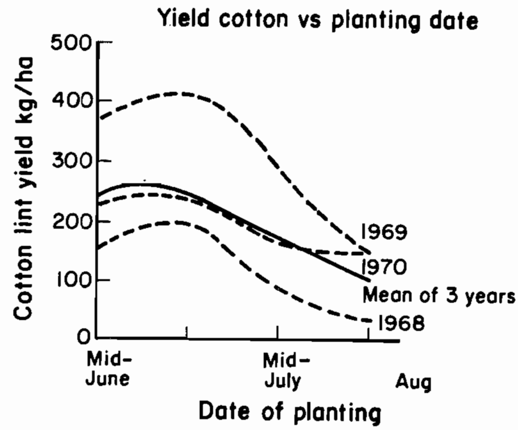


Figure 2. Effect of date of planting on yield of cotton grown on Vertisol in South Kordovan, Sudan:

Case Studies

Rainfed agriculture (single and multiple cropping)

Small-scale manual and mechanized farming

Field trials and observations of cropping on Vertisols in countries such as Sudan, Tanzania and India have clearly shown that timeliness of planting/rainfall and the control of weeds are the major field constraints to smallholder crop production. Weed control is most easily achieved by early-season seedbed preparation to enable timeliness of crop planting, which in turn allows the establishment of an early crop canopy to smother weeds. The benefits of crop-canopy control are often enhanced by multiple cropping, a well-proven traditional practice amongst many subsistence farmers. Improved cultural practices for these farmers must make timeliness of planting and subsequent weed control easier to achieve.

The lack of labour or draught power does make early (often prerains) cultivation (hoeing) difficult, and attempts have been made to assist farmers with tractor power. This has often failed in smallholder agriculture because of inadequate planning (Gibb *et al.*, 1986/87), and because in small plots tractors are inefficient, logistics are difficult, and backup services to remote areas are extremely costly and usually unsustainable (Fieldson *et al.*, in press; Willcocks, 1981).

Reduced tillage or no-till systems do have a significant role to play in alleviating some of the constraints encountered by the small-scale Vertisol farmers of Africa and India.

Observation trials in small Vertisol fields in southeastern Tanzania clearly showed that the use of Glyphosate herbicide as a field preparation activity effectively controlled difficult stoloniferous and rhizomatous weeds in rice fields. (Glyphosate functions systemically and is much less toxic than most herbicides.) The productive use of many low-cost, hi-tek, but simple, manually operated machines, like the one-wheel pull-along sprayer (Kemp, 1984), for the application of herbicides is a much better way to control weeds in smallholder fields than by spending scarce foreign currency on a few large agricultural tractors (Willcocks, 1983). It is acknowledged, however, that the concept of no-till agriculture is not generally accepted and there is a significant education/training task that is needed at all levels. A comparision of inputs for conventional tractor-ploughing and no-till systems is given in Table 2 and Figure 3. In these calculations it is estimated that Glyphosate would only be needed every third year, and the duration of its residual effect could be longer with good husbandry.

Table 2. Comparison of commercial energy requirements for conventional and reduced primary field preparation (provisional data).

Conventional primary tillage			Reduced system: (T) Tractor			(M) Knapsack	
Activity	Fuel l/ha	Energy* MJ/ha	Activity	Fuel l/ha	Energy* MJ/ha	Activity	Energy MJ/ha
YEAR ONE			Sprayer	–	35	Sprayer	50
Plough	–	120	Spraying	1.7	95		–
Ploughing	22.5	1260	Glyphosate	–	908	Glyphos.	908
		1380	(@2 kg/ha a.i.)		1038		958
YEAR TWO			Polydisc	–	100	Sprayer	50
Ploughing	22.5	1380	Tillage	5.0	280	Herbicide	276**
YEAR THREE			Polydisc	–	100	Sprayer	50
Ploughing	22.5	1380	Tillage	5.0	280	Herbicide	276**
THREE-YEAR TOTAL		4140 (100%)			1798 (43%)		1610 (39%)

*Energy values include allowance for depreciation and repairs of equipment (Leach, 1976), estimated as +40% of net fuel use (@ 40 MJ/l) for tractors.

**Paraquat herbicide @ 0.6 kg/ha active ingredient (a.i.). Energy values for herbicides from Green *et al.* (1977).

From this study it is evident that the use of herbicides requires less than half the inputs needed for conventional tillage. Another advantage of light manually operated machines is that their use is not so restricted by wet conditions, which are a severe limitation with heavy tractor-drawn implements.

Refugee smallholder farmers in East Sudan have recently adopted the 'saluka' hoe for planting their sorghum, as tractor-hire tillage was not always available for timely planting.

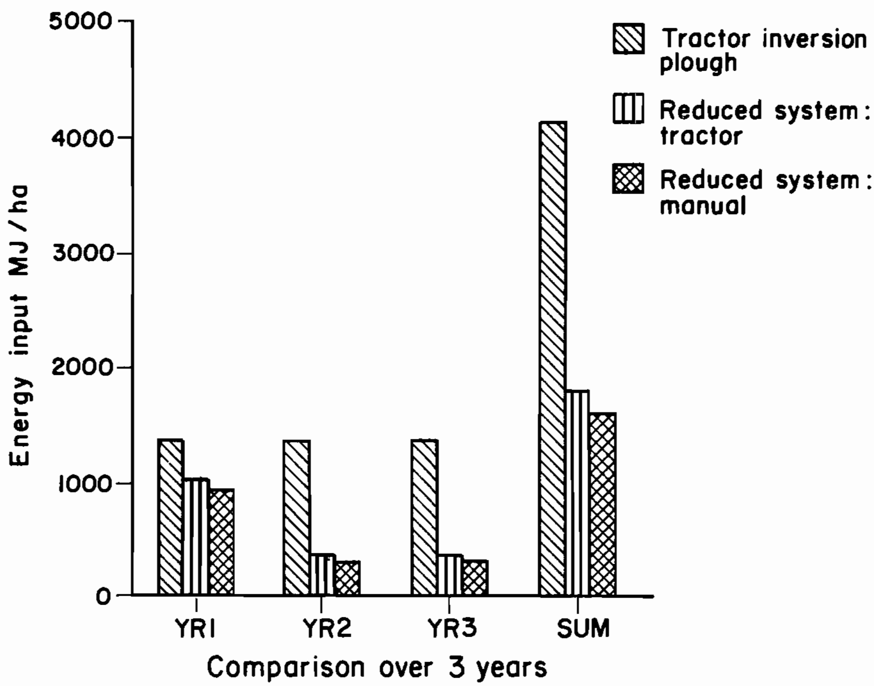


Figure 3. Input requirements: conventional tillage vs. herbicide.

In addition to allowing timeliness of planting, saluka-planted crops are in rows, which facilitates weeding operations during plant growth. A tillage/planting/weeding trial has therefore been initiated (Willcocks, 1985) to investigate the pros and cons of manual vs. tractor cultivation techniques. The 1986 trials have indicated that rolling jab planters and simple donkey-drawn weeders could be an effective and appropriate means of mechanizing a sustainable cultural practice on these Vertisols (Meredith, 1986).

Extensive mechanized farming

Vertisol areas in Sudan are generally much more extensive than in other regions of Africa, and these relatively flat areas are technically ideally suited for tractor mechanization, as are Vertisols in Texas and Australia.

The inherent density of the Sudan soils, like most Vertisols, is not limiting to crop root growth, and a shallow (0.1 m) weeding operation is all that is necessary to prepare an adequate seedbed (Willcocks, 1980).

The timing of this cultivation is important and ideally should not be before sufficient rain has fallen to replenish soil moisture through the cracks (Lock and Coughlan,

Table 3. Measurement of implement draught power and net energy requirements on Vertisols (montmorillonitic clays) in Sudan.

Plough type	Depth of work nominal, m	Width of work, m	Forward speed, m/s	Network rate, ha/h	Draught			Net energy		
					Force		Power	Implement requirement		Applied to
						Per m width				
					kN	kN/m	kW	MJ/ha	kWH/ha	soil.k.J/m³
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
Wide one-way disc 24 discs (dia. 460 mm) in 3 aligned gangs. (Approx. 20 kg/disc)	0.06	3.77	1.52	2.1	7.6	2.0	11.6	20	5.6	34
Chisel 7 tines at 400 mm centres	0.15	2.80	0.99	1.0	15.0	5.4	14.9	54	14.9	36
Offset disc harrow 28 discs (dia. 650 mm) in 2 gangs	0.08	2.65	1.42	1.4	10.1	3.8	14.3	38	10.6	48

1984) and germinate the first flush of weeds, which can then be killed by the cultivation. Clearly optional timing will not always be possible and some compromise will be necessary to ensure economic utilization of the equipment (see 'managerially optional model' in footnote above). Where prerains tillage becomes a managerial necessity during early-season operations, most open cracks will be covered and light rains can be sufficient to wet the shallow seedbed profile to a moisture content sufficient for seed germination. This moist seedbed profile will, however, be 'perched' and problems will arise if midseason rains are poor, since water replenishment of the deeper profile via the cracks will have been inhibited.

Tillage equipment for these conditions needs to be high-speed so that each implement can cultivate the maximum area during the short season (Figure 2) before the rains make the Vertisols too sticky for tractor-tillage operations. High-speed equipment is essentially low-draught, and since there is no need to loosen Vertisols deeper than 0.1 m, wide weed control equipment is very suitable. Detailed draught measurements were conducted in Sudan to measure the inputs for various tillage systems (Table 3) and establish the cost of producing one tonne of crop (Figure 4). Deep tillage as conducted in temperate agriculture is very costly under these Vertisol conditions, since it produces a cloddy tilth which requires further energy to break down the soil to an acceptable seedbed. This is clearly indicated in Table 3 and Figure 4, where the slow chisel plough system required secondary cultivation and had unacceptably high input costs per hectare. The energy cost of the chisel system per tonne of crop yield was about four times that achieved with shallow tillage. In addition to this, the seasonal area potential of the deeper cultivation system would only be about 25% of that achievable with shallow discing equipment at 2 ha/h. Clearly, therefore, high-speed shallow cultivation is the most convenient and economic method for the extensive cultivation of Vertisols.

Smallholder agriculture in an extensive region like South Kordofan can benefit from this technology, provided several plots can be cultivated at once so as to keep field efficiencies of the equipment high and thereby maintain low input costs.

Figure 4 also shows energy input costs for the cultivation and semi-arid cropping of a dense Luvisol (sandy loam) in Botswana. It is of interest to note that sorghum production is more energy efficient on the self-loosening Vertisol than on the dense Luvisol.

Irrigated agriculture (single, multiple, and double-cropping)

Irrigation of Vertisols is practiced on the vast Gezira and other Nile-dependent schemes in Sudan. The various systems of irrigation have been described by Coleman (1950), Farbrother (1972) and Spoor (1963), as summarized in the bibliography by Willcocks and Browning (1986). Mwea is an example of a smaller scheme in Kenya, and Egyptian farmers have practiced the irrigation of Vertisols for centuries.

Deep replenishment of soil moisture is most readily achieved through the cracks, but deep cracks only appear when the soil is dry (at PWP according to Coleman, 1950). Careful programming of irrigation in Egypt means that Vertisols, following the wheat harvest in June, are deeply fissured and therefore suitable for irrigation. The commonly

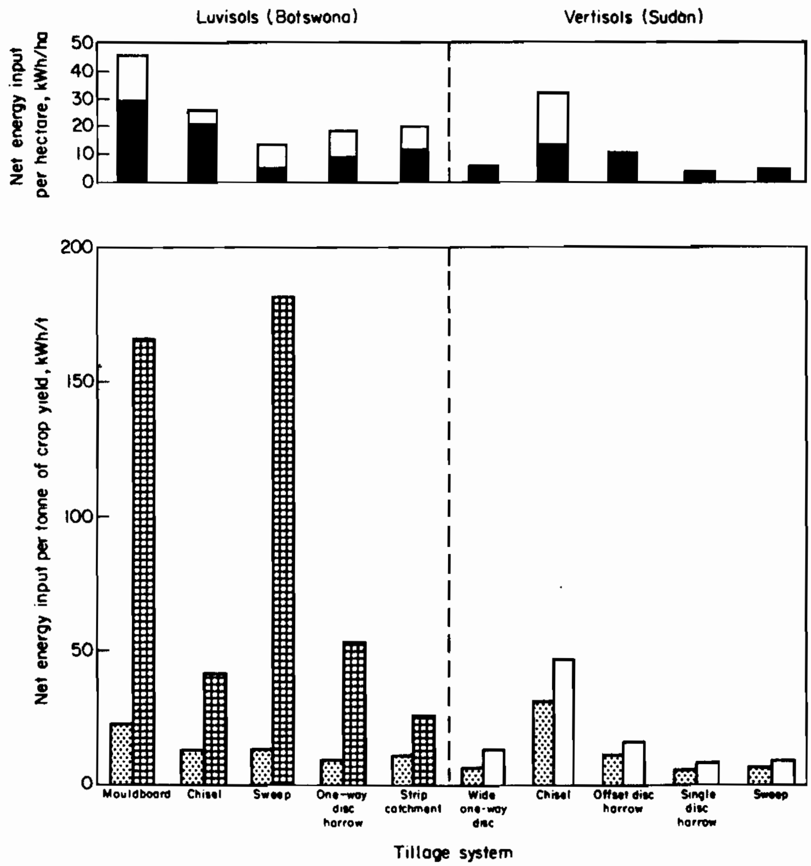


Figure 4. Net energy inputs (top) per hectare. (■ primary tillage inputs; □ secondary cultivations where necessary); and (bottom) per tonne of crop yield; (▨ sorghum, ▦ maize; □ cotton) for the various tillage treatments on (left) dense Luvisols (Botswana) and (right) Vertisols (Sudan).

used tine tillage is, however, inappropriate and costly since it produces large clods, making seedbed preparation expensive. Since the clod problem is introduced by the method of primary tillage (chiselling), improved practices need to deal with the cause instead of treating the symptom. Improved cultural practices have been recommended (Willcocks, 1983) and include no-till and shallow-tillage techniques that produce suitable seedbed tilth with one-pass implements. Polydisc and newer machines, like the twin-shaft Dyna Drive developed by NIAE or similar rotary implements, have a role in these conditions.

The production of ridges for furrow irrigation can be difficult in dry cloddy conditions when using tined implements. Instead of loosening the soil from below with a tine or lister body, a technique of progressive "scratching" from the surface can be used to produce the ridge. The "Lilliston"-type rolling cultivator fitted with helical spider wheels has proved most effective for weed control and ridge formation.

Many Vertisols are successfully irrigated for single and multiple cropping. Experience with double-cropping is very limited because it is difficult to replenish soil water adequately without the presence of deep open cracks. Shallow soil profile techniques with frequent watering and the development of common furrow techniques need to be studied and developed further so that more farmers can realistically capitalize on the double-cropping potential of Vertisols. This will need a concentrated effort by multidisciplinary teams, as outlined in the section on farming systems above.

Conclusions/Recommendations

An improved cultural practice for Vertisols in semi-arid regions needs to:

* conserve scarce water and energy resources,
* increase the farmers' ability to achieve timely planting, and
* facilitate effective control of weeds.

The identification and implementation of relevant research needs will best be achieved by multidisciplinary FSA teams (see the section on farming systems above).

Inspection of crop root systems in Vertisols will show that inherent soil density is not limiting to root elongation. This is because of the self-loosening nature of the soil, as mentioned in the section on farming systems above. Deep tillage is, therefore, unnecessary, and it will usually produce clods which make seedbed preparation difficult and expensive.

Smallholders in rainfed agriculture need low-input sustainable farming systems. Reduced-tillage hoe-planting systems enable timeliness of planting and improved weed control through row cropping. No-till cultural practices show great promise on Vertisols, and they can be efficiently mechanized with manual or animal-powered rolling 'jab planters' and 'pull-along' sprayers for the application of herbicides like Glysophate, as discussed in the section on mechanized farming above.

Extensive rainfed farming of Vertisols is economic, provided high-speed (2 ha/h) shallow (max 0.1 m) weeding implements are used as a primary, one-pass tillage operation, as pointed out in the discussion on extensive mechanized farming. This section also points out that irrigated agriculture for single and multiple cropping on Vertisols is well established, but there is still room for some reduction in inputs.

There is an urgent need for a practical and adoptable cultural practice for double-cropping on Vertisols. It is the author's belief that an in-depth study of the management of cracks would be a reliable R&D approach to achieving appropriate farming systems for double-cropping with irrigation.

It is strongly recommended that a multidisciplinary group be set up and charged with the responsibility of initiating and implementing an R&D programme to produce realistic and easily managed double-cropping systems for Vertisols.

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MANAGEMENT PROBLEMS OF COTTON ON VERTISOLS IN THE LOWER SHIRE VALLEY OF MALAWI

A.J.B. Mitchell*

Abstract

A soil survey in 1971 pointed to a number of possible causes for the uneven growth of cotton, which was particularly apparent in dry years. Lack of water in the root zone could be caused by degradation of the surface structure (accelerated runoff), saline or sodic soil at shallow depth, or shallow gravel layers.

At the same time a serious increase in soil erosion could be attributed to two main causes:

- *rapid expansion of the area under cotton, including cultivation of the diffuse drainage lines;*
- *progressive decline in the size of topsoil aggregates over a period of 4-5 years after the land is brought under cultivation.*

A research programme was initiated in 1973 to investigate management techniques that would maintain crop yields and reduce erosion. The initial findings were that conventional soil conservation techniques could result in crop reductions, and showed that the farmers' reluctance to follow the recommended practice of planting on ridges was based on sound experience; the seed failed to germinate in dry years, and floods after heavy rain could wash away the ridges. Soil conservation could result in waterlogging in wet years, though its effects could be countered by nitrogen applications.

Cotton yields in a year of good rains showed a marked local fluctuation related to gilgai, with higher yields from the gilgai hollows despite apparent prolonged waterlogging. This effect was attributed to the higher nitrogen content of the soils in the hollows.

*Land Resources Development Centre, Overseas Development Administration, Tolworth Tower, Surbiton, Surrey, England.

Introduction

The Shire Valley of Malawi is the southernmost extension of the East African rift valley, carrying the river that flows from Lake Malawi into the Zambezi. It is 16° south of the equator. Part of the floor of the lower Shire Valley contains Vertisols derived mainly from Tertiary basalts that outcrop on the western wall of the rift. The soils, locally known as Makande, have developed in alluvial and colluvial deposits of various ages. Repeated cycles of erosion and deposition have left a complex pattern in which the Vertisols alternate with calcareous rubble on old denuded ridges, and recently deposited clays in diffuse drainage lines.

The Vertisols lie between 50 m and 180 m asl, and the climate is characterized by very hot summers and warm winters. The annual rainfall is 750 mm, 90% of which falls in the summer months of November to April. The soils are associated with a distinct gilgai microtopography accompanied by significant variations in soil characteristics. The soils under the gilgai ridges are Typic Chromusterts (*Soil Taxonomy,* USDA, 1985); while those under the hollows are Typic Pellusterts. Under the *FAO Soils Legend* (FAO, 1974) they are Chromic Vertisols and Pellic Vertisols respectively.

The Makande soils have been noted for many years for their ability to produce high yields of cotton under continuous cultivation, without fertilizers. Consequently the area has been the subject of a number of schemes to promote cotton production, including a major initiative financed by the World Bank that started in 1968. Shortly after the start of this project (The Chikwawa Cotton Development Project, which became phase 1 of the Shire Valley Agricultural Development Project), there was an alarming increase in the visible evidence of soil erosion, and there were reports of very patchy cotton growth, particularly in years when the rains ended earlier than usual.

A soil survey in 1971 (Mitchell, 1973) pointed to two main causes for the increase in soil erosion:

- The rapid expansion of the area under cotton, including cultivation of the poorly defined drainage lines.
- Progressive decline in the size of the soil aggregates in the topsoil during the first 4-5 years after the land is first brought under cultivation.

The uneven growth of cotton appeared in many cases to be related to the availability of water in the root zone. Variations could be caused by:

* local runoff due to soil structural deterioration under continuous cultivation,
* the presence of saline or sodic soil at shallow depth,
* shallow gravel layers.

Some of the variation was related directly to the gilgai microtopography characteristic of the Makande soils.

A variety of other factors could also affect cotton growth, including local waterlogging, weed competition, and attack by insect pests (including harvester termites).

The Agricultural Research Corporation of Malawi (ARCM) started a programme of investigations into the productivity of the Mukande soils, starting in 1973/74. The ARCM was dissolved in April 1975, but the research programme was continued under the

Ministry of Agriculture, and reports of the investigations in the 1973/74 and 1974/75 seasons are available. The purpose of the present paper is to review briefly some of the observations from the 1971 soil survey, and how they relate to the results of subsequent trials.

Soil Erosion and Conservation

While the Mukande soils were under their natural grassland, the drainage lines were diffuse and poorly defined. A vigorous grass species, *Lachaemum brachyatherum,* grew in the wetter places and held the surface soil with a dense mat of rhizomes that slowed and diffused the flow of runoff water. When the land was cleared for agriculture, no effort was made to leave the drainage lines under grass; in fact the topography is so gentle that it was not easy to discern them. The cultivation techniques – hand-hoeing and planting on the flat – did nothing to prevent runoff, which now flowed more rapidly and began to scour out the drainage lines.

When the land is newly opened, the soil maintains a comparatively coarse crumb structure in the topsoil, but this deteriorates gradually so that after about four years the soil can be seen to comprise much smaller aggregates (Table 1) and sometimes to show evidence of surface capping by rain. These smaller aggregates are very much more transportable by water, and at the time of the soil survey in 1971 considerable alluvial deposits of this material had built up in some streambeds. The limited number of observations in Table 1 suggest that a similar decline occurs in alluvial soils, though more gradually. Interestingly, the one example that could be found of former cultivated land reverted to grass showed that under a good grass cover soil aggregates might be restored to their original size in about three years.

Apart from the loss of topsoil, the increased erosion reflects a high rate of surface runoff, and reduces crop yields directly through water shortage in a region of near-marginal rainfall. The research programme begun in 1973 included studies of methods of water conservation ranging from flat cultivation on the natural slope (the control plots) to levelled plots surrounded with bunds 0.15-0.2 m high (Jones and Herbert, 1975, and Malawi Ministry of Agriculture, 1980). The latter, with few exceptions, held all the rain that fell on the plots. The effect of the conservation treatments is shown in Table 2 for the two years 1973/74 and 1974/75, the first with good rains and the second with poor, badly distributed rains.

Soil water measurements to a depth of 1.2 m confirmed that the three water conservation treatments retained water in the soil more effectively than the natural slope. This was accompanied by a reduction in crop yields in 1973/74, apparently due to waterlogging; from February to April the crops were yellow and sickly-looking. A possible effect of the waterlogging was to reduce the nitrogen supply to the crop; the effect of applied nitrogen was to raise the control plot yield by about 15% and eliminate the yield reduction due to the water conservation treatments.

Table 1. Average sizes of water-stable aggregates of Ngabu soils in relation to the length of time under cultivation (from Mitchell, 1973).

Soil type	Average aggregate diameter (mm)										
	Grassland	Land cultivated for (number of years)									
		1	2	3	4	5	6-7	8-9	10-11	12-13	More than 13
Old alluvium of mixed origin	2.6 (8)	1.8 (11)			1.7 (2)	1.0 (2)			1.3 (2)		0.6 (7)
Recent alluvium derived from basalt	2.2 (2)	1.3 (3)									0.8 (1)
Recent alluvium of mixed origin	1.5 (2)			1.8 (2)							0.6 (2)
Vertisols derived from basalt	1.9 (4)		1.6 (5)	1.0 (2)	0.6 (2)					0.5 (2)	0.6 (7)
Vertisols of mixed origin	2.1 (10)	1.7 (4)	1.6 (2)	1.3 (4)			0.8 (3)	0.9 (6)	1.1 (4)	0.9 (2)	

Note: Figures in brackets denote the number of samples in each category

Table 2. The effect of rainwater conservation by different methods on cotton yields at two sites in 1973/74 and 1974/75.

Plot and treatment	Rain (mm) between November and April		Yield (kg/ha)	
	1973/74	1974/75	1973/74	1974/75
NSANGWE	802	484		
Control (no conservation) Flat planted on natural slope			1869	1584
Tied ridges: ridges on the contour with cross-ties			1607	1206
Levelled land: cotton planted on ridges			1404	1308
MPHONDE	695	537		
Control			1733	941
Tied ridges			1484	1085
Levelled land, flat planted			1507	1101
Levelled land, ridged			1560	1135

In the following year (1974/75), most water conservation treatments improved cotton yields, except at Nsangwe where cotton planted on ridges failed to germinate in the poor early rains and had to be replanted. This raised an interesting problem: local farmers had been unwilling to adopt extension advice that they should plant cotton on ridges for good soil conservation. Their normal practice is to plant on the flat. The research team observed that the farmers' technique of sowing cotton was to scoop a small hollow, about 0.3 m long, 0.25 m wide and 0.1 m deep, with a hoe, and plant the seed in it uncovered. After light rains the seed remained uncovered and did not germinate, but after heavier showers local runoff concentrated in the hollows covered the seeds, and enabled the crop to germinate successfully after only 12-15 mm of rain, compared to at least 50 mm for conventional planting.

There was very little waterlogging in 1974/75 apart from a short period in late February, and applied nitrogen had no effect on either the control plots or the water conservation treatments.

Another problem with ridge cultivation appeared when part of a trial was damaged by a flood 20 days after germination in 1973/74. Cotton sown on the ridges was destroyed while that planted on the flat was undamaged.

Uneven Growth of Cotton

The rains of 1970/71, immediately before the soil survey, had been below average, with very little rain after the end of February. Consequently it was possible to study a number of occurrences of uneven cotton growth in some detail, including physical and chemical soil analyses. Uneven growth could be divided into two broad categories: regular patterns associated with gilgai microrelief, and other occurrences not associated with gilgai.

Uneven crop growth associated with gilgai

Regular 'ripple' patterns could be seen during the soil survey, where poor, stunted cotton grew on the gilgai ridges while that in the hollows was tall and well developed. This pattern was often very clear on older cultivated land, though on newly opened land nearby the cotton grew as well on the ridges as in the hollows.

Certain differences between the soils of the ridges and the hollows were common to all the Vertisols. Typically the soil of the ridges was lighter-coloured or browner than that of the hollows, had slightly less clay, a lower organic-matter content and a less pronounced structure. Gravel and small stones were often found on the ridges but not in the hollows. The subsoil cracked more widely in the hollows, and the pattern of cracks was more visible on the surface. Where it could be distinguished, the substratum approached closer to the surface under the ridges. There were corresponding differences in the chemical characteristics; the ridges had higher soil reaction, exchangeable sodium and often exchangeable magnesium, but lower organic matter, phosphorus, potassium and exchangeable calcium.

Detailed examinations of the soil profiles under several examples of uneven cotton growth showed that the roots of poor cotton plants on gilgai ridges were turned aside at shallow depth (30 cm or less) while the roots of good plants under neighbouring gilgai ridges went down to below 45 cm. The subsoil under the poor plants was compact, with larger structures and fewer, finer cracks than under good plants. Soil analyses showed that this was associated with a high exchangeable sodium percentage. The plants in the hollows where the exchangeable sodium percentage was lower were unaffected. At one site the old land (cultivated for 20 years) displayed very uneven growth, while immediately adjoining it a recently opened field, cultivated for only two years, carried a uniform, good crop. The ridge soil in the new field was well structured; the subsoil was less compacted and had many wide vertical cracks. It appeared that the sodic subsoil had only become compacted as a result of the long period of continuous cultivation.

One site that displayed a regular 'ripple' pattern of very poor cotton on the ridges but good cotton in the hollows had no visible or analytical soil differences that could explain the condition, except that the soil on the ridges formed a very loose tilth that would make a poor seedbed. There was a lot of ungerminated seed on the ridges, which indicated that the farmer had had to replant several times. The variation of cotton growth with gilgai was studied in detail by Bradshaw (1976), who concluded that the main cause is the wider cracking in the hollows (allowing penetration of water into the profile), and the higher clod density of the ridge soils.

The ARCM research team sampled the soil moisture under gilgai ridges and hollows during 1973/74 (Jones and Herbert, 1975). The progress of moisture down the profile is charted in Table 3, where it can be seen that the hollows became very much wetter, and extended to a greater depth. This was during a year of good rains; in a year of poor rains, particularly when they end early, the ridge is not likely to be wetted below 60 cm.

Table 3. The wetting of soils under ridge and hollow of gilgai microrelief during the rains (adapted from Jones and Herbert, 1975).

Location and depth (cm)	Moisture content at start of rains (w/w%)	Increase in moisture as percentage of moisture content at start of rains, after: 1 month (178 mm)[1]	2 months (384 mm)	3 months (96 mm)	4 months (126 mm)
Ridge					
0-15	22	40	100	50	135
15-30	25	20	85	45	95
30-45	29	3	60	25	80
45-60	30	0	35	35	55
60-75	31	0	20	20	50
75-90	30	0	10	10	55
90-105	31	0	6	6	45
105-120	32	0	0	3	25
Hollow					
0-15	20	115	200	130	200
15-30	27	75	120	60	105
30-45	29	50	90	60	95
45-60	31	30	75	60	75
60-75	36	15	30	40	50
75-90	40	3	8	20	35
90-105	41	0	3	5	25
105-120	40	0	0	0	15

[1] Rainfall during each month is shown in brackets.

The field capacity of the soil is at a moisture content of about 45%. The topsoil of the ridges was slightly above this for brief periods, but the hollows were at or above field capacity from the first month onwards and were probably waterlogged for a considerable time. Despite this the cotton grew taller in the hollows, and yields on similar land in the farmer's field adjacent to the sampled area were twice as high in the hollows. The study was not repeated in 1974/75, a much drier year.

Soil chemical analyses from the same gilgai showed no consistent differences between gilgai ridges and hollows in mechanical analysis, pH, available phosphorus (Olsen), exchangeable bases, or cation-exchange capacity. Organic carbon and total nitrogen were always higher in the furrows, which may have been the reason for the higher cotton yields despite the waterlogging; this would agree with the findings of the water conservation trials discussed earlier, though the apparent interaction between waterlogging and nitrogen supply could not be explained satisfactorily.

Uneven cotton growth not associated with gilgai

Soil-related poor cotton growth was recorded during the soil survey in depressions and seepage areas where the soil was saline or waterlogging was prolonged, and on ridges where erosion had left less than 50 cm of vestigial Vertisol over lime rubble. These were isolated occurrences, and since little can be done economically to improve them, they were not followed up in the research programme. They are 'the tip of an iceberg', however, as the accelerated soil erosion will denude the topsoil above other gravel ridges and saline patches.

Conclusions

Soil erosion

The reason why soil erosion increases when grassland is replaced by arable cropping of Vertisols is easy to identify: removal of the perennial cover results in a faster flow of runoff, while cultivation in successive years reduces the size of the topsoil aggregates. The solutions are less easy to find; drainage patterns are often intricate, and conventional soil conservation measures can result in reduced crop yields. Control of soil water is important, to maximize infiltration but avoid waterlogging. Although the effects of waterlogging can be countered by nitrogen application, this will significantly raise the cost of crop production. There is a clear message for researchers and extension workers: to learn about the farmers' own systems and to build soil conservation recommendations around them.

Uneven growth of cotton

Availability of water seems to be the main factor causing local variations in crop growth. When this is associated with the gilgai microrelief it appears gradually over a number of years after the land is brought under cultivation, commonly due to deterioration of the structure of both topsoil and subsoil in places where the subsoil is poorly flocculated due to sodium. The obvious solution would seem to be to introduce grass fallows to restore the surface structure, but land pressure is such that this option may not be available. Effective soil conservation is essential, to halt the erosion that is continuing to expose unproductive gravel and saline subsoils.

Implications of the soil patterns for research

Any programme of research on Vertisols must take account of the intricate patterns of local soil variation – most, though not all of them, related to gilgai, that can produce strongly contrasting effects on crop growth. Although one can say that these effects average out across a field, it is important to study them in detail, since potentially valuable findings can otherwise be masked.

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Sixth session: Implementation of the Vertisols network

Chairmen: Drs. R.F. van de Weg
Dr. A. Woldeab

SOIL VARIABILITY, EXPERIMENTAL DESIGN, AND DATA PROCESSING

W. Siderius*

Abstract

In contrast to the settled opinion that Vertisols are homogeneous soils, this review indicates that they may vary greatly in almost all their properties. This variability is caused by the different influences of the soil-forming factors, of which the climate, the parent material and the topography are especially important. The one unifying feature of Vertisols is the process of swell and shrink under the influence of different moisture contents, which is caused by the predominance of clay minerals from the smectite group. This physical characteristic is of great importance in determining the suitability of a particular Vertisol for cultivation. Suggestions are made for improving the description of Vertisols, and guidelines are given for setting up research and data-processing projects.

Vertisol Variability

Variability in soils is caused by the (inter) action of independent soil variables, and this also holds true for Vertisols. These independent soil variables that define any soil system are described by Jenny (1941) as follows:

s = f (c, o, p, r, t, m), in which:

s = soil system, or a function of "f", which is dependent on:

- c = climate,
- o = organisms,
- p = parent material,
- r = relief (or topography),
- t = time, and
- m = man.

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* International Institute of Aerospace Survey and Earth Sciences (ITC), P.O. Box 6, Enschede 7500 AA, The Netherlands.

Climate

The factor 'climate' in this paper relates to the semi-arid tropics (SAT). For the definition of a semi-arid climate, the proposal by Kranz and Kampen (1978) is adhered to. This definition is based on climate analysis of the Indian subcontinent, but seems well applicable to other regions of the world. The SAT are defined as regions where the monthly rainfall exceeds the potential evapotranspiration in 2-7 months and where the mean monthly temperature is above 18°C.

A further subdivision is made with regard to the number of wet months (P>ET): dry SAT have 2-4.5 wet months, and wet-dry SAT have 4.5-7 wet months (Swindale and Miranda, 1984). The alternating dry and wet periods associated with these climates are thought to be indispensable to the formation of Vertisols (Hubble, 1984; Blokhuis, in press; Wilding, 1985a). Although a semi-arid climate may occur over large areas, considerable variations have been observed, leading to a certain zonation which is induced primarily by the rainfall pattern. For the Sudan, this zonation has been recognized by Blokhuis (1980) and Jewitt *et al.* (1979), and is associated with a number of soil properties and the grade in which they occur, e.g. stronger development under higher contrast between the wet and the dry months (xeric to ustic soil moisture regimes) of surface mulch, gilgai, crack pattern, and structure.

On the whole, the climate leads to an accumulation of constituents (like Ca, Mg and Na) in a neutral to alkaline environment, which induces the formation of smectite clay minerals. This condition has been reported by most studies of Vertisol formation under semi-arid conditions, viz. Ahmad (1983), Buringh (1979), Dudal (1965). The contrasting temperatures induce rapid mineralization of organic matter and promote physical weathering of primary fragments, especially in the transitional zone between the arid and semi-arid regions.

The occurrence of acid conditions in Vertisols in SAT regions has not been reported. Acid Vertisols occur, however, outside these areas under more humid conditions, as is the case with the Vertisols in Trinidad (Ahmad, 1985). The influence of a groundwater table for most SAT regions is negligible as it often occurs at too great a depth. Exceptions are made for situations where local relief is dominant, for example in depressional areas which are subject to ponding or flooding and for which aquic soil moisture regimes have been recognized (Blokhuis, 1985; Comerma, 1985; Grossman *et al.*, 1985).

The parent material

A large number of studies deal with the composition of the parent material on which or from which Vertisols have been developed; rocks are usually rich in ferromagnesian and/or calcareous minerals (Dudal, 1965; Mohr *et al.*, 1972; Nyamapfene, 1984). They all have a relatively low percentage of silica and a high percentage of alkaline earth metals (Ca, Mg, K, Na) in the primary mineral fraction. After undergoing hydrolysis and being subjected to the prevailing climatic conditions, the formation of minerals from the smectite group is common, as is indicated by detailed studies on this subject (Buursink, 1971; Allen and Fanning, 1983). The high SiO_2/Al_2O_3 ratio of the clay and the positive correlation with the equally high K_2O+Na_2O+MgO/Al_2O_3 ratio is indicative for Vertisols in the SAT (Siderius, 1973).

In some areas, notably where vulcanism or wind erosion is or has been active, the authochtone parent material and/or soils may be "contaminated" by particles from dust storms or volcanic ash. This admixture may have a positive or negative effect on the soils, e.g. increasing the chance of sealing, or increasing the fertility of the soil (Harmse, 1967). The churning capacity of the soil material, and also leaching and the biological mixing of the soil, may cause a fairly rapid homogenization of these constituents with the original ones.

Organisms

The activity of organisms as an independent variable in the formation of Vertisols has received little attention so far. However macromorphological observations point to the presence of small rodents, in addition to earthworms, termites, spiders, etc. Micromorphological observations of a Vertisol from Botswana confirmed the presence of isotubules and agrotubules in the subsoil of a Vertisol, indicating that the process of homogenization through soil fauna was active (Siderius, 1973). Similar observations were made by Sleeman and Brewer (1984). There is little known about changes in biological activity under different management practices.

Topography

The influence of topography (or relief) on soil formation is well known, and applies to Vertisols as it does to other soil groups. The position of Vertisols in the landscape in relation to the parent material has led to the introduction of terms like "Lithomorphic" and "Topomorphic" Vertisols (Jewitt *et al.*, 1979; Murdoch, 1970; Comerma, 1985). The first term refers to the dominancy of the soil parent rock on the formation of the Vertisol, while the latter indicates that the variable "topography" is the major soil-forming factor.

Lithomorphic Vertisols are usually less deep but may be better drained than Topomorphic Vertisols, which generally occur in relatively low-lying areas. This situation occurs frequently in denudational landscapes. Large flat to gently sloping areas of Vertisols are found in the Sudan and India. In the first case, the alluvial plain of the White and Blue Niles form the Vertisol landscape; and in the second case, the occurrence of mafic rock in flat position causes the formation (Blokhuis, 1982; Virmani *et al.*, 1985).

Vertisols in topomorphic position may have formed on materials leached from surrounding higher areas, which may be underlain by acid rocks. This situation has been observed, for example, in Nigeria and Uruguay (Purnell, 1979; Rossignol, 1983). The occurrence of Vertisols in rather flat topography results in slow water movement and prevents fast removal of soluble constituents. In some cases this may cause anaerobic conditions in the deep subsoil, and/or perched water tables.

The occurrence of Vertisols in the SAT is generally associated with subdued topography, which may be advantageous or disadvantageous. In the former case, reference is made to the minimum amount of levelling to be carried out for soil conservation measures and the ease with which water can be put to the land; in the latter case, ponding may limit the time in which the soil can be tilled.

Time

The time factor considered as an independent variable in Vertisol formation is difficult to assess, although it is relevant in relation to the degree of expression of the properties. Controversial statements have been made about the grade of development of some Vertisol properties in relation to time, and notably with regard to the occurrence of slickensides, structural development in general, and the presence of organic matter.

To some, the presence of large slickensides with depth is indicative of the young age of the soil, while to others it is seen as a relict from the parent material (Yaalon and Kalmar, 1978). The presence of many fine structural aggregates, such as wedge-shaped peds, is seen by some as a sign of old age, while to others it indicates the active midstage in Vertisol development (Nieuwenhuis and Trustrum, 1977).

Interesting results have been obtained in the study of organic matter in Vertisols through which the churning process may be evaluated. A sharp increase in the age of organic matter from 1100 to 4000 years in the subsoil (from 80 cm onwards) raises questions with regard to the effective depth of the churning process in Vertisols developed in a udic environment (Stephan *et al.*, 1983). Studies of Vertisols under SAT conditions with regard to organic matter are scarce; complete homogenization by churning of the top 100 cm is not very likely to be a fast process, as is indicated by the presence of tonging of brown- and darker-coloured soil horizons in relatively old (about 10 000 years) Vertisols from Sudan (FAO, 1970a, 1970b; Blokhuis, 1980; Beinroth, 1965).

Man

This century has seen the involvement of man on a large scale as an independent factor in soil formation, and his involvement also affects Vertisols. This is obvious with regard to the various irrigation schemes, but is also relevant to rainfed crop production. The changes man has brought about concern firstly the soil water regime (irrigation practices), and secondly the application of fertilizer and mulching (rainfed farming), or both (seedbed preparation).

Comparative land management studies have indicated an improved friability of the topsoil by minimum tillage (Kampen, 1982); structure improvement of the topsoil by sprinkler irrigation (Grossman *et al.*, 1985); and the application of gypsum to improve water intake in sodium-affected soil (Krishnamoorthy, 1978). In addition, use can be made of the specific characteristics of the nonrigid soil material for furrow irrigation design, as infiltration may be regarded as a self-regulating/self-ending process on these soils (Smedema, 1984).

To summarize, the influence of the climate is of paramount importance to the formation of Vertisols, firstly because of the release of weatherable minerals and the formation of secondary minerals of the smectite group, and secondly on account of the alternating dry and wet seasons, which induce the swelling and shrinking of the soil materials and lead to the expression of a number of well-known structural features. The influence of the composition of the parent material may likewise cause variation in soil mineral composition, although the alkaline environment prevails in the SAT. The position of Vertisols in the landscape is also indicative of their formation and is of particular importance to the soil water regime. Organisms may cause variations in Vertisols which may go unnoticed macroscopically but which could be very clear at increasing levels of detail. The influence of time and man has yet to be fully understood; however, variations in Vertisols have been observed which are caused by these variables.

Description of Soil Variability

The variation in Vertisols caused by the soil-forming factors is generally well expressed in soil-survey reports, but not by differences in soil classification. The analysis of a number of studies of Vertisols (soil profile descriptions and laboratory data) indicate their heterogeneity with regard to almost all soil properties (Ahmad, 1983; Allen and Fanning, 1983; Finck, 1963; Ikawa, 1985; Jewitt *et al.*, 1979; FAO, 1985; Murthy *et al.*, 1985). The degree of variation is inherent to the scale of mapping, which, for many areas, is at a scale of 1:50 000 or smaller. The "range of characteristics" is often the only indication of the variability of Vertisols within a certain hierarchical order of classification (FAO, 1970a, 1970b).

Recent studies on Vertisols in Australia indicate considerable differences in many properties of Vertisols within short distances, notably those caused by gilgai, which have escaped the attention of earlier workers or were not thought to be relevant for land use and/or classification. Two questions arise in this respect: first, are the present methods of soil description suited to the study of Vertisols? and secondly, should soil classification systems be reviewed so as to accommodate the variations in Vertisols that have been noticed in the field and in the laboratory?

The first question concerns in particular the description of the soil structure, which expresses to a large extent the processes by which Vertisols are named (Blokhuis, 1982; McGarity, 1985). Shape, size, and the grade of structural elements are described in a number of studies, but there is inconsistency in recording the structure. This may be partly due to the lack of suitable terminology in the present survey manuals to accommodate particular Vertisol structures such as "wedge-shaped peds and bicuneate structure" (Blokhuis, 1982). Variation in surface features caused by wetting, subsequent swelling, and shrinking upon drying of this nonrigid soil material may call for the reintroduction of terms to describe the surface mulch and/or crust (Soil Survey Staff, 1960). The relatively high percentage of (coarse) sand in the topsoil, the presence of sodium, and the influence of these materials on crust formation points to other features which have been given little attention in Vertisol studies, but are of great importance for management (Mahmoud, 1985). Thus mulching vs. nonmulching Vertisols, and soil differences induced by gilgai should once more be taken into account (Beckman *et al.*, 1984).

Secondly, present soil classification systems are rather simple with respect to the classification for Vertisols (FAO-UNESCO, 1974; Soil Survey Staff, 1975), although new studies indicate the complexity of Vertisols and call for an updating of this classification. A response is made by the ISSS Working Group on Vertisols (ICOMERT), which has issued proposals to accommodate the variations described above at all but the 'order' level (Comerma, 1984). In addition, the (arbitrary) limit in chroma of 1.5 may be questioned, as may the division between light- and darker-coloured Vertisols. Many Vertisols with a high value (like 4 or 5) are encountered with chroma of 1.5, which could hardly be called "dark", or indeed considered as indicative of anaerobic conditions. Recommendations made during the last ICOMERT workshop in the Sudan concern the recognition, where appropriate, of a vertic A horizon in addition to a cambic B horizon in Vertisols (Dzieciolowski *et al.*, 1984, Soil Survey Administration, 1985). The important role which soil classification systems like *Soil Taxonomy* may have as an aid in the transfer of technology for Vertisol areas is underlined by the ICRISAT programme (Virmani and Swindale, 1984).

Analysis of Soil Variability

The application of statistical methods to evaluate and measure variability in soil, soil materials, and soil mapping units has made considerable progress in the last decades. Studies by Bie and Becket (1971), Webster and Burrough (1974), and Dent and Young (1981) not only outline new methodology but also point to some soil properties which may be more subject to variation than others, as for example the pH (Tucker, 1984). Occasionally techniques developed by other disciplines may find an application in soil survey, as has been pointed out by Rogowski *et al.* (1985) in a study on erosion problems in areas where strip-mining of coal is planned. They found that "if a property is known to vary little within a fixed area, the use of large grid sizes for sampling may be quite satisfactory. On the other hand, if a property varies extensively, it should be sampled on a smaller grid (larger scale)".

Almost all available studies on soil variability are conducted in the western hemisphere (where the occurrence of Vertisols is rare), and involve high sampling density and/or extensive laboratory analysis (Webster, 1985). The application of spatial variance techniques to Vertisols has been extremely limited, and only one case is known concerning Vertisols, namely in the Sudan (Trangmar *et al.*, 1985). This concerned the variability of sodium in an area earmarked for irrigated sugarcane production. The results show that if geostatistics had been available, sampling for ESP could have been reduced to about 50% of the data actually collected, with only slight loss in estimation precision. Coughlan (1984) used multivariate analysis to investigate other properties that contributed to aggregate breakdown on wetting and drying of 12 Australian Vertisols. He found that by increasing the Ca:Mg ratio, aggregate porosity and aggregate macroporosity, and the stability to wetting and drying decreased.

Studies in England indicate the influence of parent material on the variability of soil properties (Culling, 1986; Nortcliff, 1978), and similarly the landscape as a whole has a decisive influence on the soil pattern and the reliability of its components. It is therefore thought that a physiographic approach in Vertisol mapping is likely to assist in the recognition of the various mapping units and in interpreting the variability which they exhibit (Briggs and Shishira, 1985; Elbersen and Catalan, 1986).

Where the aid of image interpretation is limited, as is the case in a flat homogeneous area, a grid system may constitute the only solution for obtaining the necessary data for variance analysis. The density of the observations may exceed the value indicated by Wilding (1985b), which recommends a ground distance of 20-200 m between observations to quantify the soil composition in a landscape unit, while it may have to be reduced to 0.25-0.5 m for pedon studies.

Design of Experiments and Data Processing

At the Thirteenth International Congress of the International Society of Soil Science, this topic received particular attention (Bregt *et al.*, 1986). One of the major concerns is that experiments should be relevant from the users' point of view. This is also true for experimental design in developing countries, where Vertisols are more common than elsewhere.

The approach to experimental design and subsequent data processing is twofold; one aspect concerns the properties of the soil material, especially with a view to gaining more insight into its physical and chemical characteristics; and the second aspect concerns obtaining a better understanding of the behaviour of Vertisols under different management practices. These two aspects involve respectively the following investigations:

- Research on the properties of the soil material, including a further analysis of existing Vertisol data. A possible major drawback may well be the low density of the observations in many Vertisol areas in the SAT. Procedures for checking the reliability of soil data and soil maps were demonstrated by Marsman and de Gruijtar (1986), and involve extensive use of available computer programmes such as 'Oracle' and 'Quefts'.
- The approach to the behaviour of Vertisols under different types of management combines the land factor (soil) and the management factor (land use) in the land-use system (Beek, 1978).

Placement within this framework facilitates the recognition of the requirements of the particular land-utilization type in relation to the qualities available from the soil (land). Application of the FAO framework (FAO, 1976) may therefore be used effectively to standardize procedures and indicate research guidelines.

Various land uses have been made on Vertisols in the SAT, but the identification of these uses is seldom accompanied by precise data on input or output, which is necessary to arrive at a quantitative assessment of the suitability of land for a certain use. The most detailed observations have been made on the Indian subcontinent (Krantz *et al.*, 1978; Virmani *et al.*, 1985; Oppen *et al.*, in press; Willey *et al.*, in press). A number of general land-use descriptions are available from other SAT regions (Mahmoud, 1985; Russell, 1984). The literature on the land qualities that may limit the use of Vertisols for a particular or general use is fairly extensive, but is confined mainly to a qualitative approach to the problems. Thus basic soil research remains necessary, but should be carried out as much as possible within the framework outlined above to obtain the maximum benefit for the user.

Data obtained from experiments in the field and in the laboratory can be captured, stored, retrieved and interpreted according to a growing number of programmes which are suited for personal computers. These programmes may have been developed specifically for a particular purpose, as is the case, for example, with the USDA pedon coding system; or they may be used for the capture of soil descriptions in the field (Elbersen and Catalan, 1986). Similarly, the assessment of relationships between land and land use has been subject to computerization -- as in the LECS system developed for Indonesia, a system which is also applicable to other regions (Wood and Dent, 1983). The possibility of also involving socioeconomic parameters in the evaluation could lead to the development of more comprehensive geoinformation systems by means of which land-use alternatives could be assessed.

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FERTILIZER MANAGEMENT IN VERTISOLS

J.C. Katyal, C.W. Hong, and P.L.G. Vlek*

Abstract

Vertisols of the semi-arid tropics (SAT) are universally deficient in N. N fertilization was formerly considered to be a risky enterprise, but research over the last decade has dispelled this belief. Benefits from N fertilizers fluctuate with soil depth and seasonal rainfall. With deep Vertisols, response to N is higher and stable across contrasting rainfalls, while with shallow Vertisols response to N is generally low and it decreases with increasing rainfall. Excessive loss of N (measured by N balance) is a factor contributing to decreased N-use efficiency in shallow soils. A discussion on the comparative efficiency of N sources and the methods of applying them to deep and shallow Vertisols is presented.

Next to N, deficiency of P is important in Vertisols of the semi-arid tropics, with deficiency increasing on Vertisols derived from granite parent material. Deficiencies of K and S are rarely encountered in crops grown in Vertisols. Soil analysis suggests the possibility of a widespread deficiency of Zn, Fe, Mn, and B. In some instances crops have responded to the applications of these micronutrients.

Introduction

Soils belonging to the order Vertisol occur extensively in the semi-arid tropics (SAT). Black cotton soils in India and Sudan, cracking clays of Australia, black clays of the United States, Grumusols and Regurs of the old classification system are examples of Vertisols. Of a total of 257 million ha of Vertisols worldwide (Dudal, 1965), 72.9 million ha are located in India (Murthy *et al.*, 1982), 70.5 million ha in Australia, 40 million ha in Sudan, 16.5 million ha in Chad, and 10 million ha in Ethiopia (Dudal, 1965). These five countries account for more than three-fourths of the total Vertisol area in the world.

* International Fertilizer Development Center (IFDC). Muscle Shoals, P.O. Box 2040, Alabama 35662, USA.

The outstanding features of Vertisols are their shrink/swell potential, alkaline pH, high cation-exchange capacity, high and stable water-holding characteristics, high general fertility (except N), exceedingly low infiltration rates once saturated, and poor workability when wet. Vertisols of the semi-arid tropics as a group show remarkably homogeneous fertility patterns, which may serve as a base for appropriate fertility management and fertilizer use. The dominant variables against any extrapolation of results across sites will be availability of moisture during a cropping season, and depth of soil.

In the semi-arid tropical environments, crop yields are generally assumed to be hindered by the lack of available moisture because of a high atmospheric water demand and limited water resources. Rainfall in the SAT is the most erratic of the climatic elements which are important for crop production. According to an analysis of 30-year rainfall patterns in the SAT of India (Huda *et al.*, 1985), it was evident that the overall means of monthly and annual rainfall showed coefficients of variation ranging from 39% to 225% for monthly rainfall and 32% for the annual rainfall. The sharp contrasts in rainfall patterns across years and seasons preclude uniform and firm recommendations on the use and management of fertilizers. Vertisols of variable depth (from $<$ 50 cm to $>$ 1 m) are not uncommon; therefore the mechanics and dynamics of fertilizer transformations and loss may be inconsistent. This will complicate further the choice of appropriate fertilizers and methods of application. The present paper is an attempt to highlight the interactive effect of rainfall and soil depth on the fertilizer management strategies in the Vertisols of the SAT. The main emphasis is placed on nitrogen because the major research effort thus far has been directed to this nutrient.

Nitrogen (N)

Deficiency of N is universal in tropical Vertisols. Indian Vertisols, in general, have less than 1% organic carbon (OC), and their total N content seldom exceeds 0.1% (Dudal, 1965; Virmani *et al.*, 1982; Tandon and Kanwar, 1984). Vertisols of the Sudan Gezira are still poorer in OC ($<$0.5%) and lower in total N (0.02%-0.06%) (Ayub, 1986). In comparison, Vertisols in Australia and North America have high OC (2%-6%) (Dudal, 1965; William and Colwell, 1977) and high N contents ($>$0.1%). Organic carbon seems to be uniformly distributed in the top 1 m of a Vertisol profile and decreases in the deeper horizons (Murthy *et al.*, 1982).

Organic matter is the main source of N in soils. Its readily mineralizable fraction measured by alkaline $KMnO_4$ extraction (Subbiah and Asija, 1956) provides an index of N availability over the life of a crop. Inclusion of NO_3^-–N, which represents the instant pool of available N, is suggested to improve the relationship between N availability and crop-yield response, more specifically under upland conditions (Sahrawat and Burford, 1982). Malear *et al.* (1984) found a close relationship between grain yield of sorghum grown on a Typic Chromustert and availability of N measured either by $KMnO_4$ – extraction or NO_3^-–N. Yields of cotton grown on the Vertisols of the Gezira in Sudan were positively correlated with NO_3^-–N content of the soil profile (Crowther, 1954). Rego *et al.* (1982) reported that 1 m of soil profile accumulated 65-72 kg of NO_3^-–N/ha with cropping. This finding suggested that accumulation of NO_3^-–N in the soil profile during the rainy-season fallowing will benefit the postrainy-season crop.

Fallowing land during the rainy season followed by postrainy-season cropping is the traditional practice in India. However, the benefits of fallowing may vary from year to year (Table 1). In a moderate-rainfall year (seasonal rainfall = 515 mm), safflower yield rose from 630 kg/ha after rainy-season sorghum to 1470 kg/ha after rainy-season fallowing. In contrast, in a high-rainfall year (seasonal rainfall = 913 mm) the beneficial effect of fallowing during the rainy season on grain yield of safflower in the postrainy season was not distinguishable (safflower yield = 690 kg/ha after sorghum vs. 530 kg/ha after fallowing). Kanwar and Rego (1983) cited some Indian studies that showed that during high-rainfall years there was a considerable loss of topsoil and nutrients because of erosion, runoff, percolation, and volatilization. More NO_3^-–N was lost during large storms. Thus, high rainfall during fallowing can limit the beneficial effect of NO_3^- accumulation on the subsequent postrainy-season crop.

Table 1. Seed yield (kg/ha) of postrainy-season safflower in a double-cropping system.

Treatments		1982 (Rainy-season rainfall 516 mm)		1983 (Rainy-season rainfall 913 mm)	
		kg N/ha			
Rainy season	Postrainy season	0	60	0	60
Fallow	Safflower	1470	1960	530	1460
Sorghum	Safflower	630	–	690	–
SEM		90		108	

Data from IFDC/ICRISAT Collaborative Research Project.

Despite the fact that there was a buildup of N during the rainy-season fallowing (Rego *et al.,* 1982), the postrainy-season safflower still responded significantly to an application of 60 kg N/ha (Table 1). The grain yield rose from 1470 kg/ha without N application to 1960 kg/ha with N application. When the rainfall during the rainy season was high, the response of postrainy-season crops to an N application became more striking. Application of N to a previous crop did not seem to produce a significant residual effect on the succeeding crop. Of the 20%-30% residual ^{15}N found in the soil, hardly 2% could be used by the succeeding crop. (Data on ^{15}N balance are not presented here.)

Response of crops to fertilizer-N

Historically, semi-arid tropical soils were considered to be deficient in available moisture for plant growth. Use of fertilizers was considered to be too risky to be economically viable. Contrary to this former belief, several studies during the last decade have established a positive and significant response to fertilizer-N of crops grown on Vertisols (see Randhawa and Venkateswarlu, 1980; Finck and Venkateswarlu, 1982; Kanwar and Rego, 1983; Tandon and Kanwar, 1984; El-Swaify *et al.*, 1985). The extent of the response seems to be modified by rainfall, soil depth, and native soil fertility. The influence of these variables on N response can be illustrated from results of a 4-year study (1982-85) on deep and shallow Vertisols. The study was conducted by the International Fertilizer Development Center (IFDC) in collaboration with the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT). The purpose of this research was to study the response of rainy-season sorghum to urea applied at different rates (0-120 kg N/ha) by a split-band application technique.

The 1982, 1983, 1984, and 1985 seasonal rainfall, of 516, 913, 485, and 322 mm respectively, provided contrasting environments for crop growth, yield responses, and recovery studies with ^{15}N-labelled urea. This research, similar to the findings of earlier research, conclusively established that fertilizer-N offers a considerable potential to increase yields of sorghum on Vertisols in dryland regions. Yield increases attributable to fertilizer-N varied from 300 kg to more than 2000 kg sorghum grain/ha (Figures 1 and 2). There was a general linear response up to 60 kg N/ha, and levelling off occurred at about 90 kg N/ha. Shallow Vertisols, particularly in high-rainfall years, appeared to be exceptions, in that grain yields more or less levelled off at N application rates higher than 30 kg N/ha.

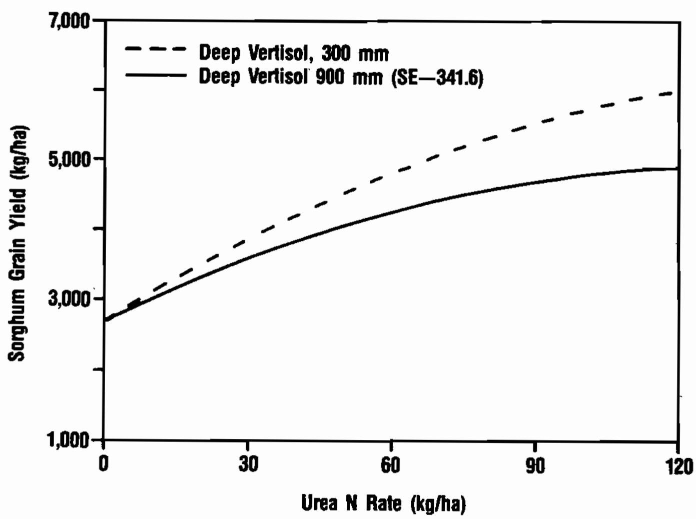

Figure 1. Grain-yield response of sorghum to nitrogen on deep Vertisols.

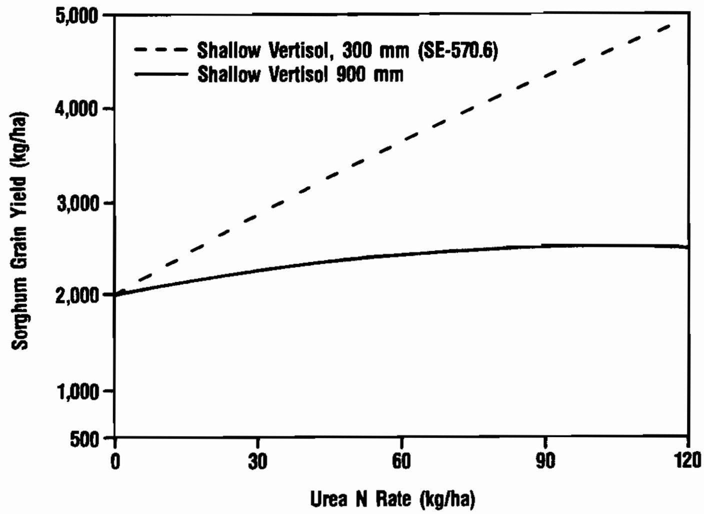

Figure 2. Grain yield response to sorghum to nitrogen on shallow Vertisols.

Agronomic efficiency

Agronomic efficiency is defined in two ways: (1) the increase in yield per amount of nutrient applied (expressed as kilograms of yield increase due to fertilizer per kilogram of fertilizer nutrient), and (2) the proportion of nutrient taken up by the crop, expressed as percent of nutrient taken up of the amount applied. The magnitude of agronomic efficiency of fertilizer-N was strongly influenced by seasonal rainfall and soil depth (Table 2). In 1985, a drought year, the agronomic efficiency on a shallow Vertisol was significantly higher than that in 1983, a year of high rainfall (30 kg grain/kg N vs. 14 kg grain/kg N). In contrast, deep Vertisols produced greater yield increases due to fertilizer-N application in high-rainfall years, provided the N application rate was 60 kg N/ha or more. Also, fluctuations in rainfall had less influence on the magnitude of response to N on deep Vertisols than on shallow Vertisols. For instance, at an application rate of 60-80 kg N/ha, agronomic efficiency in good-rainfall (1983) and poor-rainfall (1985) years corresponded to 29 and 31 kg grain/kg N respectively.

The agronomic efficiency also depends upon the native fertility of the soils. The higher the native fertility, the lower the response will be (Kanwar and Rego, 1983). In India a soil is classified as low in N availability if the topsoil contains less than 280 kg $KMnO_4$-extractable N/ha (IARI, 1980). However a contribution of N from subsoil horizons and NO_3^-–N will modify this threshold value, specifically in dryland crops.

It is presumed that higher losses of fertilizer-N from a soil lead to poor fertilizer efficiency. In sorghum experiments under rainfed conditions, higher efficiency was indeed accompanied by lower losses and higher ^{15}N recovery by the plant (Figure 3). At an application rate of 60 kg N/ha as urea, losses of N from deep Vertisols were about one-

Table 2. Agronomic efficiency of urea-N as influenced by N rate, rainfall, and depth of Vertisols.

Soil	Year	Rainfall	Check yield	Agronomic efficiency	
				30-40 kg N/ha	60-80 kg N/ha
				(kg grain/kg N)	
Deep Vertisol	1980	674	3,380	14	14
	1981	907	2,720	24	34
	1982	516	2,870	–	40
	1983	913	1,500	26	29
	1985	322	3,270	33	31
Shallow Vertisol	1983	913	670	14	21
	1984	485	1,310	31	37
	1985	322	3,390	30	18

Data from IFDC/ICRISAT Collaborative Research Project.

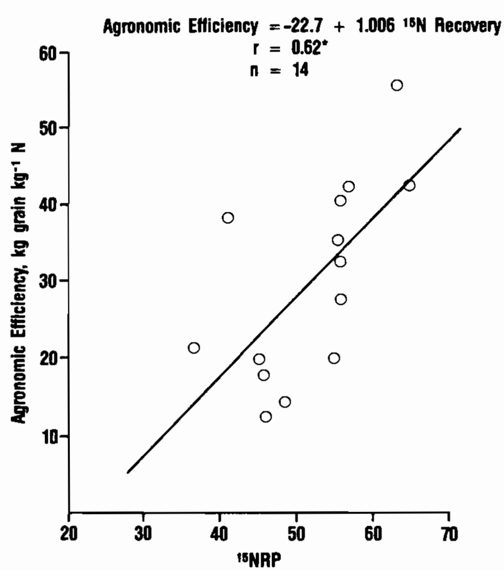

Figure 3. Relationship between agronomic efficiency and ^{15}N recovery by crop.

third the losses from shallow black soils (Table 3). Accordingly, agronomic efficiency was higher in the former soils than in the latter soils (Table 2).

Table 3. Fate of fertilizer-N (^{15}N-labelled urea) in some Vertisols.

Soil	Year	Rainfall	N rate	Apparent N recovery	^{15}N recovery			^{15}N loss
					Plant	Soil	Total	
		(mm)	(kg/ha)		(%)			
Deep Vertisol	1981	907	74	58.5	55.7	36.8	92.5	7.5
	1982	516	60	74.3	56.2	35.0	91.2	8.8
	1985	322	60	78.5	56.0	37.0	93.0	7.0
Shallow Vertisol	1983	913	60	36.8	36.3	34.6	70.9	29.1
	1984	485	60	54.5	40.7	29.3	70.0	30.0

Data from IFDC/ICRISAT Collaborative Research Project.

Relatively large recoveries of ^{15}N-labelled fertilizers by aboveground plant parts (= 55%) and limited losses of N (< 10%), particularly from deep soils, provide major support to the argument that a very high payoff can be derived from fertilizer use in rainfed crops. On an overall basis, in this 4-year study each kilogram of N produced, on an average, 25 kg grain at 30-80 kg N/ha application. An agronomic efficiency of 25 kg grain/kg N is equivalent to a value:cost ratio of 6 (at an assumed price of US$0.40/kg N and US$0.10/kg sorghum grain).

Sources of N

The extent of N loss through NH_3 volatilization, denitrification, leaching, and runoff depends on whether the N is in the form of nitrate, ammonium, amide, or a combination of these. Losses of N can be altered by amendments with certain inhibitors (nitrification or urease inhibitors) or by physical modifications (granule size or introduction of a slow-release characteristic) in a product. Soil properties, rainfall (in drylands), and method of application (discussed in a subsequent section) considerably moderate these losses by affecting fertilizer transformations and mobility.

Results of a study on a deep Vertisol showed that there was no difference in agronomic efficiency (40-44 kg grain/kg N) of fertilizer N among the different N sources – urea, urea supergranules, potassium nitrate, nitrophosphate, and ammonium nitrate (Table 4). Irrespective of the N source, the fertilizer-N (^{15}N) recovery by the plant was greater than 55% (data not presented here), which was similar to the findings reported in an earlier section (Table 3). Data on overall ^{15}N recoveries (plant + soil) revealed that the

Table 4. Effect of N source on grain yield (kg/ha) of sorghum.

	Deep Vertisol	Shallow Vertisol	
	Rainfall (mm)		
Treatment	516	485	913
Urea	5,280	3,560	1,910
KNO_3	5,390	2,870	1,780
Check	2,870	1,310	670
SEM	180	171	122

Data from IFDC/ICRISAT Collaborative Research Project.

losses of N from different fertilizer sources were low (8%-16%). Losses of N not exceeding 10% from urea (a source most susceptible to ammonia volatilization) and from KNO_3 (a source most prone to leaching and denitrification) suggested that none of these loss mechanisms were significant in deep Vertisols under the seasonal rainfall of 516 mm. In the studies of Moraghan *et al.* (1984), conducted at the same site on a deep Vertisol in a good-rainfall year (seasonal rainfall = 733 mm), recovery of ^{15}N by sorghum was identical for urea and potassium nitrate.

Urea and KNO_3 performed differently when tested on shallow Vertisols (Table 4). Regardless of rainfall, on shallow Vertisols NO_3^- sources (KNO_{3+} and the NO_3^- part of nitrophosphate) lost more N (30%-50%) than did NH_4^+ (DAP or the NH_4^+ part of nitrophosphate) or amide (urea) sources (10%-30%). Although it is not possible to partition the loss of NO_3^- between denitrification and leaching, available information on NO_3 movement (Figure 4) points to leaching as the most serious loss mechanism.

Methods and times of application

The efficiency of using fertilizer-N is significantly affected by the method of its application. Split applications (Spratt and Chowdhury, 1978) and placement below the soil surface (Fenn and Kissel, 1976) are recommended to prevent N loss from ammonia volatilization. In a study conducted by Moraghan *et al.* (1984) on a deep Vertisol in a high-rainfall year (seasonal rainfall = 907 mm), a split-band urea application (74 kg N/ha, half of it placed 5 cm deep and 8 cm away from opposite sides of plant rows at 4 and 19 days after emergence) caused about 25% higher overall ^{15}N recovery (94% vs. 74%) and 10% more sorghum in grain yield (5800 kg/ha vs. 5300 kg/ha) than did pre-emergent applications of either surface-applied or incorporated urea at the same rate. In variance with these findings, in a subsequent analogous study, also conducted on a deep Vertisol but in an average-rainfall year (seasonal rainfall = 56 mm), grain-yield response was not

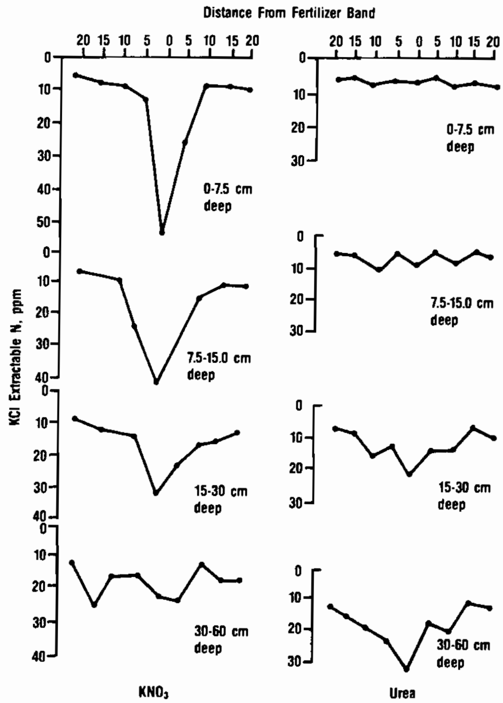

Figure 4. Distribution of band-placed urea and KNO-N in a deep Vertisol.

significantly different when the split-band method of application was compared with all basal broadcast applications (Table 5). More N was lost from the surface applications of N (18% vs. 9%), but this was still 10 percentage points less than that lost in a good-rainfall year (Moraghan *et al.*, 1984). In marked variance to these findings from India, irrigated sorghum grown on a Sudan Gezira Vertisol (pH 8.5-9.5 in H_2O) (Ayub, 1986) recovered less than 20% of the surface-applied urea. In the same study, the recovery of surface-applied urea-N was 18% by the medium-staple cotton and 24% by the long-staple cotton. Placing the fertilizer below the soil surface increased recovery to 25% and 41% respectively.

Although loss of N was not measured in any of the studies cited above, NH_3 volatilization of the surface-applied urea appeared the most likely N-loss mechanism (Finck and Venkateswarlu, 1982). Placement of urea at a depth of 5-7 cm minimized NH_3 volatilization (Fenn and Kissel, 1976). Poor efficiency of urea-N in Sudan Gezira was due to the initially high soil pH, as compared with the pH of the Vertisols of India. A high soil pH increases NH_3 volatilization (Vlek and Stumpe, 1978). Low soil moisture in an average-rainfall year may restrict urease activity and limit the buildup of NH_3 concentra-

Table 5. Effect of urea-N application methods on N uptake and grain yield of sorghum.

Treatment	Deep Vertisol Rainfall 516 mm		Shallow Vertisol Rainfall 397 mm	
	Grain yield	N uptake	Grain yield	N uptake
	(kg/ha)		(kg/ha)	
Check	2,870	40	1,310	30
Split band	5,280	84	3,508	61
Split broadcast	4,620	70	2,753	61
All basal broadcast	5,650	86	2,493	48
All basal band	5,290	82	2,328	52
SEM	180	16	170	3

Data from IFDC/ICRISAT Collaborative Research Project.

tions at the soil surface. A similar argument was given to explain the lack of NH_3 volatilization from surface-applied urea in northern Australia (Myers, 1978). On the contrary, a high soil moisture favoured NH_3 volatilization, as was the case in a good-rainfall year (Moraghan *et al.*, 1984) or with the irrigation of sorghum or cotton in Sudan Gezira (Ayub, 1986). Trierweiler and Bishop (1983) confirmed that placement of urea on the wet surface of Vertisols accelerated NH_3 volatilization. To counter NH_3 volatilization, they suggested applying urea before irrigation. Percolating water may transport the urea down below the soil surface and protect its hydrolysis products from volatilization (Katyal *et al.*, 1987).

Results on the efficiency of urea, surface broadcast or applied by split-band method to shallow Vertisols, were at variance with those obtained on deep Vertisols in a low-rainfall year. The split-band method of application produced about 1 ton/ha additional sorghum grain when compared with basal-broadcast or split-broadcast methods of application (Table 5). Why the yield from band-placed urea was higher than that from surface-broadcast urea in a shallow Vertisol is not clear, particularly when the N uptake did not vary between the two methods of application. Further interpretation of these data will have to await a more detailed analysis of the seasonal rainfall patterns.

Efficiency of fertilizer-N obtained by the split-band method could be improved further by its application (at 40-60 kg N/ha) in the seedrows. Results presented in Figure 5 show that total dry-matter yield and grain yield declined as the distance from the seedrow increased. Seedrow applications surpassed the usual application in bands located about 5 cm from the seedrow. Subsequent studies conducted across seasons and soils confirmed the superiority of seedrow application. In none of the investigations was the generally

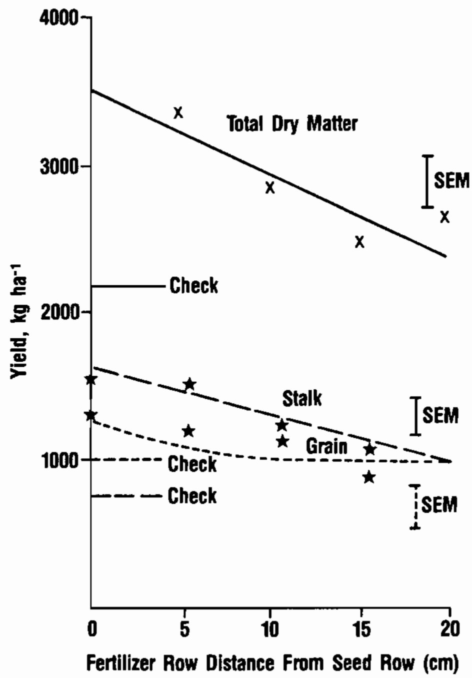

Figure 5. Effect of the distance of fertilizer row from the yields of pearl millet (Kharif, 1984).

feared germination injury from a seed-fertilizer contact observed at the levels of fertilizer applications tested (40-60 kg N/ha).

Phosphorus (P)

Deficiency of P is widespread in Vertisols (Swindale, 1982). In fact, next to N, P is the most limiting nutrient in Vertisols (Finck and Venkateswarlu, 1982). It is believed that Vertisols of basaltic origin are less prone to deficiency than those developed on granites and sedimentary rocks (Singh and Venkateswarlu, 1985). Phosphorus availability from Vertisols is largely assessed by alkaline bicarbonate extraction (Olsen *et al.*, 1954). Some Vertisols contain as low as 1 ppm Olsen-extractable P (Katyal, 1978) with a general range of 2-10 ppm.

In India, a soil is considered deficient if it contains less than 5 ppm Olsen-extractable P (Tandon and Kanwar, 1984). According to Kanwar and Rego (1983), the critical lower limit of water-soluble P for a soil to respond to P application was 0.5 ppm. On the basis of results from a 4-year study at the same level of available P, they concluded that sorghum was the most responsive to P application, followed by pearl millet. Of the crops tested, pigeonpea was the least responsive. Katyal and Venkatramaya (1983) reported that P availability fluctuated with season. Its availability from soil was suppressed by cold temperatures of the postrainy season. This explained why the postrainy-season crops depended more upon P fertilization (Kanwar *et al.*, 1973; Katyal, 1978). Venkateswarlu (1979), however, reported fairly small responses to P application under receding moisture conditions of postrainy-season crops at several locations in India (Table 6). Contrary to these findings, on Vertisols of granite origin Singh and Venkateswarlu (1985) found a high and significant response of rainfed sorghum to P (Table 7). In other studies, response of dryland crops to a P application did not become distinct as long as yields continued to be low (Singh and Venkateswarlu, 1985). In well-managed experiments with sorghum on Vertisols, yield responses of 7-20 kg sorghum grain/kg P_2O_5 have been obtained (Tandon and Kanwar, 1984).

Table 6. Response of cereals to phosphates in rainfed Vertisols in India.

Season/Location	Crop	Fertilizer dose applied (kg P/ha)	Yield (t/ha)				LSD
Monsoon							
Indore	Maize	0,22,44	2.56	2.57	2.87		N.S.
Bijapur	Pearl millet	0,18,35,53,70,88	0.54	0.58	0.82		0.14
Sholapur	Pearl millet	0, 11,22	2.79	3.15	3.21		0.30
Rajkot	Sorghum	0,7,13,20	2.87	3.02	3.34	3.46	0.23
Post-Monsoon							
Indore	Wheat	0,18	1.58	1.68			N.S.
Ballary	Sorghum	0,13,26,40	1.77	1.75	1.95	2.17	N.S.
		0,13,26,40	0.80	0.78	0.84	1.00	N.S.
Sholapur	Sorghum	0,22,44,66	0.90	0.75	0.95	0.92	N.S.
		0,22,44,66	1.04	1.08	0.92	1.07	N.S.
Bijapur	Sorghum	0,18,35,53,70,88	2.97	3.19	3.42	3.44	·0.23
			3.16	3.12			

Source: Finck and Venkateswarlu (1982).

Table 7. Effect of N and P on yield of rainfed sorghum on some Vertisols.

Location	Control	N	P	N + P
		(kg/ha)		
Hyderabad	670	780	1,160	2,240
Rajkot	360	400	220	920

Source: Singh and Venkateswarlu (1985).

Under irrigation, when higher yields were attempted with increasing application of N, higher responses to fertilizer-P were also obtained (Sharma and Kant, 1977; Mathan *et al.*, 1978). In Sudan Gezira, application of P to irrigated wheat increased significantly the uptake of soil- and fertilizer-N and resulted in higher grain and straw yields (Ayub, 1986). In the Mediterranean environment of Syria, N application in the absence of P fertilization tended to decrease barley yields at the drier sites (Harmsen *et al.*, 1983). Application of P when the N supply to the crop was adequate resulted in earlier maturity by about 2 weeks.

Broadcasting of phosphatic fertilizers on the soil surface led to its inefficient use by dryland crops (Singh and Venkateswarlu, 1985). Placing P in or near the plantrows increased its efficiency. An application rate of about 50 kg P_2O_5/ha has been recommended as a component of improved production technology (El-Swaify *et al.*. 1985). In a comparison of nitrophosphate (water-soluble P 30%) with superphosphate under rainfed conditions, sorghum response was 10%-25% higher with nitrophsophate (Tandon and Kanwar, 1984). In another study, 50% water-soluble P offered no yield advantage over 30% water-soluble P (Mahapatra *et al.*, 1973). Contrary to these findings, superphosphate proved superior to nitrophosphate for wheat grown in medium and deep black soils (Prasad *et al.*, 1971). Apparently more research is needed on the comparative performance of P sources differing in water solubility for dryland crops grown on Vertisols.

Potassium (K)

Vertisols are high in total (about 1%) and exchangeable (40-500 ppm) K (Finck and Venkateswarlu, 1982). Benefits from K fertilization have seldom been distinct in the SAT.

Sulphur (S)

As with K, a deficiency of S does not seem to limit plant growth in Vertisols. According to Finck and Venkateswarlu (1982), gypsum, the main source of native SO_4 -S, can maintain adequate levels for plant growth.

Micronutrients

A recent classification of 57 benchmark soils according to micronutrient availability (Katyal *et al.*, 1985) revealed that soils of arid and semi-arid climates had low availability of micronutrient cations, viz. zinc (Zn), copper (Cu), manganese (Mn), and iron (Fe), because of high pH, low OC, and a preponderance of Ca and Mg in their exchange complex. Vertisols as a group exhibited the highest concentration of total Zn (50-90 ppm) when compared with other benchmark soils (Malewar and Randhawa, 1978; and Katyal *et al.*, 1982). However, of the nine benchmark Vertisols used for this study, seven had plant-available Zn below the generally regarded critical limit of 0.5 ppm DTPA-Zn.

Zn deficiencies in Vertisols have been confirmed by plant analysis and actual response to Zn fertilization (Katyal and Agarwala, 1982). Rai *et al.* (1972) showed that on 15% to 43% of the Vertisols from Madhya Pradesh, crops could benefit from a Zn treatment. At research stations, crops mostly grown with supplemental irrigations have significantly responded to Zn treatment (refer to studies listed in Table 8). In only a few investigations was the response of nonirrigated crops to Zn application studied. Generally, the response of rainfed crops was inconsistent. A compilation of data by Singh *et al.* (1979) from experiments conducted in the farmers' fields showed that a soil application of 50 kg $ZnSo_4$/ha produced sorghum grain-yield increases of 0.6 to 1.1 t/ha in 3 of 6 years. With the adoption of high-yield technology on rainfed Vertisols, a more widespread and consistent response to Zn application is expected.

Table 8. Studies of crops exhibiting significant response to added zinc in irrigated Vertisols of India.

Crop	Reference
Cotton	Ramanathan and Nagarajan (1980)
Groundnut	Solanky *et al.* (1973)
Maize	Deshmukh *et al.* (1974) and Ramakrishanan and Kaliappa (1976)
Rice	Bhadrapur *et al.* (1977) and Khamparia *et al.* (1977)
Sorghum	Kene and Deshpande (1980)
Wheat	Shinde *et al.* (1977)

On an average, Vertisols contain about 800 ppm Mn, which is one and one-half times more than that of the neighbouring Alfisols (Katyal *et al.*, 1982). Despite rich reserves of total Mn, Sharma and Motiramani (1964) suspected Mn deficiency in about 11% of the Vertisols of Madhya Pradesh, India. Sharma and Shinde (1968) also noted low contents of available Mn in Vertisols. In contrast, Rai *et al.* (1970) found that deep Vertisols from the same state were adequate in Mn availability. Similarly, none of the nine benchmark Vertisols (Katyal *et al.*, 1982) tested below the critical limit of Mn availability (<2.5 DTPA-Mn). In field experiments, Patil *et al.* (1972) and Deshmukh *et al.* (1974) noted a lack of sorghum response to applied Mn. Earlier, with sorghum grown on similar Vertisols, Kene and Deshpande (1979) obtained significant response to a Mn treatment in only 1 of 3 years. It thus appears that Mn deficiency does not seriously constrain crop production in semi-arid tropical Vertisols.

On an average, Vertisols contain about 4% total Fe in the surface horizons. Despite this, Fe deficiency is frequently encountered in Vertisols because of their calcareousness. Rai *et al.* (1970) concluded that nearly 50% of the Vertisols occurring in Madhya Pradesh were deficient in Fe (<2 ppm NH_4 OAc-Fe). Widespread Fe deficiency in sugarcane growing on Vertisols of Tamil Nadu, India, was corrected by $FeSO_4$ sprays (see Katyal and Vlek, 1985). Likewise, Saxena and Sheldrake (1980) could control Fe chlorosis and increase the yield of chickpea up to 50% by $FeSO_4$ sprays. Kene and Deshpande (1979), however, did not observe any significant yield increase of sorghum in Vertisols having 4.2-7.8 ppm available Fe.

As for total Cu contents (range 40-150 ppm and mean 68 ppm) (Katyal *et al.*, 1982), Vertisols exceeded other soil orders. Because total Cu and its plant-available fraction are often closely related (see Katyal and Vlek, 1985), a Cu deficiency is seldom expected to obstruct plant growth in Vertisols (Kavimandan *et al.*, 1964; Rai *et al.*, 1970). Contrary to this background, yield increases of wheat were obtained with the application of 9 kg Cu/ha as $CuSO_4$ (Gupta and Singh, 1972). Although Cu deficiencies for plant growth are rare, a possibility of insufficiency for nutrition of grazing cattle may exist, as was reported in sheep grazing pastures of Australia (see Finck and Venkateswarlu, 1982).

Deficiency of B, despite high pH and calcareousness, has seldom been recorded in Vertisols. Availability of Mo is synergized by the high pH of Vertisols, which also precludes its deficiency in crops.

Summary and Conclusions

From the standpoint of nutrient management, Vertisols of the SAT are universally deficient in N. Contrary to the supposition in the past that excessive risks are involved in using fertilizers, research over the last decade has conclusively established that there is a remarkable potential for increasing crop yields through N fertilization of crops grown on Vertisols over contrasting rainfall environments of the SAT. In a 4-year study (seasonal rainfall = 322-913 mm) at ICRISAT in India, increases in yields of sorghum of from

300 to 2000 kg/ha were achieved through the application of 30-90 kg N/ha.

Variations in year-to-year response depended mainly upon the seasonal rainfall and the depth of the soils. On shallow Vertisols, 30 kg N/ha increased sorghum grain yield up to almost 1 t/ha in 1984 and 1985 which were years of drought (mean seasonal rainfall, 300-400 mm). In years of heavy rainfall (900 mm) response from the same level of N application was less than half, and it was accompanied by relatively low use of fertilizer-N (≅ 30%). The response of sorghum growing on deep Vertisols was found to be more stable across seasons. However, as with shallow soils, and specifically in high-rainfall years, all urea-N broadcast on the surface or incorporated to a depth of about 10 cm was less efficient than urea applied by the split-band technique (fertilizer applied in two equal splits, at planting and 3-4 weeks later, in bands 5 cm deep and 3 cm away from the seedrow and covered with soil).

^{15}N-balance studies confirmed the pattern of response viz-a-viz soil depth. Urea application (by the split-band method) resulted in rather high (≅ 55%) use efficiency of fertilizer-N by sorghum on deep Vertisols. Losses of fertilizer-N, suspected to be mainly via ammonia volatilization, were relatively low (< 10%). In high-rainfall years, losses of N tended to be high (25%-30%), and consequently ^{15}N recovery by plants tended to be low (≅ 45%), especially if urea was placed on the surface or mixed with the soil rather than placed in bands. In sharp contrast to deep Vertisols, losses of N in shallow Vertisols, even when applied by the split-band method and in low-rainfall years, were comparatively high (≅ 30%), and use by the crop was low (≅ 40%).

Several experiments on the evaluation of N sources showed that (1) for deep Vertisols, urea, potassium nitrate, or compound fertilizers could be recommended, and (2) for shallow soils, nitrate-containing fertilizers were a poor choice, since the proportion of fertilizer-N lost increased to more than 50% if amide (urea) or ammonium (DAP) fertilizers were replaced by nitrate (KNO_3) fertilizers. Leaching seemed to be a serious loss mechanism in shallow Vertisols.

Parallel to ^{15}N-balance data, over the years of experimentation, split application of N in bands was superior to broadcast application on the surface or broadcast-incorporated methods of application in high-rainfall years, and was equal to or better than broadcast application in other years. This methodology has another merit in that it allows the farmer to make midseason adjustments: (1) in a season with below average rainfall to withhold further fertilizer application, and (2) in a season with above average rainfall to apply more N. Agronomic efficiency could be increased further by the application of fertilizer-N (at 40-60 kg N/ha) in the seedrows instead of its placement in bands away from the seedrows. An additional benefit from seedrow application was the saving in draught power; a single furrow opener was required for combined placement of seed and fertilizer instead of the usual double seed-and-fertilizer furrow opener.

It was evident from the response to fertilizer-N in a double-cropping of sorghum and safflower, that additional N fertilizer was required for both the rainy-season and post-rainy-season crops. The lack of residual effect from the fertilizer-N remaining in the soil suggested that N should be applied independently to both crops. Efficiency of fertilizer-N (measured as recovery of ^{15}N by aboveground portions of a crop) did not vary between rainy-season and postrainy-season crops. Interestingly, the beneficial effect of fallowing in the rainy season on the postrainy-season crop was not constant across the seasons. The favourable effect of fallowing on the subsequent postrainy-season crop was marked in an average-rainfall year. In a high-rainfall year fallowing was not beneficial to the postrainy-season crop.

Deficiency of P is widespread in Vertisols. Several studies, however, showed that response to fertilizer-P was fairly small if the crop yields continued to be low. Response to P became more distinct in crops (1) grown on Vertisols developed on granite rather than basalt, and (2) grown under irrigation, when higher yields were attempted with increasing application of N. Placement of P in or near the plantrows increased its efficiency.

Vertisols, in general, are deficient in Zn. However, responses to Zn application have been obtained mostly for crops grown under irrigated conditions. Under rainfed conditions, benefit from Zn fertilization became inconsistent. Despite the calcareousness and high pH of Vertisols, deficiency of Fe and Mn is not commonly encountered. Vertisols are sufficient in the remaining micronutrients and in K and S. Several of the nutrient deficiencies which have been less distinct in the past may become important once high-yield technology is widely adopted.

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SUPPLEMENTARY IRRIGATION

H.G. Farbrother*

Abstract

The field capacity concept is discussed in the context of the heavy cracking clay of the Sudan Gezira Scheme. Hydraulic conductivity determinations are shown as having led the way towards understanding the practical consequences of: (a) the weight-of-overburden compaction at 20 cm depth of soil; (b) the role of the cracks; and (c) the unique 'self-regulating' characteristic of Gezira clay. The engineering and the experimental approaches to 'scheduling' of supplies in the past are shown to have had their limitations, and it is claimed that interdisciplinary 'monitoring' of the best of existing irrigation practices is a more realistic approach. An outline is given of the technical, economic and social advantages of today's field schedules, as evolved unofficially by the scheme's tenants themselves over the past 20 years.

Introduction

With at least 3000 years of history to its credit, irrigation certainly cannot be claimed as one of the products of modern science and technology. The Mareb Dam of biblical days, the network of tanks dating back almost as far in Sri Lanka, and the floodbasins of ancient Egypt must have been brilliant examples of expertise with water – probably as good or better than much of today's irrigation. Nevertheless, over the past century or so, civil engineering and agricultural science have together made an enormous contribution to the development of irrigation schemes worldwide.

Modern technology has brought irrigation water within reach of many millions of farmers in many countries. Some, such as the cotton growers of the San Joachim valley

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* 7 The Lanes, Over, Cambridge, England.

in California, and others, such as the owners of 5HP Yamaha pumpsets in Yemen, only use small and unsophisticated equipment. But the most numerous, and by far the most important class of farmer-users of water, are those earning their living in the so-called 'large-scale smallholder' irrigation schemes of the tropics and subtropics; and it is in solving their technical, economic and social problems that the irrigation sciences, irrespective of discipline, have the most rewarding contributions to make.

My theme is that in irrigated agriculture in general, and in large-scale smallholder irrigation schemes in particular, no problem should be dissected into what we conventionally take to be its separate components. The danger is that each individual topic is then pursued in clinical isolation by specialists in the relevant discipline – only to be thrown back into the melting pot when an overall solution is sought by a multidisciplinary committee. Irrigated agriculture in the tropics needs location-specific, open-ended, and fully integrated applied research policies, which cut across all professional boundaries at the local research-worker level.

As irrigation scientists, we are caught in the middle, between the civil engineers above, and the farmer-users below. Civil engineers have adopted all the advances in modern science to their own advantage with the greatest enthusiasm; but there is still universal apathy amongst farmer-users about our suggestions as to how they should irrigate, when they should irrigate, and how much water they should apply. All farmers worldwide, almost without exception, are still completely confident in their own personal judgement with regard to their tactical handling of soils, water and crops. For irrigation scientists this is an embarassing anomaly, particularly since our understanding of the role of soils, water, and climate in crop production has improved so greatly over recent years.

Background material

There is certainly no shortage of technical information on irrigation. Scientists of all disciplines have been provided with a really sound background to water use in irrigated agriculture since the publication of FAO's brilliantly comprehensive *Irrigation and Drainage Paper no. 23: Crop Water Requirements* (Doorenbos and Pruitt, 1977).

Similarly, for engineers, *Irrigation Principles and Practices* by Hansen, Israelsen and Stringham (1979), now in its 4th edition, has been a best-selling textbook on the subject for a generation or more. Although written by civil engineers for civil engineers, this American textbook is to be found, well-thumbed, on engineering and agricultural library shelves everywhere, and is particularly popular in the countries of the Third World. These 'principles' of irrigation, which are intended as generalized guidelines, have often been pressed into service as substitutes for site-specific inputs (despite appropriate warnings not to do so) to provide instant solutions to problems worldwide.

Nevertheless, *Irrigation Principles and Practices* has for a long time been a valuable reference book for all the various disciplines involved in irrigated agriculture. The popular presentation of the terminology has done much to internationalize the language of irrigation around the world, especially on the fundamentals of soils, water, and climate. There can be few students of irrigation anywhere today who are not familiar with such terms as 'consumptive use', 'PWP', 'black cotton soil', 'field capacity', 'when and how much', 'rooting zone', 'available water', 'scheduling' and so on. We have, in general, become so accustomed to using many of these terms that perhaps we are now no longer sufficiently questioning what they really stand for in situations remote from, say, Californian silty loams, or the irrigation of large level basins in Arizona.

Location-specific research

With the cracking clays of Africa in mind, and the semi-arid climatic conditions associated with them, it seems reasonable to question how the conventional terminology of irrigation stands up under this particular combination. I propose to be even more site-specific, and look critically at two of the terms in the context of the montmorillonitic clay of the central Sudan. With acknowledgements to the director and staff of the Gezira Research Station, my examples will be taken from the history of research on irrigation in Sudan's well-known Gezira Scheme.

I have chosen two technical terms for special attention, and both concern soil-water relations. Firstly 'field capacity', because of the very low permeability reported for the soils of the scheme; and secondly, 'scheduling', because the traditional (1934) irrigation regime of the Gezira originally imposed a rigid fixed-interval schedule of watering on the participating tenants of the scheme – and this 50-year-old administrative ruling continues to this day as a controversial issue in Khartoum and Washington.

I intend to use this story of development of applied research policies in the Gezira Scheme, to press the general case for more and closer collaboration in irrigation studies elsewhere in Africa. The four 'key' disciplines – soil physics, agrometeorology, crop physiology, and hydraulic engineering – must be brought into a common approach on the actual practices of irrigation.

Field Capacity in Theory and Practice

The term 'field capacity' has been selected for discussion because of its loose and sometimes uncritical use across the disciplines. Its definition is a frequent cause of trouble when supplementary irrigation needs have to be quantified in the context of a heavy cracking clay of low permeability.

In principle, there should be no problem, as textbook warnings have always insisted that field capacity is not an accurate datum point in soil-moisture relationships. Quoting from *Irrigation Principles and Practices:*

> "When gravitational water has been removed, the moisture content of soil is called field capacity. Field capacity cannot be determined accurately because there is no discontinuity in the curve of moisture content versus time. Nevertheless, the concept of field capacity is extremely useful in arriving at the amount of water available in the soil for plant use. . . . In practice, field capacity is usually determined 2 days after an irrigation. Therefore field capacity defines a specific point on the moisture-con-

tent time curve. . . . Field capacity can be measured by determining the moisture content of soil after an irrigation which is sufficiently heavy to ensure thorough wetting of the soil to be tested."

Available water

The concept of 'available' is central to both the theoretical and the practical approach to irrigation control. Field capacity is needed to define the upper limit, and permanent wilting point (PWP) the lower limit of available water. In most soils, including the heaviest of clays, PWP can be determined precisely, using either potted-plant methods or pressure plates. There is thus a strong temptation in field situations to resort to a plausible figure, or even an arbitrary figure, to stand for field capacity, if the conventional field method is inconclusive.

Whether one has a reliable figure for field capacity or not may be quite inconsequential under rainfall only. In the context of a modest rainfall regime, for example, any errors introduced by a poor estimate of field capacity are likely to be minimal, particularly on finely textured silts and clays. One of the main reasons for this is that small localized pockets of high soil moisture content after storms are rapidly redistributed in all directions, primarily in response to steep moisture gradients, rather than to the downwards pull of gravity. The microtopography typical of semi-arid areas, coupled with infiltration problems caused by capping of the soil, often encourages the accumulation of such localized pockets of soil water; but it has been observed that saturated-flow conditions do not usually persist for more than a few hours after a storm, and thus the opportunity for downwards drainage is very restricted (Farbrother, 1973).

Under irrigated conditions on many heavy clays the opposite is true: the surface soil is regularly raised to saturation capacity, and may remain so for several days during and after each field watering. Opportunities will certainly occur for the textbook's two-day draining spells; and if drainage is assumed, then the likely errors from using an arbitrary value for field capacity may be considerable.

In the particular case of Gezira clay, however, the permeability at saturation is so low that the field capacity concept is positively misleading. In research on the irrigation regimes of the Gezira, field capacity was abandoned as a datum point in 1972. The calculation of available water on Gezira clay is only of practical value when saturation capacity is used as the definition of the upper limit to available water, plus such amounts of free-standing water as may be left in the furrows on completion of watering.

This was a dramatic break from the former longstanding assumption of 36% for the field capacity of Gezira clay (Jewett, 1954). The new calculations of available water tallied with observed field data, and immediately provided a rational explanation for the tenants' field-watering practices in the Gezira.

Hydraulic conductivity

The new understanding of soil-moisture relations in the Gezira dates back to 1971, when for the first time measurements of hydraulic conductivity on Gezira clay were undertaken. The government's Soil Survey Department, together with FAO's SF/SUD/15 Soil Survey Project, investigated the effects on hydraulic conductivity of (a) changes in the level of the exchangeable sodium percentage (ESP), and (b) changes in the degree of physical compaction due to weight-of-overburden (Abdine, 1971).

Constant head apparatus in the laboratory was used, with entirely expected results as far as the level of ESP was concerned. Of far greater practical significance, however, were the findings that weight-of-overburden stresses of as little as 37, 66, and 96 gr/cm^2 (equivalent to depths of soil of only 20 cm, 35 cm, and 50 cm respectively) depressed the hydraulic conductivities to virtually zero, even at low levels of ESP. In Table 1, Professor Abdullah Zein Abdine's results are reproduced for four levels of stress and five levels of ESP.

Table 1. Hydraulic conductivity as affected by exchangeable sodium percentage under free and restricted expansion in Gezira soil (in cm/h).

	Applied stress in gr/cm^2			
ESP	0	37	66	96
Ca-sat.	0.4310	0.1180	0.0418	0.0210
3.8	0.1910	0.0155	0.0120	0.0088
8.1	0.0343	0.0043	0.0027	0.0021
16.6	0.0088	0.0021	0.0017	0.0014
28.8	0.0033	0.0018	0.0013	0.0009

Penetration to depth

These hydraulic conductivity figures gave a new insight into the behaviour of Gezira clay. The so-called 'grey layer' of high ESP and a slightly higher clay content (at 60-90 cm depth) had been assumed by the soil chemists of earlier days to be the main factor responsible for restricted penetration of irrigation water into the profile. The cyclic depth of normal irrigations in the field was known to be 60 cm or so; and no treatment such as deep-ripping or application of gypsum appeared to have any reproducible effects on the depth of penetration. Yet all the many 'before' and 'after' soil moisture profiles for Gezira clay which had appeared in the research reports over the lohg history of the Gezira, showed that in 'after' profiles the highest moisture content was always in the surface 0-10 or 0-15 cm layers.

Moisture profiles reported by a succession of agronomists and soil chemists showed a wide range in the maximum depth to which small amounts of water had penetrated, but all demonstrated a pronounced curvilinear pattern of decrease from the surface downwards (Farbrother, 1972).

A typical example of the curvilinear penetration of irrigation water is given in Figure 1. The moisture profiles shown refer to an irrigation of cotton in midseason when the early-season accumulation of subsoil moisture had reached its maximum extent. The interval of depth of sampling shown in Figure 1 was 20 cm, which masks the gradient in moisture from the immediate surface on day 1 after irrigation. The accepted figure for saturation capacity for the 0-10 cm interval of depth is 52% on average for the soils of the Gezira.

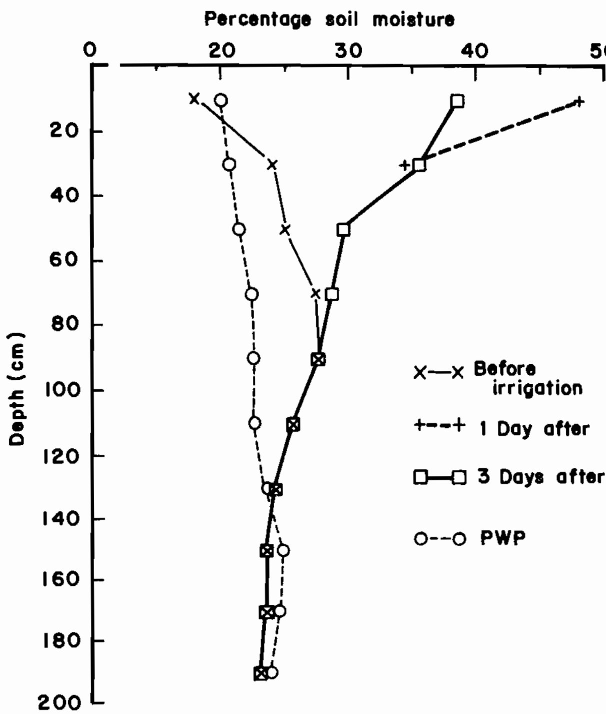

Figure 1. Soil moisture distribution to 2 m depth by 20 cm intervals, percentage gravimetric.

The role of the cracks

Once the hydraulic conductivity results had moved the focus of attention from the grey layer to the surface 0-10 cm, it became obvious that the cracks were providing the only route for movement of water downwards. The physical dimensions and the functions of the cracks that develop as the clay dries out needed further study.

The linear contraction of samples of Gezira clay over the moisture range from saturation capacity (52% gravimetric) down to air-dry (6%) has been reported as 12.6% (Farbrother, 1967). Estimates of the volumetric reduction over the same moisture range by the paraffin method on samples in the laboratory were of the order of 36%. Attempts to estimate the volume of cracks in the field failed. Nevertheless it was assumed that the total air space developed on drying out reflected the reduction in moisture content; and that over the 45 cm depth usually observed within cropped fields during the season, the volume at any depth was reasonably well correlated with the moisture observed at that depth.

Intensive gravimetric soil moisture samplings before and after an irrigation showed that the acretions were inversely proportional to the amount of soil moisture present before the irrigation. The amount of freestanding water left on the surface of the soil, of course, had to be accounted for separately. The amounts left after satisfying the soil requirements – according to 'by eye' observations of an experienced Gezira waterman – could be either nil, or halfway up the side of the ridge, or to the top of the ridge (viz. 'light' and 'heavy' waterings).

For well-made ridges and furrows at the standard spacing of 80 cm, the maximum amount that could be left in the furrow has been variously reported as between 36 and 48 mm (357 and 476 m^3/ha).

The 'self-regulating' characteristics of Gezira clay

The immediate result of irrigating a field plot is that the cracks take as much water as their volume dictates. Depending on the rate of supply, this step is rapidly completed, and is followed by the free water being absorbed by the dry walls of the cracks, and the moisture is redistributed in all directions in response to such moisture gradients as are present. The cracks also begin to close in response to the lateral expansion of the clay of the monoliths, which at any depth is effectively free to expand without the restriction of weight-of-overburden. If surplus water is available on the surface, some will replace that moved through the walls of the cracks, until such time as the cracks close completely. Redistribution continues thereafter at rates that decline with time. Near-uniformity is approached at any specific depth some three days after irrigation. The final moisture increment at any specific depth will approximate to the original cross section of the crack at that depth; and this, no doubt, is the mechanism for preserving the curvilinear form of the profile of soil moisture.

This control of the amount of water taken by the soil at each watering has been referred to as the 'self-regulating' characteristic of Gezira clay. In practice, it means that whatever the initial dryness of the profile, the postirrigation state will be much the same in each case, although it might have taken very different quantities of water to have achieved that result. With no freestanding water remaining on the surface, the available water held by the 0-60 cm depth zone in the postirrigation state is of the order of 93 mm, (929 m^3/ha), of which 49%, 33% and 18% is held in intervals of 0-20, 20-40 and 40-60 cm depths respectively.

Irrigation of virgin Gezira clay sites

Soil moisture profiles before and after irrigation have been reported for newly developed irrigation schemes eslewhere in the Sudan on Gezira clay.

In the Rahad Irrigation Project (Chesworth and Farbrother, 1984), the irrigation water was shown to penetrate in markedly greater quantities to the 20-40 and 40-60 cm depths during the first season (1977) of irrigation. A similar result on virgin sites at the newly developed Kenana Sugar Estate was reported in 1976 (Gallacher, pers. comm.). Both sites were known to have supported a dense seasonal cover of perennial grasses, and sparse 'kitr' bushes prior to being cleared for irrigation development. The remains of the rooting systems of those grasses were observed during the soil moisture sampling programme, and the atypical penetration during the first season was attributed to them.

Scheduling – in Theory and Practice

Answers on when to irrigate and how much water to apply cannot be predicted, except in a most generalized way. The daily water needs of the crop, and the capacity of the soil to store water within the rooting zone of the crop, are obviously two of the main considerations; and although predicting the daily water needs of a crop is now relatively easy, the ability to predict the detailed behaviour of rooting systems under field conditions is still the major constraint.

'Rooting zone' is a particularly controversial term in the context of Gezira clay. Below the 60 cm depth of cyclic wetting and drying, there is a slow early-season buildup of subsoil moisture. These reserves can be exploited by plants with strong taproot systems, and in some seasons provide modest buffers against chance short-term deficits of moisture in the upper soil profile.

The engineering approach

In the context of large-scale smallholder irrigation schemes, information on when to irrigate, and how much to apply has for many years been considered an essential input for engineering planning and design (Ibrahim, 1984). The objective has been twofold: firstly, to minimize seepage losses in the smaller and invariably unlined tertiary channels (by raising the designed discharge capacity of each and thus reducing the time each is in operation); secondly, to provide the means whereby the agricultural administration of the scheme can subsequently maintain water-use discipline by ensuring that the recommended rotational schedules for the proposed crops can be physically imposed by the administration on the smallholding farmer-users.

The consequence of this has been that practically all of the large-scale schemes of the tropics today still operate some form of scheduled supply on a fixed-rotation basis. In Egypt, it is not uncommon for large secondary canals to rotate supplies at the locally approved intervals, thus ensuring that the discipline of optimum watering frequency for the crops is adhered to by the irrigators (Bottrall, 1980).

In Pakistan, and in some areas of India, local 'distributaries' operate alternately for the same purpose (Wade, 1979). In the Sudan, the traditional system originally devised in 1925 for the Gezira Scheme was designed to enforce the recommended 14-day interval for cotton by operating pairs of tertiary channels alternately at two-weekly intervals (Griffen, 1951).

On the other hand, the introduction of CAD in India has encouraged much debate on the ethics of imposing rigid rotational schedules by engineering design (Hashim Ali, 1979). Under CAD, continuous supplies at each village outlet (at approximately 1 m^3/s for each unit not exceeding 100 acres) are to be maintained day and night by the operating engineers throughout the season. As many as 60 very small-scale farmer-users may depend on the one village outlet, each individual farmer taking the whole of the supply for a period of time (in hours and minutes) proportional to the area of his land. CAD departs from the traditional engineering approach in that the equitable distribution of water is now entirely at the discretion of the villagers themselves, rather than an imposition from outside the village by the officials of the district irrigation administration.

The experimental approach

Remembering that the Sudan Gezira was commissioned as early as 1925, there are lessons to be learnt from examining the history of the early experimental approach to the determination of formal irrigation schedules.

From 1925 to 1963, the scientific approach to scheduling water involved field trials repeated seasonally, testing various factorial combinations of intervals (usually 7, 14, and 21 days), and various rates of application. Before water meters became available, the rates of application were nominally designated 'light', 'medium' and 'heavy', and quantified somewhat arbitrarily as 300, 420 and 600 per feddan (71 mm, 100 mm and 142 mm). Cotton yields harvested from the replicated subplots were analyzed statistically to rank the order of responses to watering treatments. Throughout, the maximization of the yield of seed cotton per unit area of land was the main objective.

Over those 38 years in the Gezira, more than 126 such field trials testing factorial combinations of intervals and rates were conducted by staff of the Gezira Research Station (GRS). Although immense effort was put into the implementation of these field trials, statistically significant differences between treatments were only very rarely obtained, and then only between the most extreme combinations. It is also an interesting comment that never on any occasion did the 'best' irrigation treatment outyield the Cotton Breeding Section's variety trial in the same year – the latter being grown under the standard irrigation practices of the station. Nevertheless, as the number of trials accumulated, the trend overall gave strong support to the scheme's design assumption of a fixed interval of 14 days between waterings, coupled with a 'medium' (100 mm) rate of application.

By 1962, the field trials had adopted rather more sophisticated experimental layouts, with metered water supplies and soil moisture sampling programmes. Dethridgemeters were introduced to the Sudan for this purpose. In the 1962-63 season, the trial compared cotton yields at all combinations of four intervals and four rates. The results were reported in detail in the GRS annual report for that year, and I quote the table of yields below (Table 2), having converted the seed-cotton yields from the original 'kantars per feddan' to kg per hectare.

Table 2. Yields in kg/ha of seed-cotton irrigated at four intervals and four rates.

Rates: mm/day:	Intervals in days: 7	14	21	28	means:
2.5	2342	2261	2271	2019	2223
5.0	2070	2097	1957	2206	2082
7.5	2012	2019	2186	2244	2115
10.0	2026	2053	2172	2073	2081
means:	2112	2108	2146	2136	
		no significant differences			

For obvious reasons, this field trial was the last major experiment on rates and intervals at the GRS. With the mean crop water requirements (CWR) for cotton over the average season at 7.1 mm/day, it was clear that the technology of applying controlled amounts of irrigation water to relatively small subplots (12 m X 8 m) was at fault and that the unique characteristics of Gezira clay were not sufficiently well understood.

Failure to obtain statistically sound results from experimental layouts testing irrigation schedules is by no means confined to the Sudan. A number of classical examples from elsewhere were put on record in FAO's *Irrigation and Drainage Paper no. 13,* reporting the Damascus Seminar on Water Use, 1972. Some 16 field experiments on a wide variety of sites, mostly with highly sophisticated layouts (which included tensiometer-controlled intervals at 75%, 50% and 35% reduction of available water) all failed to provide statistically significant yield results.

The Alternative Research Strategy at GRS

From 1964 onwards, a new research approach to irrigation and the fundamentals of crop management on Gezira clay was initiated by the then director of the GRS, Dr. Hussein Idris. Three stages were envisaged:

1st: Integrated research on the fundamentals of soils and water on Gezira clay, bringing soil physics, agrometeorology, and plant physiology into a common approach.
2nd: Collaboration with the Ministry of Irrigation (MoI) and the Sudan Gezira Board (SGB) in the monitoring of irrigation practices in the commercial areas.
3rd: Intervention tactics.

First stage

During this stage, interdisciplinary research was encouraged to resolve the many anomolies in the field behaviour of Gezira clay, and to determine the influence of the Gezira environment on the growth and development of crops. Although the Gezira already had a long history of soils research going back to 1911, only soil chemists had until then been involved, and the hazards of alkalinity and salinity for the Gezira had dominated their thinking. Studies of the basic physical characteristics of the soils of the Gezira were therefore the starting point for the newly appointed soil physicist (Fadl, 1976). Drainage and soil aeration, and volume-weight conversion factors were also examined in detail (Hack, 1969, 1984).

In agrometeorology, the primary task was the localization of Penman methodologies: reference evaporation (E_0), evapotranspiration (ET), CWR, crop coefficients (kc), wind term and solar radiation corrections, reflection coefficients, albedo, and advective energy (Adam, 1984). Physiological contributions were made (i) on relative turgidity – ET, CWR, and yield/stress functions (Farbrother, 1973); and (ii) on leaf area indices, net assimilation rates, and growth analysis (Taha, 1969).

Second stage

This stage, which started in 1969, involved monitoring the irrigation practices of the Gezira at the field level: (a) observing and recording the day-to-day field water management tactics of the tenants of the scheme, and (b) documenting the discharges at selected minor heads and other structures operated by employees of MoI. All monitoring in this stage was passive observation by research staff, but wholly dependent on close cooperation with field staff and administrators of the SGB and irrigation engineers of MoI. The objective was to obtain a properly balanced view of the attitudes and motivations of all those with roles in water control and management.

The sites selected for monitoring were each chosen on grounds of suitability for a particular line of investigation. These varied widely, ranging from the causes of fluctuating supply levels at key points in the distributive system to the unofficial labour-saving methods of field watering introduced by experienced Gezira tenants in response to intensification and diversification of cropping.

The lesson was quickly learnt: that no single aspect of irrigation in a large-scale smallholder scheme can be isolated and studied in clinical isolation by researchers in any one discipline. The appointment of a multidisciplinary committee does not necessarily overcome the inherent tendency for disciplines to operate introspectively. In practice, it is only after working closely together in interdisciplinary monitoring exercises that individual members acquire from one another the ability to see a problem as it really is, in all its complexities, and from a properly balanced point of view. The most important point of view, of course, is that of the actual farmer-user himself; and unfortunately for conventionally trained scientists and engineers, an insight into his thinking is most difficult to acquire.

Third stage

This stage was planned to follow with a number of positive interventions on specific aspects of irrigation in the commercial areas of the Gezira – but only when the monitoring exercises had produced enough documented evidence to warrant a joint move by all three interested parties: the SGB, the MoI, and the GRS. Only one such intervention was possible – in 1977, when a project was sponsored by FAO for a field trial of CWR methods at the block inspector level, in an effort to replace the traditional indent procedure at minor heads (Farbrother, 1979).

The Gezira Tenants' Contribution

Although I have pressed the case (in the previous section) that much can be learned by monitoring the way experienced farmer-users use their available resources of water, this approach is not without its critics. In the Sudan, for example, it is widely believed that because the tenants are no longer following the letter of the old strictly disciplined ways with water in the fields, the crops must inevitably be less well watered than formerly. Even when our GRS research results demonstrated that the new field tactics should be supported as progressive on economic and social grounds, and that they were no less adequate on scientific and engineering grounds, the tendency amongst nontenants was to misinterpret the data presented, and use them simply as evidence of what they termed the 'declining standards' of the tenants.

It would not be proper for me to comment here on the current controversies over how today's Gezira tenant can be retrained to conform with the 1934 concept of his role in field water management. But as we have already discussed how the soil physicists' understanding of irrigation on this unique cracking clay has developed over the years, it is reasonable for me to outline how the tenants' understanding of the practical issues involved have developed over the 50 years that they and their fathers have had in day-to-day contact with the soils and water of the scheme.

Scheduling from the tenants' viewpoint

Formerly, the Gezira tenant had no option but to water at the 14-day (or so) interval imposed by the field staff of the scheme. The nine tenants sharing supplies delivered to one of the Gezira's standard tertiary supply channels (known locally as 'Abu Ishreen') took water for their cotton in sequence for one week, and a neighbouring group of nine tenants on another Abu Ishreen took water for the alternating week. The field staff were in control, because it was their employees, the canal 'Ghaffirs', who physically opened and closed the outlets to the designated Abu Ishreen.

The official schedule also dictated that field watering of cotton could only be done during the twelve daylight hours, and the rates of discharge at the outlet pipes were raised so that all nine tenants could complete their fields within the seven days, giving the recommended 1000 m^3 to each hectare (420 m per feddan). Without going now into too much detail, the result was that 4.5 individual tenants each had a stream size averaging some 100 m^3/h for 3 days (i.e. 42 daylight working hours, 6 a.m. to 6 p.m.) for his 4.2 ha of cotton (10 feddans).

In order to assist the tenant in spreading the water evenly over the land, the scheme management set out the 4.2 ha into a rectangular arrangement of field channels, bunds, ridges and furrows, dividing the holding into 137 small basins, each of approximately 306 m^2. The tenant's duty was then to divert his 100 m^3/h supply in succession around these small basins throughout the prescribed hours of watering.

It was not long before the tenants (or the paid watermen acting for them) discovered that this formal schedule was quite impracticable on Gezira clay, for the following reasons:

- The cross-cracks which develop in ridges and bunds during a drying cycle make it impossible for a waterman to contain water within the limits of any specified basin or combination of basins.
- With the minimum of interference by the waterman, the whole field could be evenly covered as one large basin (apart from known 'high-spots' on some difficult fields).
- The "thirstiness of the soil" (as they called it) determined the amount of water taken, and their only control over the rate was limited to small differences in the amount of standing water left in the furrows.

Putting these three reasons together, the tenants could see no virtue in being compelled to spend a seasonal total of 420 hours in the cotton field for the ten biweekly waterings given to cotton. Once the cotton plants had become established (preferably on rainfall alone), and the roots of the cotton had developed into the soil below the surface 0-15 cm (owing to its surface susceptibility to waterlogging), they then saw their necessary role reduced to simply opening the field to water, and eventually closing it a few days later.

Unpredictable fluctuations in the supplies available at the scheduled outlets were an additional reason for the tenants to abandon the official practices. The local engineers and the local field inspectorate were also embrassed by the limitations that fluctuating supplies imposed on the scheduling of alternate outlets by weeks. As early as 1956, the evidence against the need for alternating outlets already existed. Joint experimentation at a particular site in the Gezira equipped with Dethridgemeters for the purpose of measuring discharges to tenants (Faris Minor 54/55 and 55/56, MoI unpublished data) showed that an outlet continuously open to nine sharing tenants took exactly the same amount of water over the season as one opened for only alternate weeks.

The advantages of half-rate discharges for double the time were fully appreciated by the tenants. The most valuable aspect of the scheme was that rotation of water between fields within Abu Ishreens became possible, thus allowing the frequency of watering to be at the discretion of the nine tenants alone, according to their judgement of the needs of their crops.

The advantages of quarter-rate discharges at four times the number of open outlets were exploited by the tenants from the mid-1960s onwards. Diversification of cropping at that time involved a threefold increase in the numbers of outlets 'live to crops' at any one time; and the former regimented style of 'scheduling' for cotton alone at 14-day intervals proved inadequate. The current Gezira version of on-demand, continuous-flow management of Abu Ishreens soon applied unofficially throughout the scheme.

The tenants' longer intervals

The irrigation of large open fields as single basins (now halved to 2.1 ha), with low streamflows in the 25-35 m^3/h range, means that the time taken to complete watering overall is now increased to some seven to ten days or more. Moreover, on the completion of watering, practically the whole field is covered with some surplus water standing in the furrows. The tenants, very correctly, have learnt that the traditional 14-day interval has to be reinterpreted as a 14-day drying phase. The standard interval in the commercial areas of the Gezira is thus today between 21 and 25 days, depending on the variable time which it takes to complete watering.

The tenants are of course much criticized for not adhering to the longstanding research recommendation for 14-day intervals. Indeed, it is not uncommon for new research findings on intervals to refer only to the small 12 m X 8 m standard subplot size for irrigation experiments with no mention of recommendations for the large open-style fields of the commercial areas. On the other hand, one realizes that it would be totally impracticable to design and conduct formal experiments with controlled watering treatments using subplot dimensions on the 2.1 ha scale of the commercial areas!

Current monitoring projects in the Gezira

It is encouraging that the monitoring approach has been revived in the Gezira since 1984. The MoI's Hydraulics Research Station, with the support of Hydraulics Research Ltd., Wallingford, England, has initiated a project designed to provide data on the supply of water at the field level in the Gezira. On the principles established in FAO's *Irrigation and Drainage Paper no. 33,* "Yield Responses to Water", it will thus be possible to evaluate the tenants' field practices by another and more profitable route.

According to *Paper no. 33,* yield potential will be maximized when actual crop water use (CWU) is equal to calculated crop water requirements (CWR). If the water supply period by period over the season can be measured at the field level at a representative number of tenants' fields, then in will be reasonable to deduce how close they have been to achieving optimum CWU. The same principle has been used for supply and demand data at the headworks of the scheme with considerable success for a number of years (Abdu, 1984).

Assuming some measure of agreement between CWU and CWR at the field level, monitoring exercises such as this could do much to realieve the current administrative pressure on the tenants of the Gezira to return to the highly labour-intensive practices of past generations.

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Seventh session: Sustainability of improved systems

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Dr. N.N. Nyandat

APPROACHES TO EROSION CONTROL ON VERTISOLS IN QUEENSLAND, AUSTRALIA

J.A. Mullins, A.A. Webb and K.J. Coughlan*

Abstract

Vertisols are used for both cropping and grazing in Queensland. Soil erosion is one of the major problems threatening their long-term viability.

Soil conservation can be achieved on the arable Vertisols through the maintenance of high levels of protective ground cover and in conjunction with the use of structures such as graded terraces and waterways to control runoff before it reaches scouring velocities. The maintenance of ground cover using both crop and crop residues protects the soil surface from the impact of raindrops and permits maximum infiltration. This is achieved with practices such as reduced tillage, selection of crops that provide maximum cover at critical periods, opportunity cropping, strip-cropping and fallow management.

In grazing lands, erosion is controlled by the maintenance of ground cover, through reduced stocking pressures, and the strategic placement of fences, watering points, yards, etc.

Land-use planning is the recommended basis for selection of management practices and land development.

Introduction

Vertisols cover approximately 50 million ha, which is more than one quarter of the Queensland land surface (Coughlan *et al.*, 1986). Native pasture, which takes up the largest proportion of Vertisols (approximately 43 million ha), is the base of the livestock

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* Queensland Department of Primary Industries, Meires Road, Indooroopilly QLD. 4068, Australia.

industry. These areas are considered too dry for rainfed cropping as they have an annual rainfall of less than 500 mm which is highly variable.

Approximately 1.25 million ha of Vertisols are cultivated for grain production, mainly wheat and sorghum, with smaller areas of oilseeds such as sunflower and safflower.

The Vertisols are highly erodible, particularly under cropping, and considerable emphasis has been placed on the management of these soils to ensure sustainable long-term stability.

This paper presents a brief description of the soils and the climate, and describes the erosion problem on the Vertisols of Queensland, with details on the strategies used to control the soil erosion.

Soil Characteristics

The characteristics of the Vertisols in Queensland have been described by Smith *et al.* (1984), and will not be considered here in any detail. They are generally considered as two broad groups, Black Earths (approximately coinciding with the Pellustert great group) and the Grey, Brown or Red Clays (Chromusterts and Torrerts). The differences between the soils are related to the lithology of the parent material. The Black Earths are usually formed on basic rocks such as basalt, or alluvium largely of basaltic origin, while the Grey, Brown and Red Clays are formed on a range of parent materials largely of sedimentary origin. The Black Earths generally have a high clay content, high cation-exchange capacity, and low sodicity and salinity. The Grey Clays in particular are usually lower in clay content and cation-exchange capacity, sodic, often moderately saline, and have gilgai development.

Climate

The main cropping area lies between 20° and 29° S latitude and within the 500-700 mm rainfall isohyet. In this area rainfall is summer-dominant and highly variable. Pan evaporation exceeds rainfall in nearly all months. In this paper summer-dominant rainfall means that more than 50% of the annual rainfall occurs in the six months between October and March.

Although summer rainfall is dominant (the summer:winter rainfall ratio is 2:1 at 29° S and greater than 3:1 at 20° S latitude), wheat is the main cereal crop in southern areas, particularly in drier western areas where rainfall is less reliable.

Both the amount and seasonal distribution of rainfall are highly variable. Droughts and floods are experienced in most cropping areas. Rainfall intensity is high, compared to that of many other cereal-cropping areas of Australia and the world. High-intensity rainfall events are caused mainly by convective frontal storms (spring to early summer), cyclonic systems (mid to late summer and midwinter) and upper level disturbances (at any time of the year). Although high-intensity rainfall events are more common in summer, they may occur at any time of the year.

The erosion index of rainfall is highest in the months of January to March (Table 1) (Smith *et al.*, 1984).

Table 1. Climatic indices for some Queensland towns.

Town	Index	Mean Quarterly			
		Jan-Mar	Apr-June	Jul-Sep	Oct-Dec
Ayr	R	8.2	1.3	0.6	1.9
	E	5.7	4.2	4.7	6.7
	EI	366	6	11	187
Emerald	R	3.1	1.1	0.8	2.0
	E	6.7	4.1	4.7	8.0
	EI	172	16	11	106
Gatton	R	3.4	1.5	1.1	2.7
	E	6.0	3.7	4.0	6.7
	EI	157	11	15	102
Roma	R	2.5	1.1	1.1	1.9
	EI	6.9	3.3	3.4	7.1
	EI	122	16	11	71

R = mean daily rainfall (mm).
E = mean daily pan evaporation (mm).
EI = mean erosion index calculated from total energy and maximum 30-minute intensity (Rosenthal and White, 1980).

Land Use

Land use of the Vertisol areas in Queensland has been summarized by Weston *et al.* (1981) as follows:

Cropped

Irrigated	= 0.05 million ha
Dryland	= 1.2 million ha

Uncropped

Potential for dryland cropping	= 6 million ha
Limited to livestock	= 43 million ha

The predominance of Vertisols in the arable soils of Queensland is shown in Figure 1.

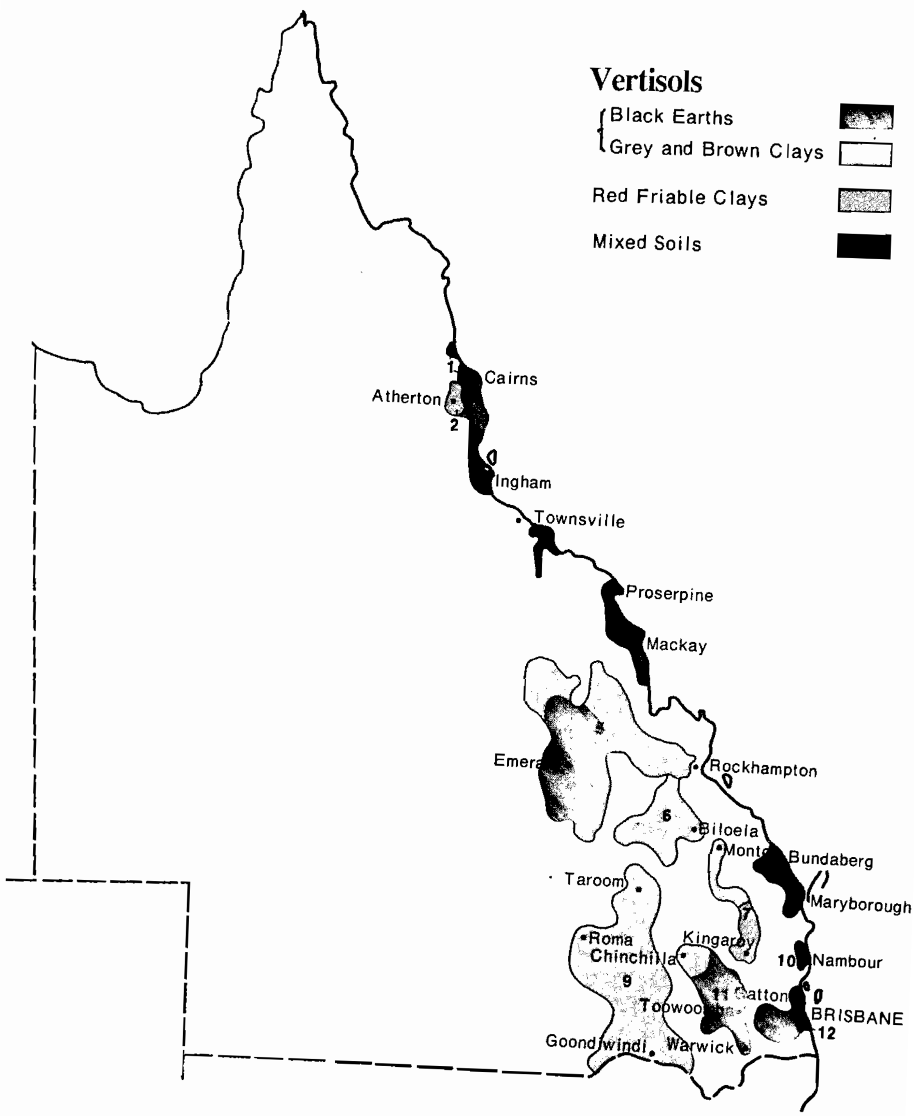

Figure 1. Major arable soils of Queensland.

The large proportion of native grass pastures used for livestock production indicates the occurrence of very large areas of Vertisols in low-rainfall regions.

Vertisols are commonly used for irrigation in Queensland despite problems of crop establishment, waterlogging and salinity in some soils. The total area of irrigated Vertisols is relatively small, but is highly valued.

Extensive dryland cropping in Queensland is largely opportunistic, as planting decisions depend both on the level of subsoil moisture available and the occurrence of planting rains. The annual reliability of rainfall thus influences the amount of crop planted each year. A fallow phase is often included to restore soil moisture to overcome rainfall deficiencies during the growing season. In traditional cropping systems, the soil surface is kept bare during the fallow period, and when high-intensity rain hits this bare and often loose surface, severe soil erosion results.

The Erosion Problem

The erosion problem on the Vertisols in Queensland is a result of the interacting components of soils, topography, management practices, and rainfall.

The Vertisols have slow infiltration when cracks are closed, and their inherent structural instability under rainfall leads to the formation of surface seals and crusts. These factors result in high runoff from rainfall. In addition, the Vertisols, particularly those developed on basalt, are highly erodible.

Vertisols occur in either plain or upland situations. Land slopes in upland situations may be very steep. Soil losses cannot be adequately controlled under cropping on land slopes in excess of between 4 and 8%. The upper slope limit depends on the local environment and the level of management practices available for the area.

Management practices which exacerbate the inherent disadvantages of Vertisols result in severe erosion. These include:

- long periods of fallow with infrequent cropping;
- frequent aggressive tillage;
- removal of crop residues; and
- cropping of shallow soils.

There is of course, a strong interaction between rainfall and management practices. In Figure 2, rainfall erosivity for the eastern Darling Downs is shown with a number of commonly practiced crop and fallow sequences. Two situations are considered:

- Where continuous winter cropping is practiced, the greatest erosion potential is in the December to May period. This is the fallow period when soil moisture is stored for the subsequent crop. The erosion index (EI) of rainfall is very high in the early part of this period. In the latter part, although the EI is less, soil water content is usually high, cracks are closed, and macroporosity is at its minimum. Under conventional tillage techniques, crop residues are also progressively reduced over the period. All these conditions lead to increased runoff and soil loss.
- When summer cropping is practiced, fallow periods occur during the months of

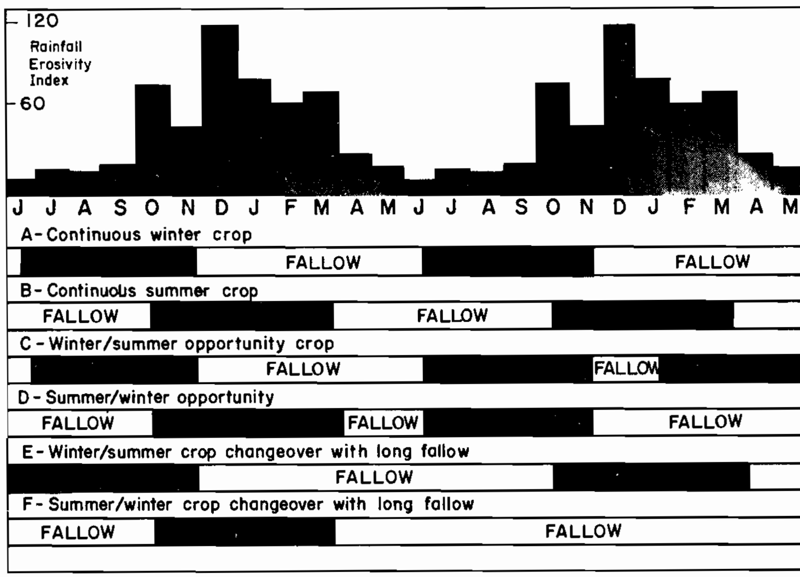

Figure 2. Rainfall erosivity for each month related to commonly practiced crop and fallow sequences used on the eastern Darling Downs.

lowest EI and when the soil profile tends to be relatively dry. The greatest erosion potential is in early summer before the summer crop is planted and immediately after planting. In the later periods of high EI, soil water deficits are created by the growing crop and this results in reduced runoff. Plant canopy cover also provides some soil protection from intense rainfall. This illustrates the advantage of matching crop growth periods with rain periods. This is only possible, however, in more reliable rainfall areas.

The main form of erosion in cropped Vertisols is rill erosion, although sheet and gully erosion also occur.

In the grazing lands erosion results mostly from overgrazing of pastures and partly from surface soil structure decline due to trampling. The dominant grass species in the native pastures are summer-growing and these are efficient at creating soil water deficits during the periods of high EI when the bulk of the rainfall occurs. Problems occur during drought periods and when grazing pressures lead to substantial loss of surface cover and eventually some pasture species. Rainfall variability and fluctuating prices make it difficult for graziers to adjust stock numbers rapidly, and overgrazing can result.

Sheet erosion tends to be the main form of erosion in grazing lands but this is often unnoticed until gully erosion occurs. Pasture regeneration and growth is usually adversely affected, and weed invasion often follows. Although erosion rates in grazing lands are generally low, the resultant effect on productivity can be considerable due to the loss of nutrients, seed source, and reduced infiltration.

Strategies for Erosion Control

Strategies for erosion control involve maximizing infiltration of rainfall, protection to the soil surface, and the control of runoff. An overriding strategy is land-use planning, which provides the basis for the implementation of the other strategies.

On most Vertisols in Queensland – apart from those on very low-gradient land slopes – a combination of conservation cropping practices and mechanical structures is needed to control soil erosion on cultivated lands. In some situations, such combinations have not been adequate to reduce soil losses to acceptable levels and a land-use reversal to pasture has been necessary.

Land-use planning

The key outcome from land-use planning is an assessment of land capability. This requires an understanding of physical resources, and particularly of soils. Land management units are delineated and appropriate land-use and management practices for sustained production and erosion control are formulated. Runoff control structures are integrated.

Runoff control

Irrespective of the cropping practices adopted, runoff still occurs when the rainfall rate exceeds the infiltration rate of water. Various techniques are used to control the effects of overland flow. The major ones include contour cultivation, terraces, diversion terraces, waterways, and strip-cropping.

Terraces

The function of terraces (commonly referred to as graded banks in Australia) is to decrease the length of slope down which water can flow. They collect water before it reaches scouring velocities and convey it at safe speeds to the side of the paddock where the water is deposited into a constructed grass waterway or a stable drainage area. The length of slope over which sheet and rill erosion will occur is reduced, and this limits the formation of major rills and gullies.

Terraces are used on land planted with a wide variety of crops, including cereal grains, oilseeds, sugarcane and some horticultural crops. For practical reasons, terraces are designed to carry the greatest runoff, expected only once in every 10-year period. Depending on the land slope and soil erodibility, terraces are spaced at intervals down the slope. The steeper the land and the more erodible the soil, the closer together the terraces need to be to reduce rill erosion. In the drier cropping areas of Queensland (rainfall less than 600 mm), terraces are spaced at vertical intervals of 1.7 m on a 2% land slope, increasing to 2.3 m on a 5% land slope. This vertical interval is reduced on shallow Vertisols and those with sodic and/or saline subsoils.

Depending on factors such as land slope, soil type, land value and land use, different types of terraces are used. On most Vertisols, it is necessary to cultivate at least the top-side of the terrace, otherwise the deep cracks which occur on these soils when they dry out allow water to break through the terrace.

On gently sloping areas with deep soil, terraces can be built with a broad base so that it is possible to cultivate along both sides of the terrace. As the land slope increases, it becomes more difficult and impractical to work the bottomside; and finally, on steep land slopes, it is impractical to build anything but a narrow-base bank, in which case only the channel can be cultivated. Because a broad-base bank requires much soil, narrow-base banks are generally used on shallow soils.

Terraces are built with a very low gradient so that water travelling along the channel does not cause scouring under cultivated conditions. Maximum permissible velocities of 0.5 m/sec are acceptable for Vertisols with nonsodic subsoils and of 0.35 m/sec on sodic subsoils. Due to the potential for major scouring, terraces are not constructed on Vertisols with highly sodic subsoils.

Terraces are built with either bulldozers, graders, or a blade mounted on a tractor. An allowance for settlement of 60% is made when terraces are constructed on Vertisols with a water content close to field capacity.

Regular maintenance of terraces is recommended, particularly following periods of high runoff. The need for maintenance is significantly reduced if conservation cropping practices are used to reduce the amount of silt deposited in the channel.

Waterways

Farm waterways play a very important role in the overall soil conservation strategy of a farm. Concentrated runoff water collected by terraces within a paddock is conveyed to a waterway and hence to a safe point of release. Because of the concentration of water flow, waterways are very vulnerable to erosion and can constitute the weakest link in a soil conservation scheme.

Where possible, waterways are located in natural depressions. However, other locations (for example parallel to a fence line) are often used in order to improve the workability of a terrace layout.

Waterways are designed to carry a certain amount of water at a safe speed. Factors such as land slope, soil type, catchment area, rainfall intensity, grass cover and rainfall duration are taken into consideration when designing a waterway. As for terraces, waterways are designed to carry the greatest runoff expected once in a 10-year period. Waterway design in Vertisols is based on a maximum permissible velocity of 1.2 m/sec and at a vegetal retardance category C.

Water flowing in a waterway reaches higher velocities than in diversion banks and terraces. It is therefore important that waterways are properly constructed and protected with a dense cover of grass before water is discharged into them. As with terraces, maintenance is required at regular intervals, especially after major events. In general, because of their high plant-available water capacity and nutrient status, Vertisols have the potential to produce good grass cover in their natural state. However, if the subsoil of Sodic Vertisols is exposed during waterway construction, the potential to establish a vigorous pasture can be markedly reduced.

Careful management is required when establishing small-seeded grass species on those Vertisols with self-mulching surfaces or coarse-surface structure. The main factors reducing seeding emergence and establishment on Vertisols are moisture stress and mechanical impedance by the dry crumbs (Leslie, 1965). A better overall establishment was often achieved when the stubble was slashed on the top of the seeds (Younger and Gilmore, 1978). The practice of growing a winter cereal crop such as wheat, oats or barley on the waterways in autumn or a millet crop in spring has been found to be very effective in protecting the waterways from high-intensity storms in spring and early summer. In addition, this crop provides a good mulch for the planting of grass species in summer (Truong, 1983).

Vertisols with highly sodic and saline subsoil at very shallow depths are not used for waterways. It is necessary to replace the topsoil when constructing waterways on shallow Vertisols or those with slight to moderately sodic or saline subsoils.

Contour cultivation

Because the infiltration of water into a Vertisol soil profile is generally slow, any practice which increases surface retention will assist infiltration. Contour cultivation achieves this on sloping lands. By ploughing on the contour, each furrow acts as a small retention dam. Studies using simulated rain (Loch and Donnollan, 1983) have shown that cultivation on the contour can increase infiltration into Vertisols by up to 13 mm of rainfall per storm event when compared to downslope cultivation.

Strip-cropping

The strategy for controlling erosion on large expanses of Vertisol flood plains of southern Queensland involves the spreading of flood runoff through predetermined patterns of land use.

In this area, with a favourable rainfall for both summer and winter crops, strip-cropping is a successful solution. This involves growing alternate strips of winter and summer crops at right angles to the direction of water flow. If strip-cropping is combined with conservation cropping techniques, there is always either crop or crop residue in every strip to help spread the water and reduce flow velocity. When possible, the strips are designed to be straight and parallel for ease of working.

Strip widths vary depending on the type of flow, presence of run-on water, surface conditions, land slope, flow obstructions, crop sequence, time of year and management (Macnish, 1980). Optimum strip width for a range of situations and management conditions were also detailed by the same author.

In the more marginal cropping areas where a rotation incorporating both summer and winter crops cannot be maintained, a rotation that includes pasture is used.

Built-up roads, railway lines, fences and irrigation works can divert and concentrate flood flows, causing serious erosion. Wherever possible, provision is made for water to drain under these structures at frequent intervals, or the features are lowered or relocated.

Division terraces

Diversion terraces are used to protect cultivation from runoff from steep timbered and rocky areas above, and to divert such water to a safe disposal area. They are also used to divert water away from unstable areas, away from buildings and into farm dams.

Apart from those situations where additional protection may be required, diversion terraces are designed to carry the greatest runoff expected once in a 10-year period. The channel of a diversion terrace is grassed and is designed for a maximum permissible velocity of 1 m/sec. Regular maintenance of diversion terraces is essential.

Conservation cropping systems

Conservation cropping systems incorporate a range of specific practices which together result in less erosion than from most conventional practices.

Typically a conservation cropping system involves management of crop and fallow to achieve maximum water infiltration into the soil, optimum use of this water by crops, and retention of crop residues on the soil surface. Antecedent moisture content is the major factor controlling infiltration. Hence any practice which creates soil water deficits at periods of high rainfall is beneficial in reducing runoff. Opportunity cropping or double-cropping, which involves growing crops whenever soil water is sufficient, is one such practice.

On the eastern Darling Downs annual winter cropping, annual summer cropping and double-cropping produced 84 mm, 54 mm and 40 mm respectively of runoff annually (Freebairn *et al.*, in press). In that environment, double-cropping is used as a conservation cropping practice.

Research into different crop and tillage options (Freebairn and Wockner, 1986) on Vertisols in southern Queensland has shown that stubble-mulch (reduced-tillage) practices produce less runoff, less soil loss and higher crop yields than practices which remove stubble (Figure 3). Zero tillage, although it achieves very low soil loss, results in more runoff and slightly lower yields than reduced-tillage practices.

One of the major findings of these studies is the benefit accrued from having soil cover. Soil erosion losses have averaged less than 5 t ha^{-1} yr^{-1} when surface cover of 20-30% was maintained over the summer rainfall period of October to March. By contrast soil erosion from bare fallows over the same period was 60 t ha^{-1} yr^{-1}.

These and other studies on the Vertisols have led to the development of specific recommendations aimed at increasing water infiltration and reducing soil erosion. These are:

- o the use of high stubble-producing crops such as wheat and barley, which with stubble retention can provide soil protection at critical periods;

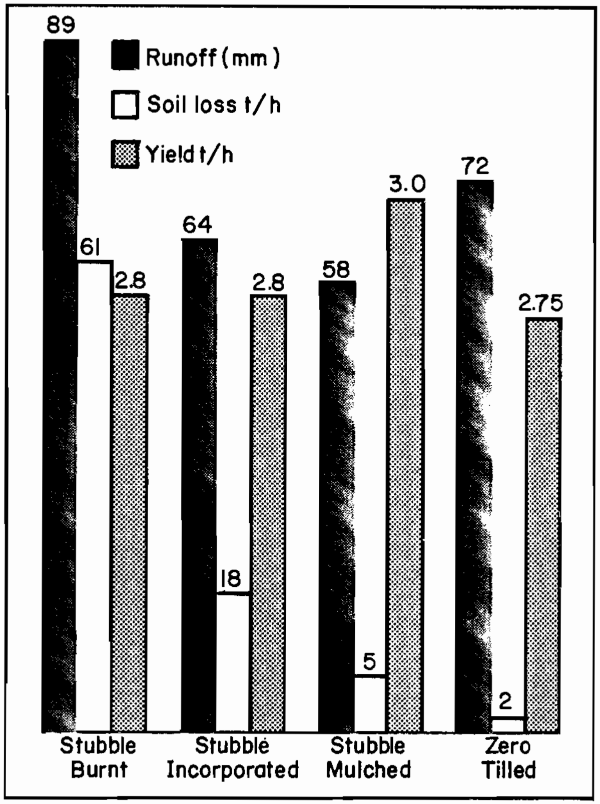

Figure 3. Average annual runoff soil loss and wheat yield recorded from 1978 to 1984 for different surface treatments on trial plots at Greenmount on the eastern Darling Downs.

- o a reduction in the number of tillage operations and the use of stubble-conserving implements, together with herbicide substitution for weed control;
- o the use of crop rotations that include only short fallow periods, especially following crops such as sunflowers which produce low levels of stubble; and
- o restricting the use of sunflower and other poor cover and residue-producing crops to land slopes of less than 1%, preferably following wheat or sorghum.

Conservative grazing practices

The major strategies for controlling erosion in grazing land involve matching stocking pressures to available feed, and the maintenance of minimum levels of pasture and litter cover.

There are few data on which to develop recommendations, but some studies in New South Wales indicate that 75% ground cover is a critical value. About 75% runoff is slight, while below 75% runoff increases rapidly.

In land which has well-developed gully erosion, grazing management is usually not sufficient to arrest or reclaim eroded areas. Under these circumstances, some disturbance and revegetation procedure is required. In the drier and less productive lands reclamation is not economical.

Generally it is uneconomic to attempt pasture renovation by cultivation and the application of fertilizer nitrogen. Pasture renovation is occasionally carried out on sown pastures in more favoured areas such as those in the cropping zone, especially when seed harvesting is practised.

Pasture spelling at critical periods to allow flowering and seeding are recommended to allow rejuvenation of pastures. Since most pasture species in Queensland flower, set seed, and germinate in response to rainfall in spring and summer, pasture spelling is best done in summer, particularly following good rainfall.

Diversion terraces are occasionally used on pastures on Vertisols, especially where runoff control is required to prevent damage to cropped areas, or where water harvesting is attempted. There are a few examples of water harvesting on Vertisols in the eastern Darling Downs. The water is used to irrigate high-value crops or pastures for milk production.

Conclusion

In Queensland, the Vertisols are the most productive soils for both cropping and grazing, but are also highly erodible. Effective soil conservation programmes to protect Vertisols from soil erosion have been developed for most of the cropping areas and some of the grazing lands of the state. Research and development is continuing in these areas for which solutions are not available. The major task of implementing these soil conservation programmes through a major extension and advisory programme is under way.

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CROPPING SYSTEMS EVALUATION

R.W. Willey*

Abstract

The paper first summarizes the different types of cropping system that are possible in Vertisol environments; it outlines how the seasonal pattern of water availability determines the potential cropping period, which in turn determines the cropping system options that can be considered.

The paper then considers the evaluation of different cropping systems at a given location. An assessment in biological (or agronomic) terms should aim to examine how fully and how efficiently different cropping systems utilize environmental resources; the value of measuring water use and light interception (or canopy cover), where these measurements are possible, is stressed. The problems of comparing the biological productivity of different crops are discussed.

It is suggested that economic evaluation at a given location should be considered in terms of input costs as well as net returns so that for any given system the level of inputs required (and any associated problems and constraints) is seen as an integral part of that system. Ideally, evaluation will be on the basis of the most limiting resource. All experiments should at least assess the cost of the inputs of seeds, fertilizers and chemicals; and where the scale of the experiment allows, the inputs of labour and animal power (and if possible their distribution throughout the year) should also be examined. The importance of on-farm studies involving the farmer is emphasized, since these studies allow management constraints to be examined.

The evaluation of different cropping systems experiments across a network is also considered. Although informal comparisons may obviously indicate which systems appear most suitable in any given environment, it is suggested that it could also be useful to examine biological efficiencies in terms of crop output per unit of environmental

*University of East Anglia, Norwich, Norfolk, England.

resource, particularly available water. Methods of comparing the stability of different cropping systems are discussed, and the contribution of network data to stability analysis is stressed.

Introduction

This paper deals only with annual crops and the term 'cropping system' refers to any combination of annual crops that is grown on the same area of ground in a given year. The different types of cropping system that can be possible in any given environment are largely determined by the length of the potential cropping period, which in semi-arid regions is usually synonymous with the period for which there is adequate moisture available for crop growth. Under rainfed conditions this moisture availability is primarily dependent on the amount and distribution of rainfall, but is of course modified by the amount of rainfall that can be stored in the soil profile to be utilized during dry periods. Vertisols have a very large moisture capacity, so in addition to whatever cropping may be possible during the rainy season itself, the residual moisture in these soils can provide a long period of cropping after the end of the rains. And of course the large moisture storage capacity of the Vertisols provides an excellent buffer against within-season droughts during periods of low or erratic rainfall.

Cropping Systems for Vertisols

Cropping systems for Vertisols have been discussed in detail elsewhere (Willey *et al.*, 1985) but the possible types are summarized here by considering environments in which the combination of rainy-season duration and residual soil moisture provides potential cropping periods of different lengths. For example, a long potential cropping period of 6-7 months is typical of the higher-rainfall areas of the Indian semi-arid Vertisols. In these areas the rainy season itself is about 100 days and a full soil profile at the end of the rainy season will provide sufficient moisture for a postrainy season of a further 100 days (Virmani *et al.*, 1978). Traditional cropping systems seldom utilize the whole of this 6-7-month period. Because of the difficulties in managing the wet and sticky Vertisols during the rainy season, crops are sown towards the end of, or even after, the rains, and are thus raised mainly, or wholly, on residual soil moisture. However, ICRISAT scientists have described a land management system that allows cropping during the rains, and certainly for illustrative purposes it can be assumed that these areas can potentially support cropping for 6-7 months.

Given this long cropping period, there is scope for several different types of cropping system. These can be summarized:

Sequential cropping

This is when two consecutive crops are grown, the second being sown after the harvest of the first. In the Indian semi-arid areas referred to above, the first crop could be a rainy-season crop of maize, sorghum, soya, mung, blackgram or sesame; while the second would be a cool-season crop of wheat, sorghum, chickpea, safflower or lentil. Such a sequential system is very productive, in effect producing two full crops in one year. However, it is managerially very demanding because of the need for a rapid turnaround between crops.

Relay cropping

In this system a second crop is sown shortly before the harvest of the first. Theoretically this is a very attractive alternative to sequential cropping because it still produces two full crops; but the total cropping period is usually 2-3 weeks shorter (reducing the probability of end-of-season drought), and sowing of the second crop is carried out before the labour bottleneck of harvesting and threshing the first crop. However, the system is not always practicable where there are difficulties in sowing into the standing first crop (e.g. where sowing is normally done by animal-drawn implements).

Ratoon cropping

In this sytem the stubble of a first crop is allowed to regrow to produce a second, or ratoon, crop. The attraction of the system is the low-input requirement of the ratoon crop. But only a few of the annuals suitable for Vertisol systems will ratoon (sorghum, pearl millet and pigeonpea) and, particularly with the cereals, the ratoon yield is low and unreliable.

Intercropping

This system is defined as the growing of two or more crops on the same area of land at the same time. The advantage of the system is that there are a number of possible interactions between crops that can increase the overall crop productivity; the commonest of these is the complementary use of resources by different component crops. With a potentially long growing period there is a choice of two types of intercropping. In one type, a "temporal" system, a rapid-growing early-maturing crop acts as a first crop, ensuring good use of early resources, and the late-maturing crop acts as a second crop, ensuring good use of later resources, especially residual soil moisture. At ICRISAT Center in India, such a temporal system used pigeonpea as the later-maturing crop, and either maize, sorghum, or one of a range of legumes as the earlier-maturing crop. Compared with a sequential system, the first crop of this pigeonpea intercropping system usually suffers a small loss in yield, and the pigeonpea then produces a little less than could be achieved by a sole crop of the best postrainy-season pulse, which would be chickpea. But despite a lower productivity than a good sequential system, this temporal intercropping system has the great practical advantage of having an already-established second crop after harvest of the first.

The other type of intercropping is a "spatial" system where crops of reasonably similar maturity are grown together. If the growing season is long enough for two consecutive crops, spatial intercropping systems can obviously be practiced during the first or second crop periods, or both. Many such intercropping systems have been examined (on many soil types) and yield increases of 20-25% have commonly been achieved compared with growing sole crops (e.g. Reddy and Willey, 1981).

With a shorter potential cropping period, the choice of cropping system is more limited. With only five months available, sequential or relay systems are not usually possible unless one or both of the crops are very short-season and therefore low-yielding. Similarly, ratoon systems would only be possible if one of the crops was cut early for fodder. The simplest option is therefore to grow a single assured crop. However, a single-crop system will often leave some of the moisture resources unutilized. For example, improved cereal varieties in the 90-100 day maturity range will not use end-of-season residual moisture; or some of the later-maturing crops that will occupy the full five-month period (e.g. pigeonpea and cotton) are very slow to establish and do not make efficient use of early moisture. An ideal system for this five-month growing period is in fact a temporal intercropping system as described above, where the later-maturity crop matches the full-season crop. For example, over a two-year period on a shallow black soil providing about five months cropping at ICRISAT Center in India, a sorghum/pigeonpea system averaged 78% of a full sorghum yield plus 82% of a full pigeonpea yield, and was therefore much more productive than growing only one of these crops (ICRISAT, 1983).

With a very short potential cropping period of 3-4 months (either because of a very short rainy season or because crops are being grown only on residual moisture), there is time for only one full-season crop. But systems do not have to be limited to growing only one crop. As indicated above, spatial intercropping systems are possible to increase the cropping intensity and to raise productivity above that of a single crop. These comments also apply to biomodal rainfall situations where there are two short and separate growing periods. In some biomodal areas, however, long-season crops may span both seasons. With cotton, for example, one of the seasons may be used simply to establish the crop, which then matures after the next season. Alternatively, a common system in eastern Africa is the temporal intercropping of maize/pigeonpea, the maize maturing after the first rains and the pigeonpea after the second. This last system is an excellent one to ensure some use of a less-assured second rainy season; it is commonly grown on Alfisols but it illustrates a type of system that may be considered on Vertisols.

Evaluation of Different Systems

This section discusses the procedures that are necessary to evaluate different systems that are being examined in field trials. It must be emphasized at the outset that there is no simple, single measure, and therefore different procedures have to be carried out to evaluate different aspects. It is usually desirable to evaluate systems both in biological (or agronomic) and in economic terms. The objective of the biological evaluation is to determine if systems are using the available environmental resources fully and efficiently. This information is important for scientists because it can indicate how systems need to be modified to improve resources use and therefore productivity. Economic evaluation is here taken to be assessments that cover both monetary and management aspects; its ultimate objective is to assess systems in practical terms that are meaningful to a farmer.

It must be emphasized that cropping systems evaluation is seldom aimed at identifying a single "best" system; more usually the objective is to describe the characteristics of a range of possible options from which the farmer can choose as he feels appropriate.

Evaluation at a given location

One of the simplest and most useful assessments for a biological evaluation in semi-arid areas is to consider how fully systems are utilizing the whole length of the potential cropping period. A classic example of systems occupying only part of the potential cropping period, and therefore underutilizing resources (ignoring for the moment any practical justification for doing so) is the traditional pattern of rainy-season fallowing on the higher-rainfall Vertisol areas (see Table 1); even where crops such as chillis or cotton are sown in the later part of the rains, there is still poor utilization of early rainfall. A further example, as emphasized earlier, is where a single-crop system occupies only the first 100 days or so of a 150-day potential cropping period, and this leaves much of the residual soil moisture unutilized. A less extreme example is the mung and sorghum system in Table 1 which has a relatively short cropping period because of the very early maturing mung. This assessment of biological efficiency could easily be quantified (e.g. actual number of days, or proportion of potential cropping period unutilized), but a formal assessment is probably unnecessary. It is probably sufficient for scientists to recognize where inefficiency occurs and to appreciate that there may be scope for improvement. To make even this informal assessment, however, it is essential to record sowing and maturity dates of all crops in cropping systems experiments.

In some instances scientists may be able to examine resource use in detail (e.g. the pattern of moisture use throughout the season). Where this is possible, very valuable information on the efficiency of resource use can be obtained, and possible areas of improvement may be identified. Even where detailed investigation is not possible, some simple measurements may be very useful. For example, a simple gravimetric assessment at final harvest of each system can indicate how efficiently residual soil moisture has been utilized. A further very useful assessment is the degree of light interception; this is important not just because all resource use must eventually be reflected in the conversion of light energy, but because light interception can be a very good general indicator of crop growth and efficiency. Although detailed investigation of light interception requires special instruments, simple measurements of canopy cover (e.g. with a grid system) can be very valuable; for instance, a period of poor canopy cover during a cropping period

Table 1. Illustration of evaluation parameters for some example cropping systems grown in operational-scale plots at ICRISAT Center (means of 4 years).

	Traditional[a]	Sequentital	Intercrop	Sequential	Sequential
1st crop	Fallow	Maize	Sorghum/	Mung	Sorghum
2nd crop	Sorghum	Chickpea	Pigeonpea	Sorghum	Safflower
Cropping period (days)	120	190	180	150	190
Yields (kg/ha) 1st	–	2440	2876	653	3337
Yields (kg/ha) 2nd	(1000)[c]	1305	936	2070	785
Nutrient value/ha					
M. cals	3049	10120	11032	7956	10765
kg protein	104	494	508	371	453
kg oil	19	157	71	48	271
Biomass (kg/ha)[c]	3300	9363	9510	6776	9023
Energy (M.cals/ha)					
Seed yields	4452	17250	17351	12407	19464
Biomass	14112	41094	41567	29821	44287
M. cals/ha/mm rainfall[b]					
Seed yields	6.85	26.54	26.69	19.09	29.94
Biomass	21.71	63.22	63.95	45.88	68.13
Gross returns (Rs/ha)	1200	7490	6727	4770	6900
Costs (Rs/ha)	600	2200	1600	1750	2450
Net returns (Rs/ha)	600	5290	5127	3020	4450
Rate of return (%)	100	240	320	173	182

a = Traditional system added for illustrative purposes. Costs from ICRISAT watershed.
b = Rainfall during potential cropping period estimated at 650 mm
c = Estimated

will usually indicate that neither light, water nor nutrients are being fully utilized.

The ultimate measure of biological efficiency is of course crop productivity. And when evaluating at a given location, where environmental resources may be regarded as constant, a very simple way of assessing the relative efficiencies of different systems would appear to be to compare their levels of productivity. However, where different crops are involved such comparisons are extraordinarily difficult because the products of different crops are seldom equatable. Broad, simple comparisons are possible and may be very informative. For example, the mung+sorghum, maize+chickpea, and sorghum/pigeonpea systems in Table 1 can all be broadly compared in terms of how much cereal and how much legume each produces. But direct comparison of any of these systems with the sorghum+safflower system would involve trying to equate an oilseed with a legume; in simple yield terms this is not very meaningful. For subsistence situations it can be useful to compare nutrient values (see Table 1). But whilst this helps to indicate what balance of crops and cropping systems might be required in the farmer's overall farming system, it still does not allow direct comparison between systems that provide different dietary requirements (e.g. protein or oil); and it does not resolve how to compare food and nonfood crops. Biomass productivity may also have a place in biological evaluation by indicating whether a low productivity of economic yield is due to poor overall growth or poor partitioning. For example, Table 1 shows that the low economic yield of the mung and sorghum system was at least in part attributable to low biomass production, which no doubt was largely a function of the shorter cropping period indicated earlier.

In truly biological terms, different crops should probably be equated in energy values – that is, by the net amount of solar energy that they have accumulated during growth. Thus Table 1 shows that the rather lower biomass and economic yields of sorghum+safflower compared with, say, maize+chickpea occurred because of the high energy needed for oil synthesis, and not because of poorer biological efficiency. But this energy aspect will be returned to later when considering evaluation across a network.

Turning now to an economic evaluation, the essential feature of this assessment is that crop productivity is expressed in monetary values. This approach does not have to assume that all crops are cash crops, though it does assume that some market value can be assigned to each crop. Apart from the obvious financial aspects, the great merit of this assessment for cropping systems work is that money provides a common unit for equating the yields of different crops. Thus in Table 1 the productivity of all systems can be easily compared in terms of a gross return; it can be seen that maize+chickpea has the highest value of production, followed by sorghum+safflower, then sorghum/pigeonpea. For these example systems the gross returns are based only on the seed yields. It must be explained, however, that where the straw or stalks have a value for fuel, fodder, etc., this value should also be included to provide the fuel returns for any system.

But obviously a more critical economic assessment of different cropping systems is their net returns. However, particularly for resource-poor farmers, net returns must be considered in close association with the input costs required to achieve those returns. Thus in Table 1 sorghum/pigeonpea has slightly poorer net returns than maize+chickpea, but because of lower input costs (mainly because of not having to establish a second crop) and a greater overall rate of return to these inputs, this sorghum/pigeonpea system could be the more attractive proposition. In contrast, despite its high gross returns, sorghum+safflower has high costs (mainly because both crops have a high fertilizer requirement) and therefore a lower net return and a lower rate of return than the two previous systems; it therefore appears a poorer proposition. In comparison with this sorghum+safflower system, the mung+sorghum has lower net returns but lower costs and a similar rate of return, so it is probably more attractive. These financial details also allow assessment of the costs and returns of changing from one system to another (Ryan and Sarin, 1981). Thus if a farmer were to upgrade his traditional system to, say mung+ sorghum the additional investment would be Rs 1150/ha with an increased net return of Rs 2520/ha, representing a rate of return on additional investment of 210%.

Quite often, however, these overall financial assessments tell only part of the story, and systems may need to be evaluated in terms of their returns to a specific input such as labour, or even animal power; assessing returns to these two particular inputs can be especially important when there are critical periods of peak demand. These approaches underline the importance of making a detailed assessment of inputs in cropping systems experiments. Even in small-plot experiments, the monetary inputs such as seeds, fertilizers and sprays can easily be costed. In fact these factors can often be variable inputs; for example, plots may be easily split for different fertilizer levels, an approach which allows specific assessments of returns to fertilizer.

Asssessing labour inputs is more difficult in small-plot experiments, and in early-stage cropping system studies this assessment is often ignored; but even general observations such as numbers of weedings and timings of different operations can be extremely useful. Large plots provide the opportunity for detailed assessments of labour demand and its distribution throughout the year. They also allow the use of field-scale equipment such as animal-drawn seeders or cultivators, so possible operational problems of different systems can be observed. There is thus a strong argument for using large plots in later-stage studies.

Other economic aspects, such as general management problems associated with a particular system, may only be assessable in on-farm studies in which the farmer himself is fully involved. For instance, in ICRISAT's early on-farm Vertisol studies, the two most attractive cropping systems in purely financial terms appeared to be the maize+chickpea and the sorghum/pigeonpea. However, the farmer greatly preferred the sorghum/pigeonpea sytem because this did not involve sowing a second crop at a time when there was a severe labour peak for harvesting and threshing the first crop; previous to these on-farm studies, this crucial labour aspect had not been fully appreciated by scientists. In the same studies, farmers also regarded mung+sorghum as a worthwhile option, despite the fact that scientists saw it as giving a poor rate of return. The farmers' assessment was clearly based on the fact that this system is relatively undemanding for a two-crop system, with sufficient turnaround time between mung harvest and sorghum sowing.

A final point on the general aspects of evaluation is related to the argument for providing a range of options. One reason for options is that different farmers may have different requirements and preferences. Another reason is that an individual farmer will commonly have to grow more than one system, e.g. to rotate crops, to reduce risks, to spread labour, etc. To return to the ICRISAT on-farm example, the sorghum/pigeonpea system cannot be grown continuously because of soil-borne diseases; thus a further factor in the farmers' liking for mung and sorghum was probably that it provided an alternate-year rotational system with the much-preferred sorghum/pigeonpea. Clearly, therefore, the evaluation process should try to avoid assessing individual systems in isolation but should try to identify what niches they may occupy in the farmer's overall system.

Evaluation across a network

Formal evaluation of cropping systems across a network probably presents even more difficulties than evaluation at a given location because the range of different crops and systems is likely to be even greater. But informal evaluation can still be extremely valuable in trying to observe any consistent patterns of performance, e.g. whether certain systems give consistently high economic performance, whether others give consistent management problems, etc. Network information also provides the opportunity of observing how environmental differences determine which cropping systems are most appropriate. Some of the problems of having to compare very different crops can be reduced by focusing on type of system rather than on individual crop combinations. Thus the general problems or advantages of, say, sequential vs. relay systems, or sequential vs. intercropping systems, can usefully be compared. With this kind of comparison in mind, when selecting treatments for study it can be advantageous to ensure that specific types of system are repeated across the network.

A rather different objective of comparing across a network could be to assess the efficiency with which environmental resources are being used at the different locations. If a single-crop system of the same crop occurred at different locations, this assessment could easily be done by comparing yields. But for systems involving different crops, there is again a problem in equating yields. This may be a situation where total crop energy can serve as a general measure of systems productivity. Table 1 shows energy values for the systems grown at the ICRISAT Center, as discussed earlier. Table 2 shows energy values for some systems grown in a much higher rainfall location in Madhya Pradesh. The latter systems involve some different crops, and range across cereal+cereal, cereal+legume and legume+legume combinations, but these were the most productive systems at the location. It can be seen that energy production was much greater at this Madhya Pradesh location. However, if the efficiency of production is examined in terms of energy produced per unit of rainfall received during the cropping period, the Madhya Pradesh systems are very similar to the best ICRISAT Center systems. (The lower values for soya+chickpea at Madhya Pradesh could be partly due to the energy cost of nitrogen fixation.)

This analysis is a very tentative one (and aspects of the calculation involved estimation, as indicated in the tables); but to take these locations as an example, it suggests that rainfall was a major yield-determining factor and each location used it with similar efficiency. On the other hand, a lower efficiency at a given site could be due to a number of factors: loss of rainfall due to runoff, etc.; systems not occupying the potential cropping period; a soil fertility limitation; or poor management factors, such as inadequate weeding. While the efficiency analysis would not indicate which of these factors was most critical, it would pinpoint the need for detailed consideration of a particular location. (Ideally, efficiency of rainfall use should be considered in conjunction with the efficiency of light-energy conversion because light energy could vary considerably at different locations; but this requires data on incident light energy which are not normally available.)

One further evaluation that can be carried out with network data is the analysis of

Table 2. Yields and energy values for four example cropping systems grown in Madhya Pradesh, India, 1982-3.

	Sequential	Intercrop	Sequential	Sequential
1st crop	Maize	Maize	Maize	Soya
2nd crop	Chickpea	Pigeonpea	Wheat	Chickpea
Yields (kg/ha) 1st	4598	4591	4547	1867
Yields (kg/ha) 2nd	2092	1368	1796	1914
Biomass (kg/ha)[a]	16742	16100	15858	12603
Energy (M.cals/ha)				
Yields	30712	27171	28258	21137
Biomass	73260	70090	68219	59320
M.cals/ha/mm rainfall[b]				
Yields	29.25	25.88	26.91	20.13
Biomass	69.77	66.75	64.97	56.50

a = estimated
b = estimated at 1050 mm during potential cropping period

stability. It is obviously very desirable to have stability information on any individual system under test, and it may also be useful to make comparisons between different types of system, e.g. intercropping vs. traditional systems, etc. The simplest and probably the most useful measure of stability is the coefficient of variation. Because it is a relative measure, the coefficient of variation allows direct comparison between individual crops whatever their absolute level and type of yield. And even in multiple-crop systems, examining individual crops in this way can sometimes be useful, for example to determine whether second crops are more risk-prone than first crops in sequential systems. But to compare the overall stability of systems in which two or more different crops are involved, which would be the main objective in a cropping systems network, there is yet again the problem of deciding on the common units with which to combine yields. Monetary values probably offer the best solution. And examining gross returns is probably better than net returns because a fixed price for any given crop can be adopted across all locations; this avoids confounding genuine crop-stability aspects with locational price differences. A common price structure is more difficult for costs, but stability of net returns might still be informative. A stability analysis of monetary values, along roughly the above lines, was carried out by Rao and Willey (1980) to compare intercropping systems and sole-cropping systems. These workers expressed stability in terms of the probability of failure, which may have more practical appeal than a coefficient of variation.

An alternative form of stability analysis is to assign an environmental index to each location and to fit a regression of productivity against this index. Breeders have used this approach to examine different genotypes, and the environmental index at a given location is taken as the mean yield of all genotypes (Finlay and Wilkinson, 1963). Rao and Willey (1981) found there could be problems using this technique with systems data if different crops responded differentially to environmental changes, because the environmental index was then less meaningful. However, if locations can be characterized in detail, it might be possible to set up an independent index on a factor such as water availability. This approach would have the advantage that any system could be examined across whichever locations it occurred at. To use the environmental index technique suggested by Finlay and Wilkinson, and ideally to use coefficients of variation, any of the systems being compared would have to be present at all of the locations used in the analysis. This is a further argument for standardizing at least some of the systems across the network. And clearly if stability analyses are intended, there is a particularly urgent need to consider treatment selection on a network rather than an individual-location basis.

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STRATEGIES FOR MAINTENANCE OF SOIL FERTILITY

J.R. Burford*

Abstract

The development of strategies for the maintenance of soil fertility should consider all the major disciplinary components – physical, chemical, and biological – rather than just the narrower chemical or nutrient base often used in the past. The underlying research should include both short- and long-term experiments and investigate interactions between the different components. Because such studies require considerable resources, particular attention needs to be paid to the guidelines proposed by IBSRAM for site selection and characterization, and for the longer-term studies, meticulous attention to detail may be required for some of the disciplinary components.

Results of some recent research on nutrients are used to provide an example of step-wise approaches in one disciplinary area.

Introduction

The maintenance of soil fertility is perhaps one of the most important aspects of the development of systems to increase agricultural productivity, yet commonly it receives inadequate emphasis. When a new system is being developed, the immediate increases in productivity are usually of greatest interest. Any queries on the sustainability of the increased yields usually tend to focus on the reliability of yield increase in the next few years. This is a logical approach in the evaluation of the first stage of success, but we should ensure that the next stage – assessing the sustainability of the system in the long term – is also initiated.

* International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Patancheru P.O., Andhra Pradesh 502 324, India.

Studies on sustainability need to be commenced early in the life of a system if most of the target farmers are subsistence agriculturalists. A substantial decline in productivity could have serious effects, especially if it occurs some years after the introduction of a new system. By then, these farmers will have become accustomed to higher yields, and thus have good reason to expect them to be sustainable.

A decline in productivity may also be masked initially by the normal season-to-season fluctuations in yield. It may be only after yields are low in several successive years, and the cause is not known, that farmers will realize that the fertility of their soil has declined. Depending upon the cause of the decline and the development of a solution, productivity may have declined much further before remedial measures have been developed. Then the farmer's situation could be bleak.

The development of severe problems can be avoided by careful research approaches. In fact, as a generalization we can state that the new systems developments that encounter problems earliest are those that have been based on the least thorough research approaches.

Strategies for fertility maintenance are needed for reasons other than preventing the catastrophic type of decline in soil fertility. They are also needed to provide guidelines for the most efficient use of resources. The simplest example involves the changes that occur with time in the amelioration of severe nitrogen and phosphorus deficiencies. The need for phosphatic fertilizer usually decreases with time due to the accumulation of phosphorus in the soil in slowly available forms. For nitrogen, the use of fertilizer is a convenient short-term means of correcting a deficiency, but inputs by legumes are usually a much less costly input. At some stages, even if not at the introduction of an improved system, policies or economic situations will dictate an evaluation of the cost-effectiveness of the inputs. To satisfy such a request and thus facilitate long-term planning, we need a sound knowledge of the soil and agricultural production systems. This will involve a strategy for the long-term maintenance of soil fertility. In this way, planning for the best use of resources will be possible.

A number of the approaches that IBSRAM is proposing in fact include provision for the early detection of declines in fertility. Timely studies on the maintenance of fertility, appropriate to the indicated needs of each major target soil, could pay handsome dividends by sustaining the productivity under recently introduced systems.

Soil Fertility

Soil fertility has been interpreted in many different ways. In this paper, the term includes soil chemical, physical, and biological components, as propounded by Hallsworth (1969) and others, rather than being used in its much narrower sense to describe just the chemical or even nutrient status of the soil. The use of such a broad meaning is justified by the fact that often we do not know the exact cause of low or declining fertility, or whether one or several different factors are involved.

An excellent example of the complexity of factors involved in a general fertility approach, and additionally a reason why we should not bias studies to chemical factors, is the development of intensive cropping systems to replace shifting cultivation on lighter-textured soils. Organic matter declines under continuous cropping, and the use of inorganic fertilizers can compensate for the diminished supply of nutrients from this natural source. But nutrient inputs cannot compensate for the effects of the loss of soil structure caused directly by cultivation.

In the next few sections, some of the known components of fertility will be discussed, and the identified problems in a few selected countries will be indicated.

Fertility components

Chemical fators

The nutrient status of Vertisols varies considerably across the SAT. In general, nitrogen and phosphorus are the two most important nutrients. In the areas of high and assured rainfall in India and Ethiopia, nitrogen deficiency can be acute, and it appears to be universal for these areas in India. Severe phosphorus deficiencies have also been recorded in these countries and in Syria. Sudan has reported deficiencies of both nutrients, but much less pronounced than in India or Ethiopia. Proposed cooperators in Zimbabwe, Kenya, and Tanzania indicated that there appeared to be little evidence of severe nutrient deficiencies on their Vertisols, though information was still being collected from their regional research centres. In Australia, the Black Earths have a high phosphorus content relative to other Australian soils (Wild, 1958). Some Vertisols of the Darling Downs in Queensland, one of the longest cultivated areas of Vertisols in the Australian sub-tropics, did not develop phosphorus deficiency until after many years of cropping, though some variation is indicated by the discovery of other nearby Vertisols with a lower phosphorus status.

These differences in the nitrogen and phosphorus status of Vertisols across the SAT would seem to reflect differences both in the soil's parent material and previous intensities of cropping. Traditional systems in some areas of India and Ethiopia would have been nutrient-depleting because they involved continuous cropping.

Of the micronutrients, zinc is the only one that appears to be of general significance. Deficiencies are common in India and Australia, and have been reported in the Sudan.

Organic-matter and nitrogen levels appear to reflect the intensity of cropping. Leguminous trees and shrubs are a common component of many Vertisol tracts prior to cultivation and cropping; it can be assumed that these provide a steady input of nitrogen to the soil. Total nitrogen contents of such soils not uncommonly exceed 0.1%, whereas old cultivated Vertisols in India may have total nitrogen contents of about 0.03-0.04%.

Many Vertisols appear to be neutral to moderately alkaline in reaction, although some are acidic, e.g. in the Ethiopian highlands and Queensland. Alkalinity is a factor in the occurrence of zinc deficiency.

Calcium status appears to be inadequate in at least two different situations: in Vertisols with extremely acid subsoils in Queensland, and in Vertisols developed on ultramafic parent material of the Great Dyke in Zimbabwe (Kanyanda, 1975).

Exchangeable sodium would be expected to have very marked effects on the physical characteristics of Vertisols because of their high clay content and low permeability, even when exchangeable sodium levels are low. A number of irrigation schemes are planned for extensive areas of Vertisols.

Physical factors

The structure of Vertisols, both in the surface soil and at depth, is one of its most interesting features. Soils that "self-mulch", i.e. form a surface layer of small granules when dry, are much easier to manage than those that have a massive structure in the surface soil. In Zimbabwe, the latter type have a lower water-holding capacity and infiltration capacity than those with self-mulching surface soils (Hussein, 1984); additionally, they are particularly compact, and thus are extremely difficult to cultivate even with heavy tractors and equipment, and some are even particularly abrasive on equipment (Marshall, pers. comm.). The stability of these properties will be of particular interest.

The low permeability of Vertisols can cause waterlogging in areas with high and assured rainfall, with implications for aeration, trafficability, nutrient availability, germination of seeds, and the biological factors promoted by poor aeration.

Erosion may not present serious problems for crop growth in the short term. On those extensive areas of very flat Vertisols, it also is not a problem; on these, heavy rain often cannot drain away quickly, and flooding appears to be the more important long-term problem. However, in some areas, the combination of slope and rainfall variability can create a high erosion risk, especially if cropping practices leave the soil unprotected at times of high probability of heavy rain; for these soils, erosion presents a very serious long-term threat to the maintenance of fertility.

Biological factors

Despite an abundance of qualititative evidence on various biological factors, these are generally rather difficult to quantify.

Weeds cause very substantial yield losses, and their control presents difficulties in both the short and the long term, although the type of difficulty differs. The immediate problems mainly relate to the farmer's management, i.e. how to control annual weeds within a very short but critical time in the development of a crop (shortly after emergence), with limited facilities for cultivation and purchase of herbicides. Perennial weeds such as *Striga* and *Cynodon* appear to become increasingly serious after the introduction of more intensive systems, especially as control is difficult without the use of herbicides.

Allelopathy has been observed with some crop sequences; crops yield less after sorghum than after maize (Reddy and Willey, pers. comm.). Without doubt there are many other effects, but this topic has received little serious attention. A "long fallow" disorder in the Darling Downs of Queensland appears to be caused mainly by diminution of mycorrhiza populations and possibly an increase in nematode activity by the end of the (bare) fallow (J.P. Thompson, pers. comm.).

"Large" soil fauna (rats, ants, termites, etc.) can cause very substantial yield reductions, and are one of the major hazards in introducing "dry-seeding" techniques. Changes in surface structure (e.g. major cracks) or drainage could markedly affect faunal habitats.

Earthworm activity appears to have been little studied, but it is known to influence aeration, and populations are particularly affected by cultivation.

Any change in drainage may substantially alter some microbiological activities. In particular, anaerobic activity will increase, with the possibility of the evolution of some phytotoxic agents (e.g. ethylene) and the certainty that denitrification will be promoted. Pathogens may be more active (e.g. wilt on chickpea).

Identified country problems

India

ICRISAT's development of an improved system based on double-cropping for an assured-rainfall target area contains a number of long-term fertility aspects. In adding a crop during the rainy season, this system reduces erosion markedly due to the protection of the soil by vegetation; additionally, the provision of the broadbed-and-furrow (BBF) land configuration provides a drainage system and at the same time minimizes erosion. Thus, the long-term erosion hazard is minimal, and in fact it is much lower than under the farmer's original system. Nutrient management was designed originally to be mainly by fertilizer inputs. The system does not aim at a rigid sequence of crops; instead a wide range of crop combinations and crop sequences have been tested to provide as many options as possible. A common two-year sequence is a sorghum/pigeonpea intercrop alternating with a maize/chickpea sequential crop: this has been found to be quite a promising simple rotation with a good legume component.

After testing the robustness of this system for almost ten years, only a few long-term fertility problems are emerging. A serious one is the increasing extent of infestations of *Cynodon dactylis,* which is difficult to control without utilizing herbicides. A longer-term strategic problem is the management of soil nitrogen; rotation experiments have been established to study long-term fertility maintenance problems. Strategic research on phosphorus is indicated, because the long-term maintenance needs of Vertisols appear to have received little attention.

Ethiopia

The Ministry of Agriculture and ILCA are currently testing solutions to the identified problems on key Vertisols with a long cultivation history in the highlands of Ethiopia. Excessive soil moisture appears to be a greater problem than drought. The main fertility-related components are: nutrient inputs, for which legumes will be used as a nitrogen source, and phosphorus, added primarily for the legumes; and drainage, using a narrow bed and furrow (NBF) system. Planting patterns for *Leucaena,* and the NBF system, will minimize erosion. It seems reasonable to speculate that the long-term fertility problems will involve strategies for phosphorus and nitrogen inputs, erosion control, and the consequences of waterlogging.

Sudan

Many different agencies have conducted an array of research efforts to improve dryland agriculture on Vertisols in the Sudan. Agronomic problems have been identified for agriculture under a rainfall which ranges from low to moderately assured. But attempts at solutions have met with only modest success: general yield levels have not been high, and responses to inputs have been very variable (Riley, 1986); a new sorghum cultivar (Hageen Dura I) is showing much promise, and may allow a better agronomic evaluation of the effectiveness of improved management practices. Immediate agronomic problems are: difficulties in soil preparation, sowing at the optimum time (especially with high variability of rainfall early in the season), possibly nutrients, and very severe weed infestations. Weed problems involve both annuals (with the severity aggravated by labour shortages) and some pernicious perennials (especially *Striga*); the latter appears to be a long-term problem. The presence of a so far unidentified factor cannot be excluded, because of the extremely large variability in agronomic results obtained previously, even in areas with relatively assured rainfall.

Identifying fertility research needs

The above brief country scenarios indicate some of the variation that exists across the major SAT Vertisol areas in system development, the identification of fertility problems, and the research needed for the development of long-term fertility strategies. In India and Ethiopia, improved systems are being developed on land that has long been cultivated by small farmers, and which consequently has a low fertility status. In Sudan, where population densities are much lower, land use on rainfed Vertisols involves a wide range of cropping intensities. Some land is used mainly for extensive grazing, and similar land may be extensively cropped with various cropping intensities; at the other extreme, land under shifting cultivation is under increasing cropping pressure and some is approaching continuous cultivation.

In these three selected major target areas of Vertisols, the long-term fertility problems involve a combination of biological, chemical, and physical factors. Clearly, the setting of priorities between the disciplinary areas will be important. Priorities within a disciplinary area will also be important, so the long-term problems are being identified as early as possible during system development. Consideration of the research strategies required for studies on nutrient management provides an example of the stepwise approach required in just one disciplinary area.

Nutrient Management

Strategy

The development of a good strategy for nutrient management involves at least four separate stepwise investigations: diagnosis, annual agronomic experiments, long-term experiments, and modelling. All stages will be required if insufficient background information is available for a chosen area.

Diagnosis of probable nutrient requirements involves an initial soil chemical characterization, preferably supplemented by additional information from plant analysis (of crops from the area) and pot or field experiments. Soil analysis gives only a general guide to nutrient status. Plant analysis appears to be more accurate for some nutrients, especially phosphorus and zinc. Simple omission-type pot or field experiments are an efficient means of providing an initial indication of nutrient needs.

Annual experiments are needed for two or three years in a new benchmark location for two main reasons: first, to provide a check on diagnoses (as these are not infallible); second, to provide preliminary information on the rate of nutrients needed (as these are usually not predicted from diagnostic tests) and on the consistency of responses between years.

Long-term experiments are required for a number of reasons. They provide an excellent basis for determining the variability in responses between seasons. They also provide the means for determining the residual effects of nutrient inputs and thus assessing the long-term effects of proposed nutrient management strategies on soil nutrient status; they are essential for determining optimum inputs of fertilizer phosphorus and legume nitrogen.

Modelling can provide a particularly useful basis for predicting nutrient inputs needed for maintaining soil nutrient status at benchmark locations, and also for predicting nutrient needs throughout an area from results at just a few benchmark locations. However, the development of useful models requires a considerable amount of input information, of the type that is provided by annual and long-term experiments, in conjunction with appropriate environmental characterizations.

The use of the above stepwise approach can be illustrated by the results from research on nutrients as a component of the double-cropping system developed at ICRISAT for Vertisols under assured rainfall in India (Kanwar and Virmani, 1987).

Example: Vertisols under assured rainfall in India

The need for nutrient inputs for cereal crops in the target area for ICRISAT's improved systems had been clearly indicated by the results of many empirical field experiments conducted by national programmes, by preliminary diagnostic experiments conducted by ICRISAT, and by further results from operational-scale research (Kanwar and Virmani, 1987). But in on-farm testing, farmers were slow to accept the first two components of the system, improved sorghum cultivar and nutrients (nitrogen and phosphorus). The reasons were not fully understood, and some did not involve fertility problems; but there was clearly a need to reassess diagnostic procedures and to determine the likely reliability of responses to nutrient inputs.

Diagnosis

Preliminary research at ICRISAT Center has shown the need for an appraisal of the effectiveness of standard soil test procedures for Vertisols. The standard critical limits used in India for the Olsen bicarbonate test for available soil phosphorus are 5 and 10 ppm, to indicate possible and probable adequacy of soil phosphorus supplies. Our preliminary results indicate that for rainy-season sorghum on Vertisols, these critical levels are only about 2.0-2.5 ppm (ICRISAT, 1985).

Analysis of young leaves of crops has been quite effective as a diagnostic technique for some nutrients. For phosphorus and zinc, concentrations of about 0.20% and 20 ppm (on a dry weight basis) in sorghum and maize leaves have been quite a reliable index of adequate supplies of these nutrients. For micronutrients, DTPA extractions of soils have not given reliable results for either zinc or iron; for iron, o-phenanthroline extractable iron in young leaves gives a much better indication of the iron status of groundnut.

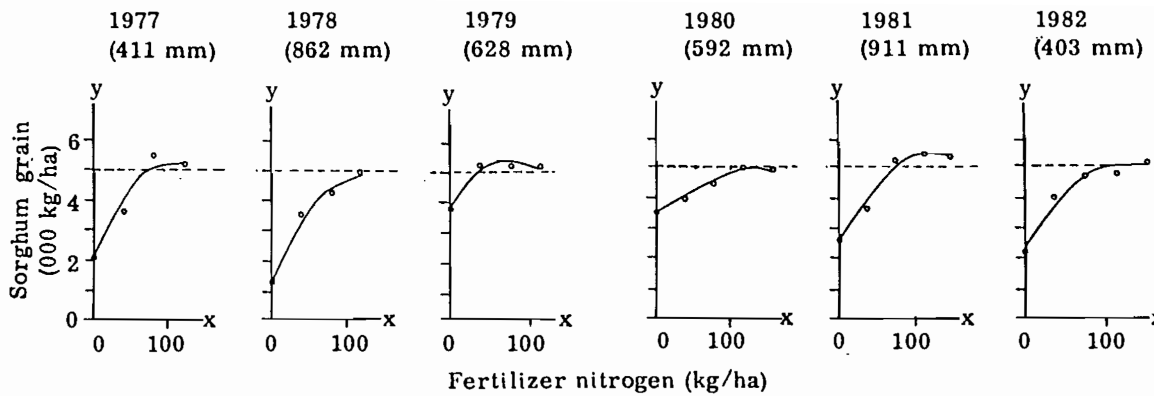
Reliability of responses

The reliability of responses to fertilizer-N was queried because of the known dependence of responses on an assured soil moisture regime. The target area for ICRISAT's improved system had been delineated, on an agroclimatological basis, as being assured for the establishment and growth of crops. But data was not available to assess the assuredness of the moisture regime of the target Vertisols for responses to nitrogen. Although empirical experiments had shown numerous examples of good responses to nitrogen, the magnitude of responses varied widely (Rao and Das, 1982) but the causes were not known.

To obtain information on the reliability of responses, we compared the response curves from fertilizer-N experiments conducted over 6 successive seasons at ICRISAT Center, which lies at the edge of the delineated assured-rainfall area. These results (Figure 1) show clearly the importance of nitrogen supplies for rainy-season sorghum. Variations in seasonal rainfall did not affect maximum yield, which was in excess of 5000 kg ha^{-1} in every season. Yields were as low as 1000-2000 kg ha^{-1} when fertilizer nitrogen was not applied. Particularly relevant to our concern about the adequacy of seasonal rainfall was the attainment of an adequate maximum yield in 1979, which was a very harsh year with long droughty spells up to anthesis.

Although the above results showed the importance of the total nitrogen supplies to the crop, and that responses to a small input of fertilizer-N would always be economic, the response curves do not indicate large consistency between years in the rates of fertilizer-N needed. In fact, the responses are inversely related to the amount of N supplied by the soil.

Because ICRISAT Center is located on the dry edge of the 'assured' rainfall area for Vertisols, we can therefore conclude from the above – with only minor reservations – that responses to fertilizer nitrogen will not usually be limited by droughtiness. In fact, within this area, excessive soil moisture may limit the effectiveness of fertilizer nitrogen. Substantial losses (>25%) of fertilizer-N in a high-rainfall year at ICRISAT Center (Moraghan *et al.*, 1984) were probably due to denitrification. Although these losses were reduced markedly by improved fertilizer application techniques, the probability of losses occurring would increase with an increase in average rainfall.



Regression equations:

1977: $y = 1920 + 62.4x - 0.28x^2$ $R = 0.81$ rse = 1063
1978: $y = 1310 + 53.3x - 0.19x^2$ $R = 0.97$ rse = 386
1979: $y = 3920 + 37.8x - 0.23x^2$ $R = 0.92$ rse = 280
1980: $y = 3340 + 19.6x - 0.59x^2$ $R = 0.99$ rse = 123
1981: $y = 2580 + 44.3x - 0.17x^2$ $R = 0.97$ rse = 358
1982: $y = 2340 + 40.8x - 0.15x^2$ $R = 0.91$ rse = 510

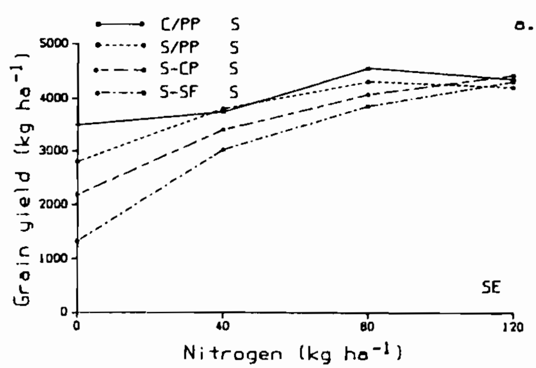
Figure 1. Response of sole-cropped hybrid sorghum (CSH 6) to applied N on deep Vertisols, ICRISAT Center, rainy seasons 1977-82. Seasonal rainfall given in parentheses after year. (ICRISAT, 1984).

Legume-N inputs

The promising results for fertilizer-N use shown in Figure 1 contrasts with the farmer's slowness to adopt improved cultivars and fertilizers. Fertilizers are an expensive input for subsistence farmers; the use of legumes for N inputs would seem to be a viable alternative. Legumes have been an acceptable option for situations where the financial returns from fertilizer-N use are unattractive due either to an unfavourable price:cost ratio, or to increased riskiness in drier environments (Donald, 1964; Russell, 1984).

Grain legumes have given excellent residual effects at ICRISAT (Kumar Rao *et al.*, 1983). A long-term experiment was therefore initiated to provide information on the role of these legumes in maintaining fertility, using a number of different combinations with nonlegumes. The first agronomic results show quite clearly the effectiveness of the legume inputs, which could give a sorghum grain yield of 3400 kg ha^{-1}, whereas the yield after nonlegumes was only 1450 kg ha^{-1} (Figure 2).

However, the agronomic yield increases resulting from a prior legume crop represent only part of the benefit of legume-N inputs. Ladd and Amato (1986) estimate that only about one-third of a legume-N input is available to a subsequent cereal crop in a Mediterranean climate. Because the annual inputs by legumes to this pool are small in relation to the size of the pool, and the spatial sampling errors involved in estimating its size are appreciable, measurements of the contribution to the soil pool have usually been made over a period of several years.



1983/84 system

C/PP S $y = 3420 + 17.0x - 0.072x^2$ $R = 0.48$

S/PP S $y = 2790 + 32.8x - 0.175x^2$ $R = 0.81$

S-CP S $y = 2200 + 34.8x - 0.136x^2$ $R = 0.97$

S-SF S $y = 1360 + 47.7x - 0.194x^2$ $R = 0.95$

Figure 2. Effect of cropping system grown in the 1983/84 season on the response of rainy-season sorghum grain yield to fertilizer-N in 1984. The cropping systems were cowpea/pigeonpea (C/PP) and sorghum/pigeonpea (S/PP) intercrops, and sorghum-chickpea (S-PP) and sorghum-safflower (S-SF) sequential crops (ICRISAT, 1986).

Modelling

From a combination of the results from both annual and long-term experiments, attempts can be made to develop models that predict the effects of various crop and fertilizer combinations on productivity and soil nutrient status. Data of the type given in Figure 1 allow an assessment of the desired crop yield to be made, based on current economics of fertiliser use. In association with data of the type given in Figure 2, we can decide the balance between fertilizer-N and legume-N inputs desired for the range of legumes and nonlegumes available. For these ranges of possible production factors we can calculate the likely affects on the maintenance of soil nitrogen status. For fertilizer-N, modelling is much easier, because the output (offtake) data is known from the associated plant-N removal data. Removal from the zero-N plot gives us an estimation of the mineralization of soil N, and immobilization of N can be assessed by using ^{15}N-labelled fertilizer, as can the losses of N by denitrification.

Accurate determination of legume-N inputs have encountered difficulties because of the errors associated with some of the field measurements. In the past, the only solution was to conduct long-term experiments; from the measured removal of N in plant products

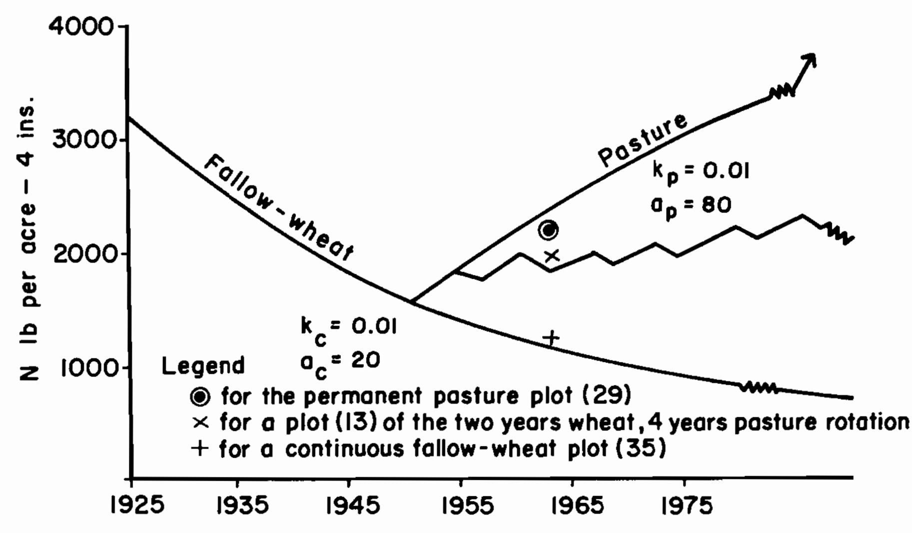


Figure 3. Changes in the nitrogen content of the 0-4 inch soil horizon under continuous fallow-wheat, and under pasture and pasture-wheat rotations, assuming the changes to follow the equation $dN/dt = -kN + a$. Under fallow-wheat it has been assumed that $k_c = 0.04$ and $a_c = 20$ lb per acre, and under pasture kp = 0.01 and $a_p = 80$ lb per acre. Years and nitrogen levels have been chosen to correspond to plots in the permanent rotation trial (C1) at the Waite Institute. Actual levels of nitrogen are shown in 1963 (Greenland 1971).

and changes in soil N, the net addition of nitrogen by biological-N fixation could be estimated. A more accurate estimation requires inclusion of estimates of additions or losses in rainfall, leaching, gaseous losses etc. Such experiments are laborious, and require meticulous attention to detail to measure the changes in soil N, including corrections for changes in bulk density. Only a few institutions have the resources to conduct experiments that require such continuing attention.

From the approaches given above, relationships can be established that show the effects of different proportions of legumes and nonlegumes in crop sequences and combinations of soil nitrogen contents (see Figure 3, from Greenland, 1971). This represents the type of information that is needed for planning crop options with regard to maintaining soil nitrogen status.

Measurement of the inputs by biological-N fixation has been hindered in the past by the high cost of resources for conducting the appropriate long-term experiments. Development of techniques using dilution of ^{15}N raised hopes that measurements could be made in just a single season, but their accuracy was dubious because of nonuniform labelling of soil nitrogen, both in time and with soil depth. By allowing time for equilibration, it appears that the accuracy of the ^{15}N technique will be much better (Ladd and Amato, 1986).

Integration of Fertility Research

The results shown above for soil nitrogen indicate the considerable amount of research effort required to develop a strategy for maintaining one aspect of soil fertility. Obviously, if several factors are involved, research efforts will be substantial. However, the overall effort can be minimized by careful selection of the few factors that are most important. The results in Figure 1 confirm that the high priority to nitrogen research was warranted.

Future nutrient management research on Vertisols will involve studies of the behaviour of phosphorus, as discussed earlier. However, interactions between nutrients and other components will require increasing attention. For Vertisols under high rainfall, there appears to be a potential for substantial losses of nitrogen, depending upon the attention given to drainage. For Vertisols under unreliable rainfall regimes, the effectiveness of nutrient inputs needs consideration in relation to water supplies both for the crop and for nutrient availability.

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APPENDICES

Appendix I

WORKING GROUP REPORTS

On the two days following paper presentations, country proposals were presented by the country representatives, and reviewed with the Network Coordinating Committee. The proposals emphasized current research procedures in the various countries concerned, the objectives envisaged, and the means of obtaining these objectives. While the project proposals were being finalized, three groups drafted the methodology to be applied for site characterization, physicial and chemical analytical methods, and the monitoring of farming systems.

Working Group A

Site Characterization

The group considered two major topics: (i) criteria for site selection, and (ii) data to be collected for site characterization.

Criteria for site selection

The first sites to be considered should be those meeting the following criteria:

- they are occupied by Vertisols which comply with the FAO/USDA definition;
- they have a growing season of at least 70-90 days;
- they are farmed by an established rural population.

The representativity of the site should be assessed using existing soil maps and complementary investigations:

Data to be collected for site characterization

- Soil:
    * detailed map of the site (1:1,000);
    * soil morphological characters as described by the *Guidelines for Soil Description* (FAO, 1967);

  * landscape description – physiography, topography, parent material;
  * sampling and measurements by horizon for taxonomic purposes, and composite fertility samples for experimental purposes;
  * physical parameters and chemical characters;
  * the designation of the horizons should follow the conclusions of the Internation Commission on Vertisols (ICOMERT).
- Climate:
  * general description of the climate of the site regarding temperature and rainfall;
  * characterization of the site using FAO's agroecological zoning stipulations, and giving details of the soil moisture and temperature regime;
  * measurement on the site of the following features: daily rainfall, maximum and minimum temperature, and potential evapotranspiration.
- Other data on the natural environment:
  * incidence of flooding and ponding;
  * incidence of biotic yield reducers – pests and diseases;
  * natural vegetation and agricultural history of the site.
- Human environment:
  * farming systems used in the region;
  * endowment of resources;
  * profiles of cropping systems;
  * marketing;
  * farmers' perception of difficulties.

Working Group B

Soil physical and chemical characterization

The group considered a set of soil characteristics relevant to crop production which can be measured simply.

Physical characteristics

- From surface observations, three characters seemed important: dry aggregates (presence, size, thickness), cracks (presence, width), and gilgai (presence, wave length, amplitude).
- From profile observations, a number of characteristics should be determined from a freshly opened pit: the depth, texture and consistency of the different horizons, the cracks, macrovoids and slickensides, the size of the structural units, and the presence of roots.
- Field measurements: At maximum field water retention after rain or irrigation, it is important to determine the saturated hydraulic conductivity, the maximum water content with the associated bulk density, and the wet penetration resis-

tance. In addition, the maximum rate of drying of the surface mulch and the surface aggregate size can be measured.

– Laboratory measurements: Shrinkage (COLE), the porosity of dry clods (Protor test), the plasticity index, and the aggregate breakdown with wetting and drying are recommended measurements. Others which can be useful are those provided by a mechanical analysis, and by measuring the 15-bar water content, the hydraulic conductivity of the surface layer, and the soil coherence.

Chemical characteristics

The following analyses are considered to be of primary importance: CEC, exchangeable cations, soluble salts, pH, total organic matter, total elements (N,P,K,Zn,Cu,Mn,Fe), carbonates, and available P (Olsen).

The group also made the following recommendations:

– that a central laboratory be used for certain measurements;
– that such problems as cohesion and adhesion in tillage be regarded as a research requirement;
– that support should be given to some cooperators to attend a workshop/training course on the effect of soil management on soil physical properties to be held in September 1987 in Australia.

Working Group C

Monitoring of improved systems

The aim in monitoring improved systems is to assess the extent of changes by measurements of well-chosen components using reliable and preferably simple methods.

Environment

Climatic components, such as rainfall, temperature, solar radiation, and wind speed, can be measured automatically. Details on evaporation, soil temperture (5-10 cm) and long-term weather patterns should also be available.

Soil physics

Soil water should be measured all the year round, either by neutron probe or by gravimetry, and the water table can be monitored by piezometers. Runoff and erosion measurements would also be useful.

Soil structure

The stability of the surface aggregates is important and should be measured. The width and spacing of the cracks and root penetration on the subsoil should be noted.

Soil chemistry

It was felt that in all probability changes in the soil chemistry will be small, but the total C, available P, and pH could usefully be monitored.

Soil biology

Not too much importance was attached to this aspect as it is difficult to quantify. It was suggested, however, that the increase in rhizobia is important, and should be evaluated by monitoring root nodule counts.

Other soil considerations

It was felt that in cases where the microtopography is important, it should be monitored in special experiments.

Crop measurements

The dates of sowing, emergence (50%), maturity, and harvest are essential observations. Yields (quantity and quality) and by-products from the crops are also essential data. In addition, it is useful to record growth (average height at maturity), and to assess pest/disease damage, weeds, and light interception or canopy cover.

Socioeconomic considerations

It would be valuable to monitor the acceptability of the proposed innovations. Existing agriculture should be the base of a low-level technology combination. A medium-technology combination should be monitored in on-farm trials parallel to the core programme.

Appendix II

SEMINAR RESOLUTIONS

Proposed MOVUSAC Regional Network

The network organization has been described in other IBSRAM publications, mainly in the reports of the inaugural workshops, the *IBSRAM Highlights,* and the newsletters. By and large these descriptions remain valid; but in order to achieve better efficiency a regional approach has been adopted.

The title of the proposed network is Management of Vertisols under Semi-Arid Conditions in Africa (MOVUSAC). This regional network is part of the global network on the management of Vertisols for improved agricultural production. However, its aim is more restricted than the global one as it addresses problems which are mainly relevant to Africa and to upland rainfed conditions.

Organization of the MOVUSAC Network Programme

The proposed organization of this regional network will be similar to that envisaged for the initial global network. It will comprise three components, namely:

- *Cooperators,* who will initiate and operate the soil management programme activities. Four types of participation are possible.
  * simple participation in the different programme activities, mainly with a view to sharing information;
  * active participation – both by having an accepted programme, and by participating in all the various programme activities;
  * basic participation – by having an approved programme, some strategy research related to the objectives of the network, and also participation in all the programmes;
  * support participation by international and other research agencies, by undertaking some part of the basic research related to the objective of the network, either alone or in conjunction with other cooperators.
- *IBSRAM,* which through a programme coordinator backed by the Network Coordinating Committee, will catalyse, coordinate, and assist cooperators in

conducting their activities. IBSRAM provides assistance in the preparation and in the presentation of the projects to donor agencies. The coordinator acts as a link between the cooperators and IBSRAM. He helps strengthen the national cooperators' programmes by regular visits and consultations and by backstopping the following network activities:

* site characterization;
* exchange of control soil samples and analytical methods;
* design of experiments, analyses, and interpretation of the data arising from the experiments;
* technical assistance;
* regular meetings, during which programmes will be reviewed and eventually revised;
* monitoring tours;
* training courses;
* creation of a data base;
* review of past and ongoing research, and bibliographical information services;
* provision of a programme newsletter, publications, and documentation.

– *Donors,* who will fund the programme coordination and, in part, the activities of the individual national cooperators.

Mechanism of Approval of National Project Proposals

One of the main objectives of this meeting was to revise and approve national project proposals in order to establish the regional network programme. The mechanism of approval, which has already been put into effect, consists of the following steps:

– A project proposal on Vertisol management is presented to IBSRAM by a national institution (coordination between national organizations is favoured). More than twenty projects have been presented for this MOVUSAC network.
– The project is reviewed by the Network Coordinating Committee (NCC). Until now, the initial interim NCC formed during the inaugural workshops has been used. The NCC consists of the active, basic, and support cooperators, the main donors, and the IBSRAM coordinator. The IBSRAM Board must then endorse its acceptance of the project proposals.
– After approval, an official letter of acceptance is sent to the cooperators, who may use it as a letter of support for fund seeking. During the regular meetings of the network, cooperators will present their results, and these will be discussed and reviewed by the participants in order to maintain a high scientific and development standard in the programme.

Criteria of Approval for National Project Proposals

The criteria for the approval of a national project proposal are as follows:

– The project must fulfill the network objectives as defined during the inaugural workshops and as clarified during the present seminar.

- The project must be technically acceptable, i.e. it must follow the approach and methodology defined during this seminar.
- The project must be economically acceptable.
- The country must already be involved in research of the type proposed, or be willing to invest in training for its personnel to achieve worthwhile participation.
- If a basic research project is proposed, it should have a broader objective than the country objectives *per se,* i.e. it should have implications on a wider scale. This criterion will not apply to validation projects.

Network Implementation

Immediate action will be taken by the director of IBSRAM to implement this MOVUSAC network. As ODA has agreed to fund the coordination of the network for an initial three-year period, a coordinator will be recruited and assume his duties as soon as possible. For the time being, the most important step is to revise the project proposals with a view to ensuring that they follow the recommendations of the workshop as regards the approach which is to be adopted.

After they have been revised, the proposals will be evaluated and, if accepted, will be presented in a portfolio of MOVUSAC project proposals suggested by IBSRAM for initial donor support. This portfolio will be widely disseminated amongst donors for funding, either on a bilateral basis or through IBSRAM. At the same time, the MOVUSAC coordinators (accompanied by one or two experts) will tour the different cooperating countries in order to assess the practical modalities for the implementation of their projects.

In order to ensure a smooth sequence of administrative operations, it is suggested that cooperators and relevant organizations carry out the various functions set out below:

- Cooperators – to send a revised project proposal drafted in accordance with the recommendations of the seminar.
- IBSRAM – to recruit a coordinator, to review and edit the project proposals, to seek funding for their implementation, and to organize a first visit of a team composed of the coordinator and one or more experts.
- Cooperators – to follow up activities in the proposed project which have already started, or to start activities as soon as possible, even on a small scale.
- Cooperators – to send IBSRAM an inventory of their available laboratory equipment and to list their needs regarding soil and plant analyses.
- Cooperators – to send their training plans and a list of available facilities at different levels in order to organize training sessions. IBSRAM will encourage cooperators to send participants to ICRISAT and other similar organizations which plan soil management training courses on Vertisols.

Appendix III

PROGRAMME OF THE SEMINAR AND FIELD TOUR

Monday 1 December

Registration (Serena Hotel)
Opening session

- Opening remarks: Dr. Marc Latham – Director, International Board for Soil Research and Management (IBSRAM)
- Inaugural address: Mr. Wapakala – Director of Research, Ministry of Agriculture
- Welcome address: Dr. F. Wang'ati – Secretary of the National Council for Science and Technology
- Master of Ceremonies: Mr. F.N. Muchena

First session: IBSRAM's network approach

Chairmen:	Dr. F. Wang'ati	
	Dr. J.S. Kanwar	
	IBSRAM's Vertisols network management	M. Latham
	Taxonomic characterization of Vertisols	J.L. Sehgal
	Vertisols in eastern Africa	R.F. van de Weg
	Farming systems approach	T. Walker
	Vertisols network: goal and objectives	J.R. Burford
	Discussion	

Second session: Site selection

Chairmen:	Prof. K. Zake	
	Dr. S.M. Virmani	
	Criteria for site selection in Vertisols	P. Brabant
	Case study: India	J.L. Sehgal
	Case study: Kenya	N.N. Nyandat

Third session: Site characterization

Chairmen:	Dr. A. Osman	
	Dr. M. Rasheed	
	Physical and mechanical properties	K. Coughlan
	Water management	D. Yule
	Chemical fertility parameters	P. Le Mare
	The occurrence and management of Vertisols for the production of cotton and other crops in western Tanzania	J.G. Mowo
	Conservation measures under large-scale wheat farms on Vertisols in northern Tanzania	R. Ngatoluwa

Tuesday 2 December

Fourth session: Management systems

Chairmen:	Dr. J.R.J. Hansell	
	Dr. O.T. Mandirangana	
	Management of Vertisols for improved crop production in the semi-arid tropics: a plan for a technology transfer network in Africa	J.S. Kanwar and S.M. Virmani
	African highlands (ILCA)	T. Abate

Fifth session: Management systems (cont.)

Chairmen:	Mr. F.N. Muchena	
	Dr. J.C. Katyal	
	Soil conservation and agroforestry	A. Young
	Semi-arid Mediterranean areas (ACSAD)	A. Osman
	Avenues for the improvement of cultural practices on Vertisols	T.J. Willcocks
	Management problems of cotton on Vertisols	A.J.B. Mitchell
	Discussion	

Sixth session: Implementation of the Vertisols network

Chairmen:	Dr. R.F. van de Weg	
	Dr. A. Woldeab	
	Experimental design and data processing	W. Siderius
	Fertility control and fertilizer management (IFDC)	J.C. Katyal
	Supplementary irrigation	H.G. Farbrother

Seventh session: Sustainability of improved systems

Chairmen: Dr. T. Walker
Dr. N.N. Nyandat

Erosion control	K. Coughlan
Cropping system evaluation	R. Willey
Strategy for fertility management	J.R. Burford
Discussion	

Wednesday 3 December

Eighth session: Country reports – project proposals

Chairman: Dr. R. Willey
Rapporteurs: Dr. D. Yule
Dr. J.R. Burford

– Egypt
– Pakistan
– Sudan
– ACSAD
– Tunisia
– Zimbabwe
– Kenya
– Tanzania

Chairman: Dr. S.M. Virmani
Rapporteurs: Dr. G.G. Ristori
Dr. J.R. Burford

– Uganda
– Mali
– Burkina Faso
– Botswana
– India

Chairman: Dr. T. Willcocks
Rapporteur: Dr. P. Le Mare

– Report and projects: Ethiopia
– General discussion

Thursday 4 December

Ninth session: Working groups

Site characteirzation
Chairman: Dr. T. Walker
Rapporteur: Dr. P. Brabant

Physical and chemical analytical methods
Chairman: Dr. K. Coughlan
Rapporteur: Dr. M. Razig

Monitoring of soil properties
Chairman: Dr. A.M. Virmani
Rapporteur: Dr. T. Mitchell

Friday 5 December

Field tour

Leave Six-Eighty Hotel
Arrive site 1
Leave site 1
Arrive site 2
Leave site 2
Arrive site 3
Leave site 3
Stop for lunch
Leave for Masinga Matuu area
Short stops on the way
Short stops at Matuu
Leave Matuu for Thika
Arrive at Thika Blue Post Hotel
Leave Thika for Nairobi
Arrive Nairobi

Saturday 6 December

Tenth session: General discussions and conclusion

General discussions on the working groups' reports
Report of the NCC
Formation of the network programme and discussion
Closing session

Appendix IV

LIST OF PARTICIPANTS
(in order of country work base)*

AUSTRALIA

COUGHLAN, Kep
Soil Conservation Research Branch
Queensland Department Primary Industries
Miers Road
Indooroopilly
Queensland 4068
Tel. 61-07-3779462

YULE, Donald
Queensland Department Primary Industries
PO Box 683
Rockhampton
Queensland 4700
Tel. 079-360253

BOTSWANA

GAKALE, Lucas P.
Agricultural Research
BP 0033
Gaborone
Tel. 52381
Cable: RESAGRIC

REMELZWAAL, Arie
FAO
c/o UNDP
PO Box 54
Gaborone

BURKINA FASO

ZOMBRE, Prosper
Bureau National des Soils
BP 7142, Quagadoubou
Tel. 3352-39

EGYPT

RASHEED, Mohamed Abbas
Soils & Water Use Department
The National Research Centre
Dokki
Cairo
Tel. 701211, 701615

*Representatives from international organizations are listed separately at the end.

ETHIOPIA

GETACHEW, Alem
Agricultural Research Institute
PO Box 2003
Addis Ababa
Tel. 160309

ASKANEW, Woldeab
Agricultural Research Institute
PO Box 2003
Addis Ababa
Tel. 160309

FRANCE

BRABANT, Pierre
74 Route d'Aulnay
93140 Bondy
Tel. (1) 48473195
Telex: 215203 F ORSTOM

INDIA

SEHGAL, Jawahar Lal
National Bureau of Soil Survey and
Land Use Planning
Amravati Road
Nagpur – 440 010
Tel. 34664
Telex: 0715-262 NBSL IN

ITALY

RISTORI, Giuseppe G.
Centro di Studio Colloidi Soulo
Pzole Cascine 28
50144 – Firenze
Tel. 055 364491
Cable: CONSIGLIONAZ RICERCHE

KENYA

CHWEYA, James
Department of Crop Science
University of Nairobi
PO Box 29053
Nairobi

ENGELEN, Vincent van
Kenya Soil Survey
PO Box 14733
Nairobi
Tel. 48211

GACHENE, Charles K.
Kenya Soil Survey
PO Box 14733
Nairobi
Tel. 48211

GATAHI, Milton M.
Kenya Soil Survey
PO Box 14733
Nairobi

IKITOO, Edwin C.
Mwea-Tebera
Agricultural Research Station
Ministry of Agriculture
PO Box 2298
Kerugoya

MANGALE, Besbert
Kenya Agricultural Research Institute
PO Box 30148
Nairobi
Tel. 32883

M'ARIMI, A.M.
Tana and Athi Rivers Department
Authority
PO Box 47309
Nairobi
Tel. 332455

MOCHOGE, Benson
University of Nairobi
PO Box 30197
Nairobi
Tel. 592154

WEEDA, Nout
Kenya Soil Survey
PO Box 14733
Nairobi
Tel. 48211

WOKABI, Stanley Mwangi
Kenya Soil Survey
PO Box 14733
Nairobi
Tel. 48211

MALI

BAGAYOKO, Miramba
IER/DRA/SRCVO
SRCVO B 438
Satuba – Bamako

NETHERLANDS

VAN DE WEG, Roel
Netherlands Soil Survey Institute
(STIBOKA)
PO Box 98
6700 AB Wangeningen
Tel. 80370-19100
Telex: 75230 VISI NL

SIDERIUS, Wout
ITC
PO Box 6
7500 AA Enschede
Tel. 053-320330
Telex: 44525 NL

WANG 'ATI, Frederick
National Council for Science and
Technology
PO Box 30623
Nairobi
Tel. 336173
Telex: 25356 KI TACCHIT
Cable: SCIENCENTECH NAIROBI

MUCHENA, F.N.
Kenya Soil Survey
PO Box 14733
Nairobi
Tel. 49501/02

NJIHIA, Christopher Mugo
National Agriculture Laboratories
Ministry of Agriculture
PO Box 14733
Nairobi
Tel. 48211 or 49501

NYANDAT, Nelson Nyambiah
National Council for Science and
Technology
PO Box 30623
Nairobi
Tel. 336173

OCHIENG, Nicholas Patrick
Kenya Soil Survey
PO Box 14733
Nairobi
Tel. 84211/273

OGUTU, Christopher
Kenya News Agency
PO Box 75638
Nairobi
Tel. 333561

OSORO, Michael
NSRS, Ministry of Agriculture
PO Box 1221
Kisumu
Tel. 2293

PAKISTAN

KHAN, Aurangzeb
Soil Survey of Pakistan
P.O. Shahnoor
Lahore – 18
Tel. 430101
Cable: PAKSOILS, LAHORE

SAUDI ARABIA

MOHAMED, Gailey Abdel Razib
Alowaidah Agriculture Company
PO Box 41880
Riyadh
Tel. 4793700
Telex: 240858 MWADEO

SUDAN

BABIKER, Ibrahim Ahmed
Agricultural Research
PO Box 126
Medani
Tel. 2232 MEDANI
Cable: TAOARIB MEDANI

MOHAMMED, Hassan Hag Abdulla
Agricultural Research
PO Box 126
Medani
Tel. 2232 MEDANI

TANZANIA

HAULE, Lallisto
TARO – Mallingano
BP Tanga
Telex: 45095 TACORD TZ

MANSOOR, Hussein Ahmed
Tanzania-Canada Wheat Project
PO Box 6024
Arusha
Tel. 3883

McKEAGUE, Alex
Tanzania-Canada Wheat Project
CIDA
PO Box 6160
Arusha
Tel. 3883

MOWO, Jeremias
Tanzania Agricultural Research
PO Box 1433
Mwanza
Tel. 40596/7

NGATOLUWA, Ramadhan
Tanzania-Canada Wheat Project
PO Box 6024
Arusha
Tel. 3883

TUNISIA

MIZOURI, Maaouia
Direction des Sols
Ministere de l'Agriculture
42 Avenue de la République
1001 Tunis-Port, Tunis
Tel. 246-232

UGANDA

ZAKE, K.
Makerere University
PO Box 7062
Kampala

UNITED KINGDOM

FARBROTHER, Herbert G.
7 The Lanes
Over
Cambridge
England

GUYVER, Patrick
Landell-Mills
65 Maidenhead Road
Stratford-on-Avon
Warwickshire
England
Tel. 0789-205052

LE MARE, Peter
Department of Soil Science
University of Reading
London Road, Reading RG 1 5AQ
England
Tel. 44 734 875234 ext. 280
Telex: 847813 RULIB G

MITCHELL, Anthony
Land Resource Development Centre
ODA
Tolworth Tower
Surbiton
Surrey, KT6 7DY
England
Tel. 01-399-5281

WILLEY, Robert W.
School of Development Studies
University of East Anglia
Norwich NR15 1SW
England
Tel. (0603) 56161

WILLCOCKS, Theo J.
Overseas Division
AFRC Institute Engineering Research
Silsoe
Bedford MK45 2BB
England
Tel. (0525) 60000
Telex: 825808

ZAMBIA

MUTELO, Joseph
Ministry of Agriculture
PO Box 50291
Lusaka
Tel. 253008

MUKANDA, Nawa
Mt. Makulu Railway Station
Department of Agriculture
Soil Survey Unit
PB7
Chilanga
Tel. 01-278087

ZIMBABWE

MANDIRINGANA, Owen T.
Soil Productivity Research Laboratories
PO Box 2757
Marondero
Tel. 3621
Cable: AGRICSEARCH ZW

INTERNATIONAL ORGANIZATIONS

ACSAD

OSMAN, Ahmed
PO Box 2446
Damascus
SYRIA
Tel. 755713
Telex: 412697 SY

EEC

SMITH, Anthony
EEC
PO Box 45119
Nairobi
KENYA
Tel. 333592

FAO

PHILLIPS, John C.
PO Box 30470
Nairobi
KENYA
Tel. 725069 (359) (369)
Telex: 23016 FOODAGRI NRB

IBSRAM

LATHAM, Marc
PO Box 9-109
Bangkok 10900
THAILAND
Tel. 5797590, 5611230
Telex: 21505 IBSRAM TH
Cable: IBSRAM

CHALINEE, Niamskul
PO Box 9-109
Bangkok 10900
THAILAND
Tel. 5797590, 5611230
Telex: 21505 IBSRAM TH
Cable: IBSRAM

ELLIOTT, Colin R.
PO Box 9-109
Bangkok 10900
THAILAND
Tel. 5797590, 5611230
Telex: 21505 IBSRAM TH
Cable: IBSRAM

ICRAF

LUNDGREEN, Bjorn
PO Box 30677
Nairobi
KENYA
Tel. 29867

YOUNG, Anthony
PO Box 30677
Nairobi
KENYA
Tel. 29867

ICRISAT

BURFORD, John R.
Resource Management Program
ICRISAT Patancheru A.P. 502324
INDIA

KANWAR, Jaswant S.
ICRISAT
Patancheru
A.P. 502324
INDIA
Tel. 224016

VIRMANI, Surinder M.
ICRISAT
Patancheru
A.P. 502324
INDIA

WALKER, Thomas S.
ICRISAT
Patancheru
A.P. 502324
INDIA

IFDC

KATYAL, Jagdish
IFDC
Muscle Shoals
PO Box 2040
Alabama 35662
USA
Tel. (205) 381-6600

ILCA

ABATE, Tedla
ILCA
PO Box 5689
Addis Ababa
ETHIOPIA

ODA

HANSELL, John
British High Commission
PO Box 30465
Nairobi
KENYA

UNDP

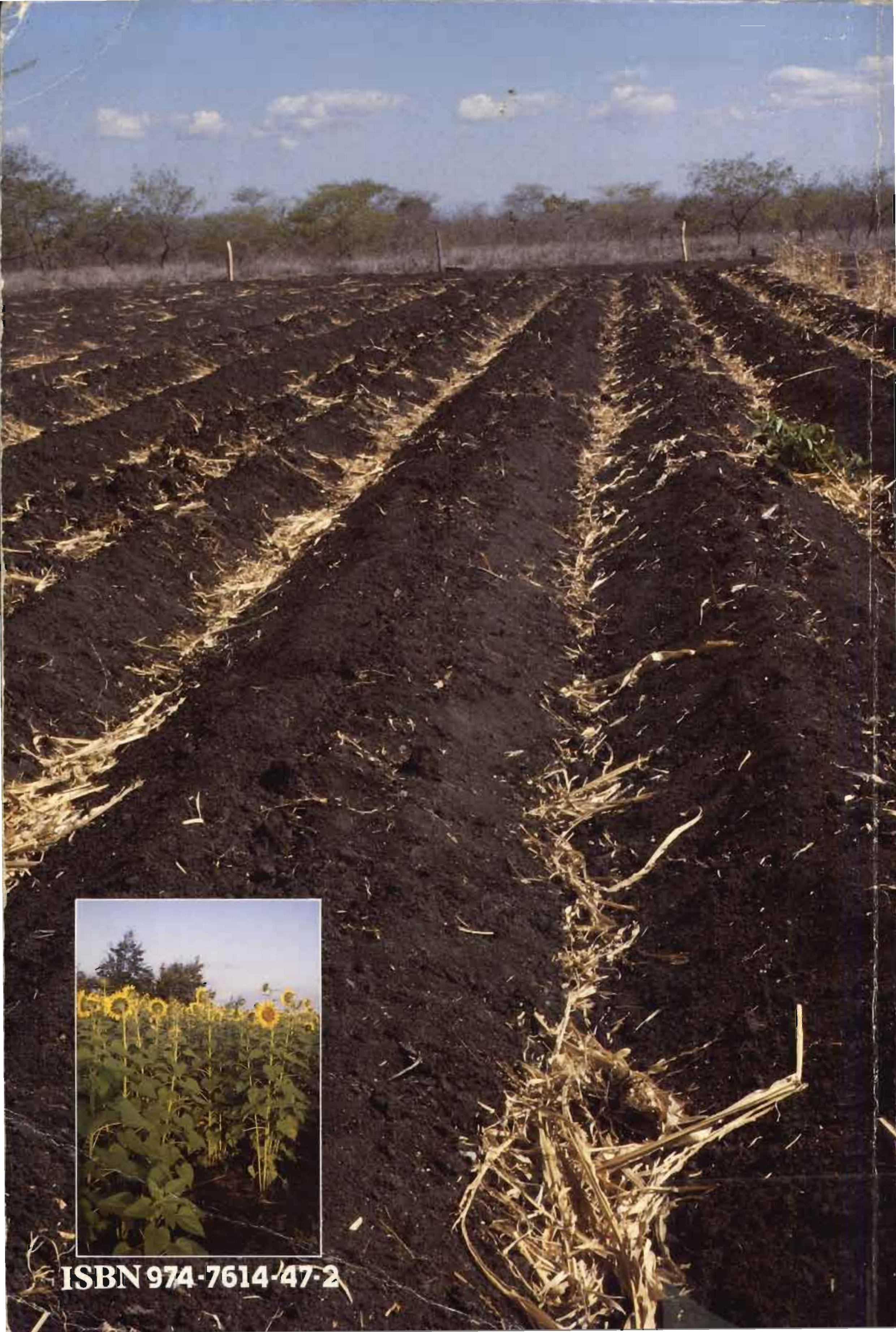
YAYA, C.W.
UNDP
Nairobi
KENYA

USAID

LUNDBERG, David
PO Box 30261
Nairobi
KENYA

IBSRAM
BOARD OF TRUSTEES

IBSRAM
International Board for Soil Research and Management
Inc. – Headquarters
P.O. Box 9-109
Bangkhen
Bangkok 10900
THAILAND
Phone: 579-7590, 561-1230
Telex: 21505 IBSRAM TH, Cable: IBSRAM



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