Management of Vertisols for Improved Agricultural Production

An IBSRAM Inaugural Workshop

International Crops Research Institute for the Semi-Arid Tropics

Abstract

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This volume includes 23 papers presented at the workshop, the welcome address, summaries of discussions, and the recommendations. Covered are such themes as approaches to management of Vertisols in different agroclimatic zones, research needs and constraints, technologies available and their components, methods of technology transfer, and the concept of a Vertisols network.

Résumé

Référence : ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1989. Gestion des Vertisols pour l'amélioration de la production agricole : comptes rendus du Colloque inaugural de l'IBSRAM, 18–22 fév. 1985, Centre ICRISAT, Inde. Patancheru, A.P. 502 324, Inde : ICRISAT.

Cet ouvrage regroupe 23 communications présentées lors du colloque ainsi que l'allocution de bienvenue, procès verbaux des discussions et les recommandations. Le colloque a été centré sur des thèmes tels que méthodes d'approche à la gestion des Vertisols dans les zones agroclimatiques différentes, besoins et contraintes de la recherche dans ce domaine, composantes des technologies disponibles, méthodes du transfert de technologies et le concept d'un réseau de recherche sur les Vertisols.

The International Crops Research Institute for the Semi-Arid Tropics is a nonprofit, scientific, research and training institute receiving support from donors through the Consultative Group on International Agricultural Research. Donors to ICRISAT include governments and agencies of Australia, Belgium, Canada, Federal Republic of Germany, Finland, France, India, Italy, Japan, Netherlands, Norway, Sweden, Switzerland, United Kingdom, United States of America, and the following international and private organizations: Asian Development Bank, Deutsche Gesellschaft für Technische Zusammenarbeit (GTZ), International Development Research Centre, International Fund for Agricultural Development, The European Economic Community, The Opec Fund for International Development, The World Bank, and United Nations Development Programme. Information and conclusions in this publication do not necessarily reflect the position of the aforementioned governments, agencies, and international and private organizations.

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Management of Vertisols for Improved Agricultural Production

Proceedings of an IBSRAM Inaugural Workshop

(International Board for Soil Research and Management)

18-22 February 1985
ICRISAT Center, India

Sponsoring Organizations

ACIAR	Australian Centre for International Agricultural Research
ADAB	Australian Development Assistance Bureau
AID	Agency for International Development
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IDRC	International Development Research Centre
ORSTOM	Institut Français de Recherche Scientifique pour le Développement en Cooperation, France
SMSS	Soil Management Support Services

International Crops Research Institute for the Semi-Arid Tropics

1989

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Vertisols are among the most productive soils in the semi-arid tropics. Improved production systems developed on these soils have given reliable high yields for decades under rainfed conditions in some areas; in others, Vertisols remain under traditional systems of land use that are relatively unproductive. Additional improved systems are being refined and developed.

The diversity of current use of Vertisols provides an excellent opportunity for the development of a useful network to facilitate research and exchange of information among scientists working to improve the utilization of these soils.

The workshop reported in this volume preceded the formal establishment of IBSRAM's headquarters in Bangkok, and it was hosted by ICRISAT on IBSRAM's behalf during 18-22 February 1985 at ICRISAT Center. In some ways, the meeting provided the basis on which IBSRAM established itself. We are pleased that the support received at this meeting has resulted in the formation of a Vertisols network in Africa. The first regional workshop of the network was held at Nairobi in December 1986 and a Network Coordinator appointed in May 1987.

We hope the information presented in this volume will serve both as a valuable reference and as a continuing stimulus for efforts to improve food production in the semi-arid tropics.

L.D. Swindale
Director General, ICRISAT

Introductory Session

Welcome Address

L.D. Swindale[1]

Let me extend to all of you a hearty welcome to ICRISAT. The Institute is not new to many of you, I know, and to those of you who have been here before, we say "welcome back."

ICRISAT is pleased to be associated with this inaugural workshop of the International Board for Soil Research and Management (IBSRAM). Our Institute was involved in the initiatives that led to the formation of IBSRAM, and we are greatly interested in its activities. We hope that activities such as this workshop will lead to an effective research network among the national and international programs represented here. As Dr Bentley will tell you later on, IBSRAM's major goal and objective is to assist developing countries in strengthening soils research and making it more effective. From this workshop, we hope to develop a network of activities that IBSRAM can help guide and for which it can find financing.

Several organizations have been responsible for developing the workshop to this stage. As one of the sponsors, ICRISAT is providing the venue of the workshop, support for the workshop arrangements and operations, and substantial funds from its regular budget to bring in participants and to publish the proceedings.

The other main sponsor is the Soil Management Support Services (SMSS), and I would like to recognize at this time Dr Hari Eswaran, who has done much to bring about this workshop. SMSS—a joint activity of the U.S. Department of Agriculture (USDA) and the U.S. Agency for International Development (USAID)—currently assists in activities related to soil survey, soil classification, and soil interpretation for soil management and soil development.

USAID is also a cosponsor and has provided substantial funds and support for this workshop. So, too, have the Australian Centre for International Agricultural Research (ACIAR) and the Australian Development Assistance Bureau (ADAB). The International Development Research Centre (IDRC), of Canada, and the Office de la Recherche Scientifique et Technique Outre-Mer (ORSTOM, subsequently renamed Institut Francais de Recherche Scientifique pour le Developpement en Cooperation), of France, are also cosponsors. We thank them all for their contributions.

Though this is not the time for a vote of thanks, I would also like to acknowledge the hard work of the local arrangements committee, led by Dr John Burford. The Committee has worked diligently and well to complete the necessary operational arrangements. This has not been easy, because they have been getting advice from all the sponsors and the advice has not always been consistent. I would like to thank them on your behalf, and I hope that they will be pleased to see that, in the end, this has been an effective workshop in which a lot of people worked together to develop an effective research network for the future.

We here in ICRISAT are very interested in the potential value of this workshop. We are interested in your knowing about our technology and what we think it can do, so that you can consider it and decide what you wish to do with it. We would like to be associated with a wider program of research on Vertisols in the developing world, so that we can learn more and add to our program of research those new concepts and ideas that others have developed. To a large extent, our work has been focused on the Vertisols of Central India, because it is natural that our work tends to be focused on what is closest to us. But we are an international organization, and it is our responsibility to serve client countries throughout the semi-arid tropics. We would like this workshop to develop a network in which we can participate, so that we might add this very important extra dimension to our work in developing improved soil management for Vertisols.

Now I would like to invite Dr Fred Bentley, Chairman of the Board of IBSRAM, to speak about the purpose of the workshop. Dr Bentley, a Canadian citizen, has had a very distinguished career in soil science. He was Dean of the College of Agriculture, University of Alberta, from 1959 to 1968 and, from 1974 to 1978,

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[1] Director General, ICRISAT, Patancheru, A.P. 502 324, India.

President of the International Society of Soil Science. Equally important, at least to many of us here, he was the first Chairman of ICRISAT's Governing Board and he served in that position for 10 long years. Long, because they were the years of ICRISAT's formation, of setting its original orientation and getting the Institute moving. You will see in the course of the next few days the excellent facilities now available for ICRISAT's work. A great deal of this is attributable to the vision of the first Chairman of our Board, Dr Bentley. We are deeply grateful for all that he has done. We very happily welcome him back to ICRISAT, and we hope that he will be able to contribute in the same way to IBSRAM as he has to ICRISAT.

Introduction to IBSRAM and Purpose of the Workshop

C.F. Bentley[1]

Abstract

IBSRAM (International Board for Soil Research and Management) is a new international agency, established to assist and speed the flow of existing and newly developed knowledge of soil science and soil management within developing countries for applications that will increase food production. Thus, IBSRAM will facilitate uses of soil science so that developing countries may wisely select, use, manage, and protect lands for production of food and other agricultural or agroforestry crops.

IBSRAM will not conduct research but, through soil management networks, will assist national programs to increase the amount and quality of soil-related research on the special problems of the various networks to be established.

Résumé

Introduction de l'IBSRAM et but de l'atelier : *Le Conseil international de recherche et de gestion pédologique (IBSRAM) est une nouvelle agence internationale, créée afin d'aider et d'accélérer le flot de connaissances acquises dans le domaine de la science et de la gestion des sols à l'intérieur des pays en voie de développement. L'IBSRAM facilitera ainsi les applications de la science des sols et permettra à ces pays de choisir, d'utiliser, de gérer et de protéger les terres de façon judicieuse pour la production alimentaire et d'autres cultures agricoles ou agroforestières.*

L'IBSRAM n'entreprendra pas de recherche par elle-même, mais par l'intermédiaire des réseaux de gestion des sols, elle assistera les programmes nationaux d'accroître la quantité et la qualité de la recherche pédologique relative aux problèmes particuliers des différents réseaux à établir.

Why IBSRAM?

During the last two or three decades, world food production has increased at a rate roughly matching the unprecedented rate of increase in world population. However, across regions and countries, the situation has been rather uneven. Food production increases exceeded the rates of population increase in most industrialized countries. Some populous countries—China, India, Indonesia, the Philippines, and Thailand, to name a few–have recorded gratifying increases in per capita food production, and so have various other developing countries. The major increases in food production in developing countries have resulted primarily from such activities as (1) use of improved, high-yielding varieties; (2) development of new lands for food production; (3) expansion of irrigation; (4) intensification of cropping; and, in some areas, (5) increased use of fertilizers.

Unfortunately, in many developing countries the rate of food-production increase has not kept pace with population increase. A recent FAO study (Harrison 1984) reports that in 1975, at least 54 countries (> 45% of the 117 countries in the study) could not have produced enough food for their people even if all land suitable for any type of arable agriculture

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had been in food production under low-input ("traditional") agriculture. FAO reports that by the year 2000 there will be 65 countries (> 54%) unable to produce enough food to satisfy their own needs, even if they use all their agriculturally suited land and apply traditional farming methods. Many of those countries do not have prospects, currently or in the near future, of exports that could earn the foreign exchange needed to pay for food imports. Moreover, opportunities for economically viable development of new lands by traditional methods, or for more intensive cropping by the usual method of shifting cultivation, are becoming very scarce—and give rather small increases in food production in relation to the human toil or the costly investments put into them. For new irrigation developments, the potentials for affordable and satisfying increases in food production by such traditional methods are now rather few, and prospects are generally unfavorable for meeting increasing needs for food in those ways.

How then are future needs for increases in food production to be met in developing countries with rapidly increasing populations—especially in those that already have genuine food problems?

Basic and applied research by industrialized countries, by national agricultural research programs in some developing countries, and by the 13 International Agricultural Research Centers (IARCs) have made—and are making—very important contributions to new, improved methods of agricultural production. They have assisted world food production by developing higher-yielding crop strains, encouraging new methods of soil and crop management, finding or breeding crop resistance or other effective controls for some diseases and pests, and so on.

As a result, there are now high expectations, especially for the IARCs, to solve food-production problems. However, several limitations prevent the IARCs from easily solving these problems. A major limitation is that individual developing countries need improved technological packages of agricultural practices suited to their individual conditions. Other limitations include the following:

- Each IARC has specific responsibilities and is not authorized to undertake new activities without approval to do so, and without funding for them.
- For several years funds for the International Centers have been less than the amounts requested by them, and as a group they are near a "no-growth" situation.
- The IARCs are unable to undertake activities in all the individual countries that might desire assistance and cooperation from the Centers.
- The primary focus of most of the Centers is on crops or animals: CIMMYT—primarily wheat, maize, beans; IRRI—rice; ICRISAT—sorghum, millet, pigeonpea, chickpea, and groundnut; and so on.
- Moreover, most of the research by the IARCs is done at a limited number of locations—with specific soils and agroclimatic conditions. Soils and other conditions in many countries differ from those where the Centers work.

During recent years there has been a growing awareness that, increasingly, soil problems and soil-related constraints hamper or prevent increases in food production in many places. For example, returns from investments in land-clearing projects and irrigation development have sometimes been very disappointing because of soil-related problems. The groundnut scheme that failed in eastern Africa is an illustration. So, too, was a recent wheat-production project in southern Africa, where soils and climate appeared to be favorable for that crop—and it took several years to prove that the utterly unsatisfactory yields were due to sensitivity of wheat to toxic amounts of aluminum.

By the late 1970s, it was recognized that there was an increasing need to focus on the potential contribution of soil science to sustainable increases of food production in many parts of the tropics. As a result, a "soil constraints meeting" was held at IRRI in the spring of 1979, under the joint sponsorship of the International Rice Research Institute (IRRI) and the New York State College of Agriculture and Life Sciences, Cornell University, in cooperation with the University Consortium of Soils for the Tropics (see IRRI 1980).

After the soil-constraints meeting, an ad hoc international committee was established and charged with the responsibility for finding ways and means to create an institution that would concentrate on the major soil constraints that limit increases in productivity. This institution was to develop practical, sustainable mechanisms and technologies to reduce such soil constraints, so that the genetic potentials of agricultural crops may be more fully used in the interest of mankind—especially in developing countries.

Four years were required for the ad hoc committee—assisted by modest funding from American, Australian, Canadian, and German sources—

to develop the concept and do the groundwork that led to the launching of IBSRAM (International Board for Soil Research and Management) at Townsville, Australia, in September 1983 (ACIAR 1984).

What IBSRAM Will Do

IBSRAM is a unique type of international development agency, established to encourage and assist national agricultural research institutions in developing countries to test, adapt, validate, and, above all, apply on the lands of farms existing and emerging knowledge about soil science and soil management that have important potentials for increasing food production. The IBSRAM focus is on applied testing and adaptive research that will contribute to profitable, sustainable increases in food production, thereby benefiting both farmers and consumers. IBSRAM does not intend to support or assist basic or academic research, nor will IBSRAM employ its own staff to do research.

In summary, IBSRAM was established to accelerate and facilitate practical applications of soil science in developing countries in order that they might wisely select, use, manage, and protect lands for production of food and other agricultural or agroforestry crops.

Encourage Cooperation and Coordination

IBSRAM will operate by cooperating with other institutions and will coordinate the results of various activities to assist and expedite the use by farmers of new technologies that will improve the profitability of their farming and put it on a sustainable basis. To that end IBSRAM will:

- Cooperate with IARCs wherever possible.
- Through its networks, promote intercountry and interagency exchanges of knowledge and new research results.
- Seek cooperation from, and participation by, institutions in developed countries.
- Keep in close contact with the Consultative Group on International Agricultural Research (CGIAR)—and, indeed, IBSRAM hopes to become a member of that Group.

Work through National Programs

The primary objective of IBSRAM is to provide support for national programs to assist them to undertake adaptive research, technology transfer, and practical validation of existing and emerging results of soil research and management investigations, which are deemed to have important potential to increase sustainable food production in developing countries.

Organize Soil Management Networks

To achieve its goals, IBSRAM will work with national organizations in developing countries to form Soil Management Networks (SMNs) focused on a variety of specific soil-related problems. For example, it is expected that this workshop will lead to the formation of a Vertisol SMN.

After such networks are formed, IBSRAM will seek funding for, and provide technical advice and guidance to, SMNs whose specific proposals to conduct adaptive research and practical training programs have obtained IBSRAM endorsement. Thus, IBSRAM will encourage and assist coordinated, interdisciplinary activities to develop, test under practical conditions, and promote on-farm applications of improved technologies for agricultural land identification, land use, crop production, soil management, and soil conservation. To achieve such goals, IBSRAM will support practical training, in a limited way, for the professional and technical personnel needed to execute such activities. The compilation and dissemination of data from IBSRAM-supported and other related investigations and from world sources will be another helpful activity.

Seek Reduction of Soil Constraints

IBSRAM activities are intended to find practical ways and means to reduce some of the soil and soil-management constraints, which so extensively limit attainment of the food-production potential of improved crop varieties developed by plant scientists.

Form Linkages in Soils Research

IBSRAM is intended to be a bridge between four major and sometimes rather separated types of soils work:

- basic soil research,
- soil management research (usually on a particular soil),

- soil survey and classification, and
- soil conservation,

with a view to their coordination and use to increase food production. IBSRAM will also be an interdisciplinary bridge between soil scientists, agronomists, and plant scientists.

Plan of Operation for IBSRAM

IBSRAM will establish a headquarters in Bangkok, Thailand, with an Interim Director funded by ORSTOM (Office de la Recherche Scientifique et Technique Outre-Mer, subsequently renamed Institut Francais de Recherche Scientifique pour le Developpement en Cooperation). There will be a small professional and support staff. The initial professional officers are foreseen as:

- a Director (who will be a member of the Board of Trustees),
- an Operations Officer,
- a Training Officer, and
- an Information Officer.

The IBSRAM staff will encourage and assist the formation of SMNs operated by Working Groups, most of whose members will be leaders of national programs of soil and agronomic research and extension. Networks will be concerned with specific problems or activities, such as soil and crop management for a particular and important type of soil (Vertisols are an example), or with the selection, clearing, and development of forested areas for food production.

Specialists from IARCs, other agencies, industrialized countries, and IBSRAM staff will assist and encourage the national programs participating in a particular SMN to develop a program (or programs) designed to test, adapt, validate, and then promote farmer use of new, improved technologies for food production which reduce or overcome, under practical farm conditions, some of the soil constraints to higher yields.

Funding

IBSRAM will seek three types of funding from donors:

- Core funding for the operation of the small IBSRAM staff and headquarters.
- Special project funding to enable the establishment of individual Soil Management Networks and the holding of periodic workshops and conferences needed to assist and encourage the exchange of relevant knowledge and ideas within the individual networks.
- Bilateral funding to strengthen National Cells (defined in the next paper) in countries participating in the various networks.

IBSRAM's role will be to help identify research activities with important potentials for payoffs, to assist with development of well-conceived plans for efficient execution of needed investigations, and to solicit funding for the resulting, carefully considered programs of action.

Other Types of Support

Donors or developing countries may post scientists or other types of personnel to IBSRAM offices, or to a network, or to a National Cell as contributions in support of IBSRAM activities. Similarly, supplies, equipment, or other types of in-kind assistance may be provided to help the activities of IBSRAM or of the various Soil Management Networks.

Additionally, some supportive research may be performed in some donor country or countries—and so too may some short-term, applied training.

Philosophy of the Agency

IBSRAM does not have aspirations to become a large organization. The number of employees and the size of the headquarters will be strictly controlled.

Through the network concept on which it is based, the Trustees of IBSRAM confidently foresee the agency as assisting with the building of national research capabilities and thus making a significant contribution to increased food production in developing countries. In addition, IBSRAM hopes to promote the conservation of land resources and maintenance of the productivity of agricultural lands by encouraging the practical application of existing and emerging soil and agronomic knowledge by farmers.

Principles for Network Success

How are networks formed? How do they work? Plucknett and Smith (1984) have listed seven principles that are basic to the successful formation and operation of international agricultural research networks. Because those principles are so important to what we hope will result from this workshop, let me list them and relate them to our discussions this week.

1. The problem should be clearly defined and a realistic research plan must be prepared.
   - The problem this workshop is concerned with is "Management of Vertisols for Improved Agricultural Production."
   - At the conclusion of this workshop it is hoped a working group will be established to refine the proposals for research to be conducted by the various "National Cells."

2. The problem should be one shared by the participants.
   - Most countries represented at this workshop wish to learn how to increase the productivity of their Vertisols.

3. The participants must have a strong self-interest.
   - That is why your governments have authorized your attendance at this workshop.

4. Participating countries must be able and willing to commit resources such as scientists, technicians, research facilities (including experimental fields, equipment, laboratories, and so forth), and operating budget funds in order to conduct the testing and applied research program which each country undertakes to do through its National Cell in the network.
   - Countries unable to provide personnel and the other resources needed to do network research cannot become National Cells in the network. However, such countries will be eligible to receive IBSRAM newsletters and other publications providing information about the network and the results being obtained by the program of field experiments and on-farm tests.

5. Outside funding is important to the establishment and the first few years of operation of a network.
   - Funds for this workshop have been provided primarily by Soil Management Support Services (SMSS/USDA/AID) and by ICRISAT. In addition, IBSRAM has had some input.
   - The network we hope to establish will require donor support for three purposes:
     - To meet some of the needs of individual National Cells, so they can do the research planned, and do it effectively.
     - For meetings of the network Working Group to review research results over a period of years at the various National Cells.
     - For the core budget of IBSRAM to enable employment of a coordinator for the network, to maintain the information services and other IBSRAM activities, and to provide specialist assistance to the network by IBSRAM staff.

6. Participating National Cells must have scientists on the National Cell staff with the time, the personal interest, the scientific training, and the expertise gained from experience, which, in combination, are essential to the successful execution of the applied research being undertaken.
   - Expatriates from donor countries and IBSRAM staff members or brief training programs can update knowledge of the personnel engaged in the network research program.
   - However, neither the network nor IBSRAM can engage in the long-term task of basic education and training for agricultural research and field experimentation.

7. Networks must be assisted, at least initially, by visits from strong, efficient outside personnel who are able to guide and support the National Cells in the execution of their programs of field experimentation and on-farm testing.
   That assistance is to be provided by the network coordinator, by IBSRAM staff members, and, in some cases, by specialists from IARCs or donor countries.

In conclusion, it is appropriate to emphasize that there are understandable limitations on what donors, IARCs, and agencies such as IBSRAM can do for individual national agricultural research and extension programs. However, participation in a network can be of great benefit to national programs. It is hoped that this workshop will result in the establishment of a Vertisol Soil Management Network, which will make important contributions to improved agricultural production as well as to the building of the capabilities and confidence of the participating scientists and institutions. Finally, it is expected that the results and spin-offs from the Vertisol SMN will be very helpful to countries unable to join the network at the outset.

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The Concept of a Vertisol Soil Management Network

C.F. Bentley[1]

Abstract

This workshop has been organized by IBSRAM, ICRISAT, and the Soil Management Support Services (SMSS) of the United States to establish a Vertisol Soil Management Network (SMN). The purposes of such a network will be to assist and speed applications of soil science knowledge in the management of Vertisols to increase agricultural production from those extensive soils.

IBSRAM is so new that as yet it does not have a director or other professional employees. In addition, this is the first IBSRAM effort to organize a Soil Management Network, and therefore this workshop is a new experience. Rather than attempt a detailed description of the Vertisol SMN proposal, this paper presents one concept of how an SMN proposal might evolve and the practical considerations essential to its success.

Résumé

Le concept d'un réseau de gestion des Vertisols : *Ce colloque a été organisé par l'IBSRAM, l'ICRISAT et les Services de soutien de la gestion des sols (SMSS) des Etats-Unis afin d'établir un réseau de gestion des Vertisols (SMN). Le but d'un tel réseau consistera à aider et à accélérer les applications de la connaissance de la science des sols dans la gestion des Vertisols afin d'augmenter la production agricole de ces vastes étendues de sols.*

L'IBSRAM est tellement récent qu'il n'a pas encore de directeur ou d'employés professionnels. En plus, il s'agit du premier effort de l'IBSRAM d'organiser un Réseau de gestion des sols, et par conséquent ce colloque est une nouvelle expérience. Au lieu de tenter de faire une description détaillée de la proposition d'un réseau Vertisol (SMN), cet article présente un concept qui explique comment une proposition SMN pourrait se développer et les considérations pratiques essentielles pour son succès.

Introduction

IBSRAM is a new organization, and it will be some months before the Interim Director will take up his duties. Because this is the first IBSRAM workshop intended to result in the formation of an SMN, it is unclear exactly how the establishment of a Vertisol SMN will proceed. We hope and expect that things will proceed somewhat as follows, however.

Possible Sequence of Events

1. If a Vertisol SMN is to be formed, it will probably begin with two, three, or four countries as participants in the network. Each initial country, or "National Cell"[1] in the network, will need to have

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[1] At the end of the workshop, participants agreed to use the term "Network Cooperator" rather than "National Cell."

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a research station or some other government agency, which is already involved in some way in applied research on the use and management of Vertisols. The research station or agency selected to represent a country will, therefore, have some facilities and staff already engaged in Vertisol work.

An official from the prospective National Cells is representing the country at this Vertisol workshop.

2. During this workshop, representatives of some prospective National Cells will briefly present a draft proposal outlining what investigations for improving the use and management of Vertisols the countries would like to conduct.
3. The workshop program indicates that:

A. Each tentatively identified National Cell will make a presentation of about 20 minutes, describing what that Cell wishes and plans to do to improve the use, management, and, above all, the actual crop yields and production from Vertisols.

B. A few highly qualified experts will describe and/or illustrate techniques, methods, results, principles, and so forth, related to improved use, conservation, and management of Vertisols.

C. A field trip will enable participants to see land at ICRISAT Center and at a village 35 km from Patancheru, where substantial increases in production are being obtained by improved Vertisol management. This management enables production of two crops a year where only a single crop has been traditionally grown.

D. After items A, B, and C have been completed and participants have discussed them in working groups, a decision will be taken on the question: Are some countries interested in, and authorized to participate in, the formation of a Vertisol Soil Management Network?

E. If the answer in D is yes, a Network Coordinating Committee (NCC) will be formed with about five to eight persons, providing adequate representation to prospective National cells, international specialists, and donors, and supported by an IBSRAM representative.

4. The proposal developed by the NCC will be taken to the respective countries by the representatives of the National Cells. In each country where there is to be a National Cell, the specific plan and proposal for that country will be revised and developed in detail. An important part of that activity will be to prepare a detailed list, with cost estimates, of the requests being made for assistance to execute the proposal.

A. When the proposal of each National Cell has been officially approved by the government concerned, it will be forwarded to IBSRAM.

B. IBSRAM will review the proposals received from the National Cells in the network. If necessary, some changes or some integration of requests may be made. For example, three separate requests of a generally similar nature for training programs might be combined into a single request for such training to serve the three countries.

After IBSRAM has approved the proposals and requests described, funding will be sought, perhaps by both IBSRAM and some of the individual National Cells. Some donors may prefer to provide funds to IBSRAM but may specify which activities are to be supported in which country(ies). Other donors may want to provide support to selected National Cells on a bilateral basis; sometimes donors may choose to support only specific activities of a particular National Cell and on a bilateral basis.

C. If donor funding enables the research activities to proceed according to the requests of the individual National Cells, then matters will proceed on that basis. If, after several months of seeking donor support, there are shortfalls in funding for the requests made, the NCC may have to meet and work out some adjustments.

If the requests made are realistic and modest, prospects for adequate funding are considered good.

5. Once the network is established and funded:

A. IBSRAM will somehow provide or arrange for a coordinator or coordination to assist the individual National Cells during the initial 1-3 years.

B. Provided the necessary funding is available, arrangements will be worked out for the NCC to make field visits to one National Cell per year on a rotational basis to view work in progress and to review and evaluate the results.

Such reviews and field visits may lead to adjustments or changes in plans for the work to be done during the next year or two.

C. If a National Cell fails to perform the work it has undertaken to do, its participation in the network and any further support for its activities will be discontinued unless there are exceptional circumstances to explain the failure.

6. When the network has been established and is successfully operational, additional National

Cells wishing to join the network will have opportunities to do so.

In addition, network newsletters and other IBSRAM publications will be available to interested countries wishing to receive such information, even if they are not able to join the network.

7. There are several advantages for developing countries accepting the invitation to participate in the IBSRAM Vertisol Soil Management Network. They include:

- The opportunity to send a participant to this workshop, with all expenses met by the workshop funds.
- Receipt of information about Vertisols, their extent and variability, as well as observing how improved Vertisols management may increase productivity under certain conditions.
- A chance to seek membership in the network likely to be formed and thereby to be included in:
  - IBSRAM requests to donors for funds to support applied research and on-farm investigations by National Cells;
  - IBSRAM information services, providing the newest technical information about ways, means, costs, and results of various methods of Vertisol use and management;
  - from year to year, field visits to view the investigations and experimentation on Vertisols by other National Cells in the network;
  - the annual review and evaluation of results from the various National Cells in the network;
  - regular visits to each National Cell by IBSRAM officers who will provide information, advice, and encouragement; and
  - training courses or visits by expatriate specialists, which IBSRAM may be able to organize.

National Cell Preferences

Several donors have been insistent that networks are not to be directed by IBSRAM, by IARCs, or by other agencies. Donors insist that the countries making up a network, the National Cells, must make the major decisions about what the network research programs are to be, what is to be done, and how it is to be done by the individual National Cells.

That principle was applied at the meeting of the Organizing Committee for the workshop, held at ICRISAT last September. Before that meeting, one prevalent view was the Vertisol SMN would test the ICRISAT double-cropping technology and variations of it in other locations. As you will hear and see while you are here, the technology being used is very successful in this semi-arid region. However, representatives of two potential National Cells attending the meeting last September had different interests.

It was pointed out that Vertisols occur in various climatic regimes. In semi-arid areas, such as here at ICRISAT, the basic problems are moisture conservation and the cultivation of Vertisols when they are too dry or too wet. In Venezuela, the main problem in using Vertisols is drainage—the removal of excess water so crops can be planted and so they can grow. In the Sudan, there are extensive areas of Vertisols where it is so arid that irrigation is essential if crops are to be produced, so the problems of using such soils are different. As a result, the concept that evolved at the Organizing Committee meeting in September was that there should be a representative National Cell in each of those agroclimatic regions: (1) in semi-arid areas, (2) in a subhumid region where the main problem is drainage, and (3) where there are problems associated with irrigation of Vertisols in an arid climate.

Since then, national preferences have been illustrated again. In the Sudan, the largest area of Vertisols is in a semi-arid region that has a potential for agricultural production many times that of the irrigated areas. Therefore, because development and improvement of agricultural production in the rainfed semi-arid Vertisols of the Sudan is the national priority, if there is to be a National Cell there, it should work in accordance with that priority.

Practical Results Needed to Attract Support

IBSRAM is still just an idea. So far donor support has been very modest because it has not been demonstrated that our new agency can in fact help increase food production in developing countries. Donors are very anxious to see definite, unquestionable results from the funds they provide.

It thus becomes important that IBSRAM networks be concerned with applied research and testing that have a realistic potential to bring about increases in food production within a few years. Without significant results of that kind, donor support will probably stop.

For that reason, IBSRAM does not intend to support basic or academic research in its networks at this time. It might be very interesting to do research on the minerology of Vertisols in a particular region: 20 years from now such knowledge might be useful, but it might also be of no practical use even after this time. IBSRAM intends to encourage and assist applied research that has the potential to increase food production—and within the next 5 years, if possible.

Thus, there is a strong preference for projects by National Cells that include experiments and tests at off-station locations and also on the fields of ordinary farmers. Research or experimental station locations often have soils that are rather different from important areas being used by farmers. In addition, farmers tend to be reluctant to accept results from experimental stations, whereas they may readily accept the same results when they are obtained on the land of ordinary farmers. Many donors are, therefore, willing to support on-farm applied research and testing, where the problems and conditions are closer to those encountered by farmers.

Initial Successes: Keys to the Future

I hope this workshop will lead to the formation of a Vertisol SMN of a very practical nature, which will contribute so much to improved agricultural production that donors will be delighted. Such a result will attract increased donor support for your future work. It will also enable IBSRAM to grow and expand its efforts to increase food production through wise applications of soil science.

I hope you will find the workshop informative and practical. I also solicit your best efforts to develop a proposal for a Vertisol Soil Management Network which will:

- Be very attractive to your governments, thereby winning their approval and financial support.
- Appeal to donors who will, as a result, want to support your proposals.
- Offer improved use and management that lead to sustainable and substantial increases in agricultural production with profitability for farmers working on Vertisols in developing countries.

My best wishes for success.

Discussion

Swindale: What is the timetable you suggest for development and implementation of the Vertisol Soil Management Network?

Bentley: After the proposal, I expect it will take 1 year to get donor support. The National Coordinating Committee should meet within a month after this workshop; the Board meeting is in August to October. By the end of 1985 the final proposal could be ready.

Stewart: What is the thinking of IBSRAM regarding the number of networks that are being planned?

Bentley: The IBSRAM Board considered four networks: wetlands, Vertisols, acid tropical soils, and land clearing. The wetlands are already covered somewhat by IRRI (International Rice Research Institute), and workshops are being planned for later this year for the the acid tropical soils and land clearing network proposals.

Cooper: (1) Will there be any overlap between objectives and members of IBSRAM and other networking systems which exist (such as IBSNAT, RAIN)? (2) Is there a need to coordinate networking systems to avoid any potential overlap and thus potential confusion, which could harm the outcome of the network?

Bentley: (1) Yes, IBSRAM is aware of this possibility and will attempt to avoid any overlap. This can probably be done through USAID, which support networking. (2) Maybe a "network of networks" is needed.

Eswaran: Point 6 of Plucknett's list (of 7 points for successful networks) requires in-house capabilities to become a full participant of the network. Some countries may not have the capabilities, and yet they are the most needy for assistance. What will be IBSRAM's policy regarding this?

Bentley: We will have to begin with those which do; to begin with, the agency will have to have some resources to commit.

Blokhuis: Dr Bentley, you mentioned that IBSRAM would assist applied research in the network countries, that it would be expected to give direct and measurable results in, say, 5 years. But if more fundamental research is neglected, we may be left with some basic problems; such problems should be resolved, even if this would take, say, 10 years. Should there be such a discrepancy between applied and basic research?

Bentley: I have stressed the practical, applied results in the early years of IBSRAM because we hope this would get support funding for the future. It may be that some of the basic problems would be tackled in laboratories of developed countries who already have suitable resources and facilities. Our long-term basic goal is to help develop, improve, and expand the capability for planning and extension of research in developing countries.

Approaches to the Management of Vertisols in the Semi-Arid Tropics: The ICRISAT Experience

S. M. Virmani[1], M. R. Rao[2], and K. L. Srivastava[3]

Abstract

Vertisols are potentially productive soils within the dry tropics. When deep, these soils have a high water storage capacity, which allows 6-7 months of cropping in India if the rainfall exceeds 750 mm. However, because of their high clay content and related physical properties, they present a challenge in their management for increased crop production. The small farmers of limited means in the Indian semi-arid tropics generally prefer to raise only one crop in a year (during the postrainy season) on these soils even in areas with high and assured rainfall.

ICRISAT has now assembled a technology for improved management of Vertisols. It involves growing two crops, one in the rainy season and another in the postrainy season. Application of the technology has resulted in considerable improvement in erosion control and moisture conservation, higher rainfall-use efficiency, and annual yields of about 3000 kg ha^{-1} of cereal and 1000 kg ha^{-1} of legume grains for the last 9 years at ICRISAT experimental watersheds.

The technology has been evaluated in on-farm tests in a few agroclimates of the Indian semi-arid tropics with moderate but dependable rainfall. Gross profits from the improved technology were 2 to 5 times higher than those from the traditional technology, which involved only postrainy-season cropping. The improved technology required additional expenses ranging from Rs 590 to 1480 ha^{-1} (US $ 1 = Rs 12 approximately), but it gave a marginal rate of return averaging 230%. The tests also showed that the technology can be adapted to local conditions by suitable modification of one or more of the components involved. The transfer of this technology to other Vertisols in agroclimates similar to that of ICRISAT Center is relatively straightforward, but transfer to those in other agroclimates requires further testing. Establishment of a coordinated program for multilocational testing would help rapid exchange of information on experiences with the performance of the technology in various environments.

Résumé

Une approche pour la gestion des Vertisols dans les tropiques semi-arides—l'expérience de l'ICRISAT : *Les Vertisols sont potentiellement un des ordres de sol les plus productifs dans les zones tropicales arides. Lorsqu'ils sont profonds, ces sols ont une grande capacité de rétention d'eau qui permet 6-7 mois de culture en Inde si la pluviométrie dépasse 750 mm. Cependant, à cause de leur forte teneur en argile et des propriétés physiques reliées, ils posent un sérieux problème. Les paysans disposant de faibles moyens dans les tropiques semi-arides de l'Inde préfèrent normalement de ne*

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ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1989. Management of Vertisols for improved agricultural production: proceedings of an IBSRAM Inaugural Workshop, 18-22 February 1985, ICRISAT Center, India. Patancheru, A.P. 502 324, India: ICRISAT.

produire qu'une seule culture sur ces sols après la saison des pluies même dans les régions à pluviométrie élevée et sûre.

L'ICRISAT a élaboré une technologie pour une gestion améliorée des vertisols. Cela implique la culture de deux récoltes, une pendant la saison des pluies et l'autre après. La mise à l'épreuve de la technologie a abouti à un bon contrôle de l'érosion, à une meilleure préservation de l'humidité, et a une efficacité accrue de l'utilisation des précipitations comparée aux systèmes de culture traditionnels. Dans les bassins versants expérimentaux de l'ICRISAT, cette technologie a produit des rendements de 3000 kg ha^{-1} de céréales et 1000 kg ha^{-1} de légumineuses par an pendant les 9 dernières années.

Cette technologie a été évaluée en milieu réel dans certaines régions tropicales semi-arides de l'Inde, où les précipitations sont modérées mais sûres. Les bénéfices brûts de la technologie améliorée furent deux à cinq fois plus élevés que ceux de la technologie traditionnelle qui consiste à ne cultiver qu'après la saison des pluies. La technologie améliorée nécessitait des frais supplémentaires qui s'échelonnaient entre Rs 590 et 1480 ha^{-1} (US \$ 1 = Rs 12 environ), mais donnait un taux marginal moyen de rendement de 230%. Ces tests ont également montré que la technologie peut être adaptée aux conditions locales en adaptant n'importe laquelle des composantes impliquées. Le transfert de cette technologie à d'autres Vertisols dans des conditions agroclimatiques semblables à celles du Centre ICRISAT est relativement facile, mais la transposition à des agroclimats différents nécessite des essais approfondis. L'établissement d'un programme coordonné pour des essais multilocaux permettrait un échange rapide de l'information sur les résultats de la technologie dans divers milieux agroclimatiques.

Introduction

The major areas of Vertisols and associated soils are located in Australia (70.5 million ha), India (70 million ha), Sudan (40 million ha), Chad (16.5 million ha), and Ethiopia (10 million ha). These five countries contain over 80% of the total area (250 million ha) of Vertisols in the world (Dudal 1965). In India, substantial Vertisol areas occur in Maharashtra, Madhya Pradesh, Gujarat, Andhra Pradesh, Karnataka, and Tamil Nadu (Murthy 1981). Most of these receive 500 to 1300 mm of annual rainfall, concentrated in a short period of 3 to 3.5 rainy months interspersed with droughts. Crop yields in this area are low and vary from year to year.

The aim of our Vertisol management research over the past 10 years has been to evaluate the traditional practices in terms of productivity and soil and water losses, and then to develop and test approaches for improving productivity through greater rainwater utilization and minimizing land degradation. This paper discusses some major constraints that limit productivity of Vertisols in the Indian semi-arid tropics and presents approaches and our experiences in Vertisol management. We believe that several of these methods and their underlying principles will find relevance for improved management of Vertisols located in other parts of the tropical world.

Attributes of Vertisols

Vertisols in India are heavy soils. Their texture may be clay, clay loam, or silty clay loam, with the clay content generally ranging from 40% to 60% or more. They have high bulk density when dry (clod density 1.5-1.8 g cm^{-3}); high cation exchange capacity (47-65 cmol kg soil^{-1}); and pH values usually above 7.5. Tropical Vertisols are low in organic matter and available plant nutrients, particularly nitrogen, phosphorus, and zinc. The dominant clay mineral is smectite.

Because of their high clay content and related physical properties, these soils have a high moisture storage capacity. Average field capacity of the 185-cm Vertisol profile at ICRISAT Center is about 810 mm, and the lower limit of plant available water is 590 mm (Russell 1980). Thus, this typical deep Vertisol profile is able to hold about 220 mm of available water. (The lower limit is the observed minimum water content in the profile, as measured in the field under a well-managed, deep-rooted, long-season crop; the field capacity (upper limit) represents the amount of water retained by an uncropped Vertisol profile after drainage stops.) Based on the estimates of week-to-week changes in available moisture in relation to rainfall and potential evaporative demands, Krantz et al (1978) determined that the growing season on a deep Vertisol ranged from 21 to 33 weeks (147–231 days) in different years.

Vertisols are very hard when dry and very plastic, sticky, and not trafficable when wet. Their optimum soil moisture range for tillage is very narrow. Because of this, draft-power needs for land preparation are extremely high during the dry season. Farmers await the onset of the rainy season: but the early rains in many parts of India have a tendency to persist, and thus farmers cannot prepare their land or plant their crops in time because of poor trafficability.

Vertisols have a low terminal infiltration rate (about 0.2 mm hr^{-1}). During the rainy season, water may pond if drainage is inadequate and then crops suffer from waterlogging. Soil erosion is another serious problem in Vertisols, particularly in situations where soil cover is sparse and where concentrated flow of water occurs through unprotected channels.

Traditional Management of Vertisols in India

The management practices being used on deep Vertisols in India have been described and discussed by several authors (Michaels 1982, Ryan et al. 1982, Kanwar et al. 1982). In traditional management, deep Vertisols are usually fallowed during the rainy season and cropped only in the postrainy season on stored soil moisture. Frequent cultivation by a blade harrow (Fig. 1) is done during the fallow period, primarily to control weeds. Improved cultivars and chemical fertilizers are generally not used. Annual yields from farmer's fields on Vertisols in selected villages of peninsular India have been reported (Kanwar et al. 1982) to be quite low. Yields of some typical crops are:

Sorghum	500–900 kg ha^{-1}
Wheat	300–700 kg ha^{-1}
Chickpea	200–500 kg ha^{-1}
Safflower	300–500 kg ha^{-1}
Chillies, dry	200–700 kg ha^{-1}

The consequences of rainy-season fallowing in areas with dependable and high rainfall are serious

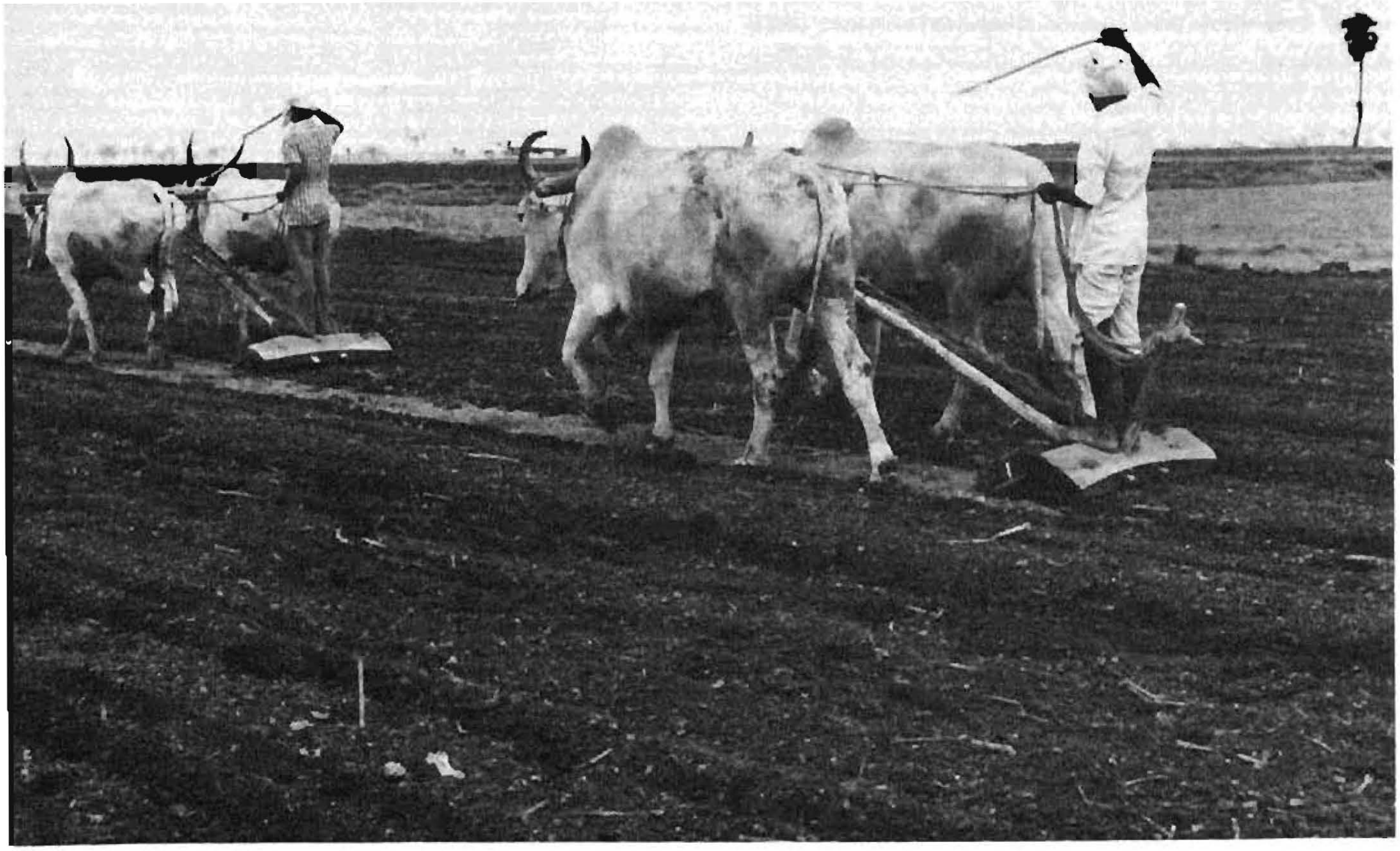


Figure 1. In traditional farming, repeated cultivation with a blade harrow (*bakhar*) keeps the fallow land free of weeds in the rainy season.

Table 1. Runoff and soil loss from Vertisol watershed under improved and traditional management, ICRISAT Center.

		Management system			
		Improved[1]		Traditional[2]	
Year	Seasonal rainfall (mm)	Runoff (mm)	Soil loss t ha^{-1}	Runoff (mm)	Soil loss t ha^{-1}
1976/77	688	73	0.80	238	9.20
1977/78	586	1	0.04	53	1.68
1978/79	1125	273	3.40	410	9.70
1979/80	690	73	0.70	202	9.47
1980/81	730	116	0.90	166	4.58
1981/82	1126	332	5.00	435	11.01
1982/83	615	10	0.20	20	0.70
1983/84	956	154	0.80	289	4.70
Mean	814	130	1.48	227	6.38

1. Improved system: Double-cropping with improved (broadbed-and-furrow) land management system.
2. Traditional system: Traditional flat system, with a single crop in the postrainy season following rainy-season fallow.

in terms of both low yields and high soil and water losses (Table 1). Water-balance studies of traditional Vertisol management systems at ICRISAT Center indicated that of the total rainfall, 24% was lost as runoff and 46% was lost as evaporation and deep percolation, thus leaving only 30% of rainfall for use in crop production (Table 2).

In the following section, we discuss the components for improved resource utilization and productivity of Vertisols.

Components of the Improved Technology

Land and Water Management

Improved land and water management practices for alleviating the physical constraints of Vertisols should promote intake of water, improve aeration and workability, reduce erosion and runoff, and facilitate safe disposal of excess water. To imple-

Table 2. Comparison of estimated water balance in Vertisol watersheds under improved and traditional management systems at ICRISAT Center over eight years (1976-83).

	Management system			
	Improved[1]		Traditional[2]	
Water-balance component	Amount (mm)	% of rainfall	Amount (mm)	% of rainfall
Water used by the crops (evapotranspiration)	607	67[3]	271	30[3]
Water lost as surface runoff	130	13	227	24
Water lost as bare soil evaporation and deep percolation	180	20	416	46

1. Improved system: Double-cropping with improved (broadbed-and-furrow) land management system.
2. Traditional system: Traditional flat management system, with a single crop in the postrainy season following rainy-season fallow.
3. Rainfall-use efficiency.

ment the improvements in drainage and runoff utilization, the topographical features of the land and the natural drainage pattern need to be taken into account. In our studies at ICRISAT Center, microwatersheds (3-15 ha) were taken as units for land and water management, and for agronomic practices. Because surface water in a watershed drains to a single outlet, we believe that the watershed is better suited than other land units for planning and installing efficient water conservation and reuse systems. Land smoothing and construction of surface drains are the first steps for improving surface drainage. In order to achieve greater efficiency, smoothing should be done in the direction of cultivation. Often, it is possible to improve the natural drains by clearly delineating, shaping, and straightening them. Animal-drawn implements and human labor were found to be adequate for executing land smoothing (Fig. 2) and surface drain construction at a reasonable cost in India (Kampen 1982).

Land Configuration

At ICRISAT Center, a broadbed-and-furrow (BBF) system—involving graded wide beds separated by furrows, which drain into grassed waterways—has been found to improve surface drainage and workability of the Vertisols. The flat bed and the furrow portions are 100 and 50 cm wide, respectively. A schematic sketch of the layout for a BBF system in a self-contained watershed is shown in Figure 3. The runoff water may be either drained out of the watershed or collected and stored in tanks within the watershed for later use as supplemental irrigation. The decision about runoff-storage tanks and their design should be based on runoff characteristics, seepage and evaporation losses, and response of crops to supplemental irrigation (Harikrishna 1982).

On the Vertisols at ICRISAT Center, the draft power requirements for cultivation operations were lower by about 30% in the BBF system than in the flat. Lower penetration resistance on beds (Fig. 4) facilitated land preparation during the dry season, as well as placement of fertilizer and seeds in dry soil at the desired depth (8-10 cm). Furthermore, air-filled porosity in the upper 15-cm layer was found to be significantly higher for BBF than for the flat system during wet spells (Fig. 5). Use of BBF increased profits by 30% compared with flat cultivation of a

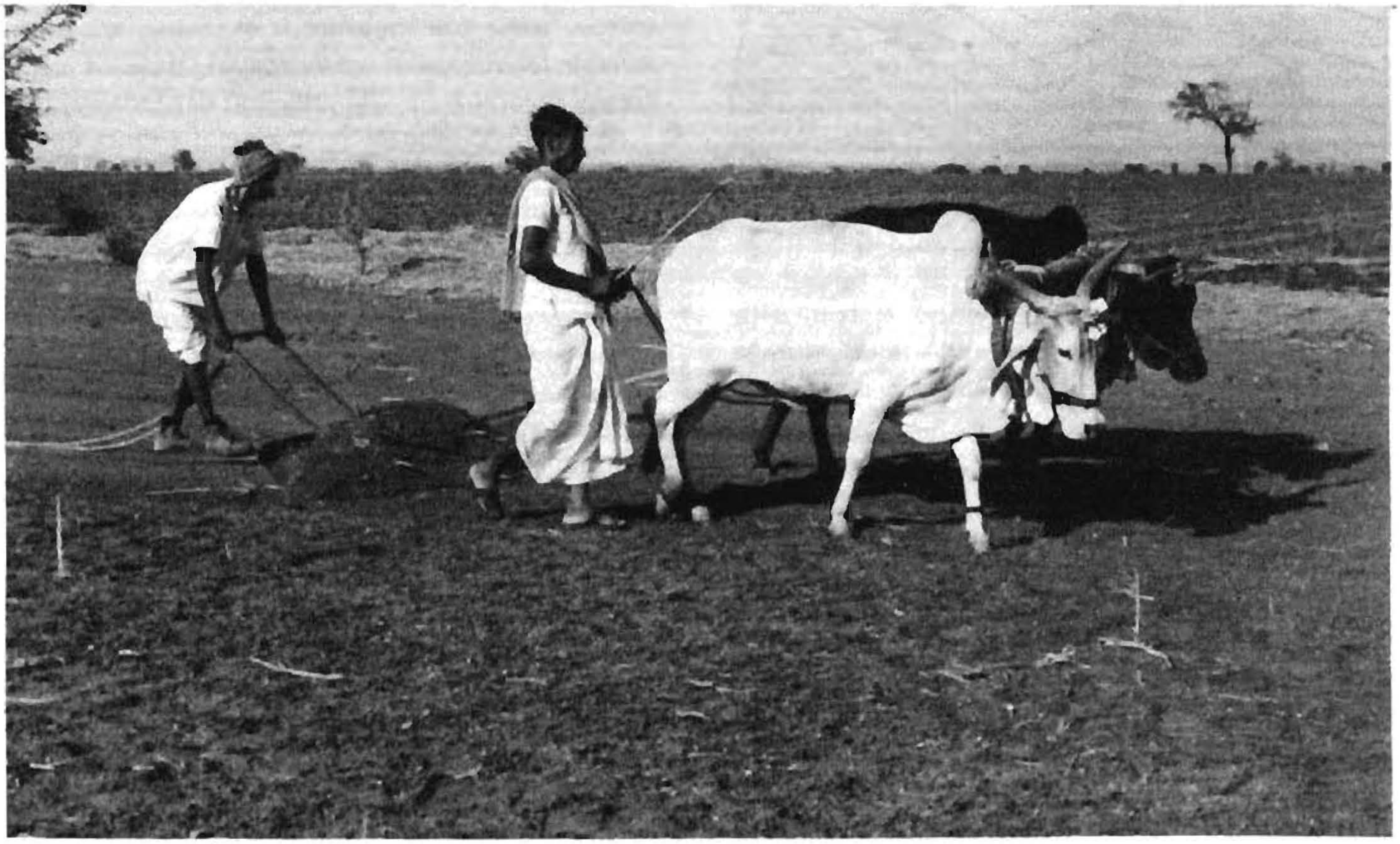


Figure 2. Land smoothing by a bullock-drawn scraper.

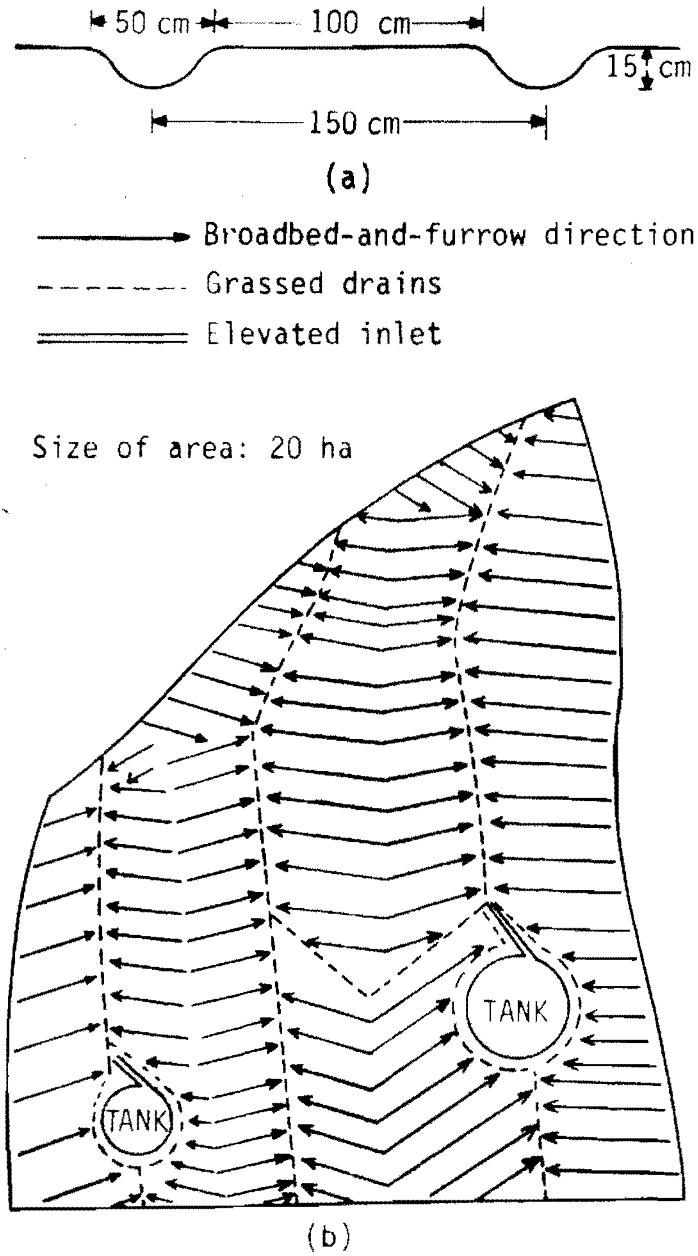


Figure 3. (a) A section of the broadbed-and-furrow configuration; (b) schematic sketch of watershed-based land and water management system, with broadbed-and-furrow layout and runoff storage tanks (After Krantz et al. 1981).

maize/pigeonpea intercrop, and by 20% for a maize-chickpea sequential system (Ryan and Sarin 1981).

Dry-Season Tillage

At ICRISAT Center, primary tillage operations to loosen the soil and prepare a rough soil surface are carried out just after harvest of postrainy-season crops in February or March. This leads to a cloddy soil surface. During the period from March to May, clods gradually disintegrate due to premonsoon rains and fluctuations in diurnal temperatures. If blade harrowing is done soon after such rains, the clods easily shatter and a satisfactory seedbed is attained.

Dry Sowing Ahead of Rainy Season

At ICRISAT Center, crops are planted in the dry soil just ahead of the monsoon rains to ensure early establishment and avoid the difficulty of planting in the wet, sticky soil. But success of dry sowing is dependent on both fairly dependable rainfall in the beginning of the rainy season, and deeper placement of seeds. Good stands can be established by dry seeding of crops such as mung, sunflower, maize, sorghum, and pigeonpea. Results were not satisfactory, however, for pearl millet, soybean, and groundnut.

Improved Cropping Systems

Improved cropping systems are a key component of the improved technology because they contribute substantially to increased crop yields and higher returns. Systems that provide crop growth from the beginning of the rainy season well into the postrainy season, while soil moisture is available, are most suitable for situations where annual rainfall is moderately favorable (> 750 mm, and dependable).

At ICRISAT, the intercropping of a short- and a long-season crop—such as pigeonpea—or sequential cropping of two short-season crops has been found most suitable. A number of crops can be fitted into these two basic systems: pigeonpea, for example, can be intercropped with maize, sorghum, soybean, cowpea, sesame, and sunflower. In the sequential system, maize, sorghum, or soybean can be followed by wheat, chickpea, safflower, or postrainy-season sorghum.

The production potential of a number of cropping systems options, as examined in small-scale experiments at ICRISAT Center, has been discussed by Willey et al. (1989). The discussion in this paper is limited to our experiences on operational-scale watersheds.

Fertility Management

Vertisols are generally deficient in nutrients. Fertilization is needed because the improved cropping systems, covering the rainy and postrainy seasons, have greater nutrient demands than the traditional single-season cropping system, particularly when crops in both seasons are non-legumes (e.g., maize-safflower); the potential benefits of improved cropping systems and management are not realized fully without adequate fertilizer input.

The three important components of the improved technology—improved genotype, improved management of both land and crop, and use of fertilizer—were examined individually and in combination on a maize/pigeonpea intercrop. Improvement in genotype or land and crop management resulted in only small improvements in yield. Applying fertilizer alone doubled the cereal yield, even

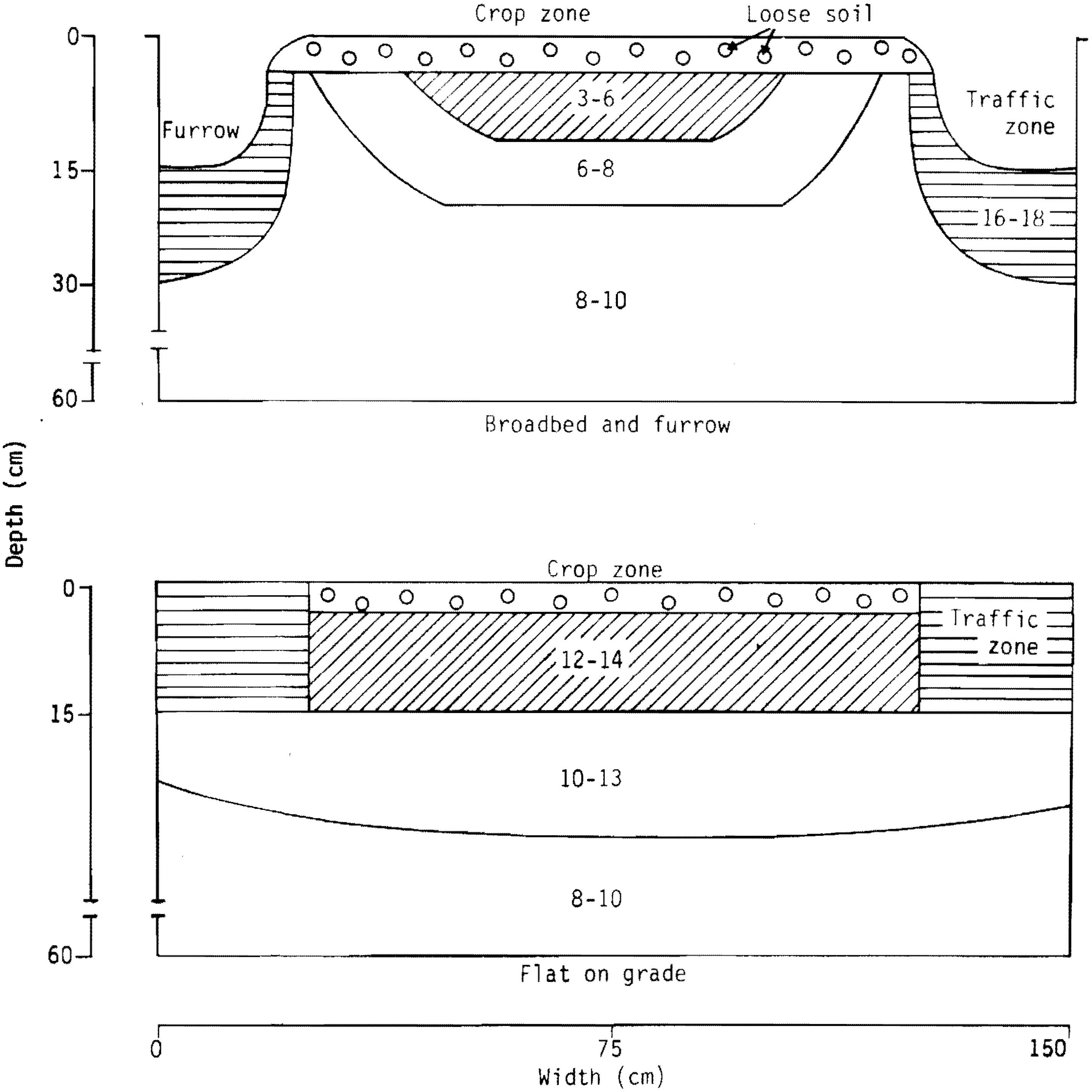


Figure 4. Penetration resistance zones (expressed in kg cm^{-2}) under broadbed-and-furrow and flat systems on Vertisols at ICRISAT Center. Gravimetric moisture contents were 24 ± 1.9% for 0–15 cm soil depth, 31 ± 2.4% for 15–30 cm, and 33 ± 2.9% for 30–60 cm. (Source: Srivastava et al. 1983).

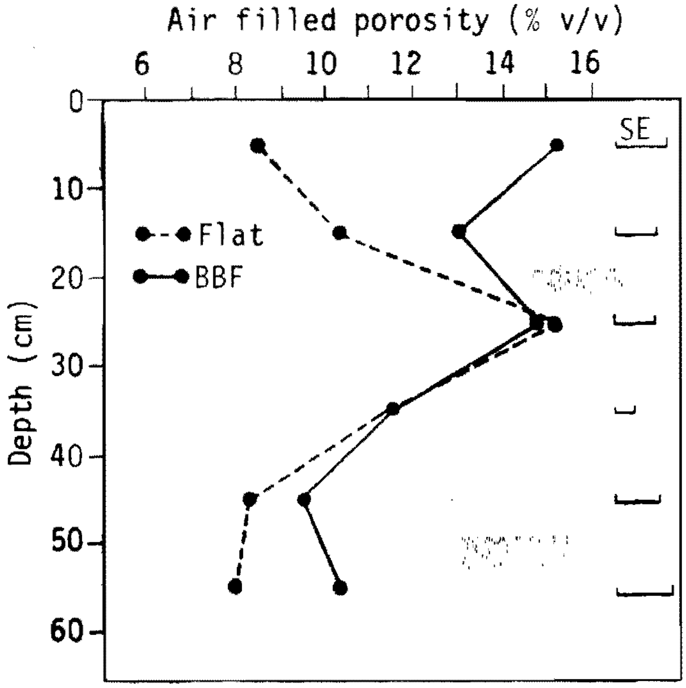


Figure 5. Air-filled porosity of Vertisols at high moisture content, under broadbed-and-furrow and flat land-management systems at ICRISAT Center, late August–early September, 1980 (Source: Srivastava et al. 1983).

though other components were not improved. But the effect of fertilizer was much more striking in combination with improved genotype or improved management, where the yields increased by twofold to threefold. When all the three factors were combined, the yields increased by more than fourfold (ICRISAT 1980). These results highlight the importance of fertilizer application and the synergistic effects than can occur among various inputs when they are used in combination.

Responses to N fertilization were much higher than with any other nutrient, and in a given year, response in the rainy season was greater than in the postrainy-season. Seasonal differences in rainfall and its distribution influenced the nitrogen responses (Burford et al. 1989). Other studies have confirmed that the cereals in intercrops respond to fertilizer N as in sole crops. Responses to P are also widespread especially in the case of cereals, and 15 to 20 kg P ha^{-1} can be recommended as a component of the improved production technology on Vertisols (El-Swaify et al. 1985). K fertilization is not required for rainfed Vertisols in India. Zn deficiency, seldom noticed under traditional systems, soon develops under continued intensive cropping with high-yielding genotypes; it needs to be corrected for sustained crop yields.

Equipment

For the successful implementation of the watershed-based Vertisol management system, an animal-drawn wheeled tool carrier has been adopted at ICRISAT to carry out such operations as seedbed preparation, sowing, fertilization, and weeding. This equipment helps improve the efficiency of bullocks, the most abundant locally available power source (Bansal and Srivastava 1981). Our recent experience in Central India has shown that the BBF system could also be successfully laid out by using tractor-drawn implements. The central aim of introducing some level of mechanization is to adequately prepare the land in time.

Pest Management

Weed Control

Weeds have not been a serious problem in the traditional low-production systems of Vertisol management because farmers are able to control them by repeated cultivation of the land during the fallow period. But in the double-cropping systems, especially with rainy-season crops planted by the dry-seeding technique, increased weed infestation is observed, which, if not managed properly, may lead to serious losses in crop yields. Since dry seeding precludes mechanical control of weeds that emerge with early showers, weeds also establish well along with crops. The restriction of cultivation to the bed area in the BBF system further increases weed infestation.

Three different weed management systems (hand weeding, herbicide, and smother-crop systems, in which extra-early-maturing, low-canopy legumes were introduced into main crops to suppress weeds) and a weedy check were compared with a weed-free system on an operational scale at ICRISAT Center (Table 3). Returns were 62% less in the weedy check than in the weed-free system. The herbicide and smother-crop systems with cowpea achieved 93% and 88% of the potential returns, respectively. Binswanger and Shetty (1977) have discussed the use of herbicides vis-à-vis hand labor for weeding: in situations where manual or mechanical weed control is difficult because of wet soil conditions, the use of herbicides appears desirable.

Table 3. Effect of weed management systems on yields and gross profits in a maize-chickpea sequential system in Vertisols over 2 years (1979/80 and 1980/81) at ICRISAT Center.

Weed management system	Grain yields (kg ha^{-1}) Maize	Chickpea	Gross returns (Rs ha^{-1})	Cost of weed control (Rs ha^{-1})	Returns minus cost of weed control (Rs ha^{-1})
Hand weeding (2 in rainy season + 1 in postrainy season)	2830	550	4870	430	4440
Herbicide system (Atrazine to maize and 1 weeding each in rainy and postrainy seasons)	3390	610	5630	550	5080
Smother-crop systems: (Smother crop + 1 weeding each in rainy and post-rainy seasons)					
(a) Smother crop of mungbean	2390	560 (220)[1]	5050	410	4640
(b) Smother crop of cowpea	2750	560 (200)[1]	5250	410	4840
Weed free (3 weedings in rainy season + 2 in postrainy season)	3660	690	6180	700	5480
Weedy check	1340	190	2000	-	2000
SE	±198	±42	-	-	

1. Yields of smother crops.

Insect Control

Our cropping entomology unit experimented with Controlled Droplet Applicator (CDA) units, mounted on the animal-drawn wheeled tool carrier. Each unit covers 1.5 m, and three such units were mounted on a machine having high ground clearance to avoid damage to pigeonpea. This required only one laborer and covered 1 ha in about an hour; thus the labor cost was only Rs 1.25 ha^{-1} (Pawar 1985). Another advantage with the CDA is that the quantity of water required for preparing the spray mix is very small (8–10 L water, compared to 500–600 L with the normal high-volume sprayers). For the most important insect pest on pigeonpea, *Heliothis*, spraying is recommended when infestation exceeds an average of 100 eggs and/or 3–5 small larvae (3–5 mm long) per plant.

Evaluation of Alternative Technologies at ICRISAT Center

Two main types of cropping systems were successful on experimental watersheds at ICRISAT Center: (i) the sequential system, with two crops grown, one during the rainy season (e.g., maize) and the other during the postrainy-season (e.g., chickpea); and (ii) the intercropping system, in which two crops are sown simultaneously at the beginning of the rainy season; one of them matures at the end of the rainy season (e.g., maize), and the other during the postrainy season (e.g., pigeonpea). Comparisons have been made between these two improved cropping systems and the traditional system of rainy-season fallow. The crops in the improved systems were grown on BBF using improved cultivars, and a moderate level of fertilizers (60 kg N and 13 kg P ha^{-1}). All field operations were carried out with the animal-drawn wheeled tool carrier. The yields of these systems over an 8-year period are given in Table 4.

Yields from the improved systems were substantial; averaged over 8 years, they were 3230 kg ha^{-1} of maize and 1170 kg ha^{-1} of chickpea in the sequential system, and 2710 kg ha^{-1} of maize and 1120 kg ha^{-1} of pigeonpea in the intercrop. Both these systems substantially outyielded the traditional system where only a single postrainy-season crop of chick-

Table 4. Grain yields of improved (double cropping) and traditional (postrainy-season) cropping systems in operational-scale watersheds at ICRISAT Center over eight years, 1976/77 to 1983/84.

	Rainfall during cropping period	Improved systems				Traditional system	
		Maize/chickpea sequential		Maize/pigeonpea intercrop		Single crop, postrainy season	
Year	(mm)	Maize	Chickpea	Maize	Pigeonpea	Chickpea	Sorghum
		(kg ha^{-1})					
1976/77	708	3120	650	3290	780	540	440
1977/78	616	3340	1130	2810	1320	870	380
1978/79	1089	2150	1340	2140	1170	530	560
1979/80	715	3030	590	1950	890	450	500
1980/81	751	4190	790	2920	970	600	560
1981/82	1073	3450	1320	2840	1070	1050	640
1982/83	667	3420	1380	2970	1030	1240	630
1983/84	1045	3020	2120	2780	1740	480	840
Mean	833[1]	3230	1170	2710	1120	720	570
CV (%)	25	18	43	16	27	41	25

[1] Mean rainfall over 70 years (1901-1970) is 760 mm, with a CV of 24%.

pea or sorghum was grown without the benefit of broadbed-and-furrows, improved seeds, or fertilizer—and yielded less than 750 kg ha^{-1}, on average. The variability in crop yields, as measured by the coefficient of variation, was much lower in the improved systems than in the traditional system. Between the two improved systems, the better performance of the intercrop is noteworthy. Cereals' yield in the intercrop was only slightly lower than in the sequential system: pulse yields were similar, but they were less variable in intercropping than in the sequential system.

Maize is the preferred cereal in the improved systems because its cultivation poses fewer problems than cultivation of sorghum: it does not tiller; it does not suffer from shoot fly attack; it does not get head-mold infestation, which can be a problem on sorghum sown early so as to permit planting of a second crop. Unlike sorghum, maize does not ratoon and hinder planting of postrainy-season crops; further, maize tops can be removed or 'doubled over' after physiological maturity to minimize competition to pigeonpea in intercropping.

Monetary returns from these improved watershed-based technological options, compared with the traditional system, were evaluated by Ryan and Sarin (1981). Gross profits from the improved maize/pigeonpea intercrop averaged Rs 3650 ha^{-1}a^{-1} over a 5-year period (1976 to 1981), compared to Rs 490 ha^{-1}a^{-1} from the traditional system. Though the improved system required an additional investment of Rs 1140 ha^{-1}, it earned an additional profit of Rs 3160 ha^{-1}, giving a most attractive rate of return (277)%. The sequential system, however, incurred higher costs from additional expenses for planting the second crop, giving a 155% rate of return. The intercropping system is attractive for other reasons as well: (1) it avoids planting the second crop in October when demand for labor is at a peak, and (2) it obviates the risk of the crop not getting established when the rains cease early and the surface soil becomes dry.

On-Farm Verification

Testing at Different Locations

To test the performance of the improved technology, on-farm tests were initiated in 1981 in Taddanpally village, 42 km northwest of ICRISAT Center (Ryan et al. 1982). The soils there are deep Vertisols (> 1 m deep), and a substantial area is fallowed in the rainy season. The initial test was conducted on a small watershed of 15.4 ha, involving 14 farmers, in collaboration with the Andhra Pradesh State Department of Agriculture, Andhra Pradesh Agricultural University, and the All India Coordinated Research Project for Dryland Agriculture. The experiment was meant to assess the biological and economic performance of the system. Subsidies or inputs to farmers were kept to a minimum. Farmers were encouraged to use the existing institutions for credit and input supplies. However, as a step toward winning the confidence of the farmers, an assurance was given that they would be compensated for any losses from the application of the improved technology.

ICRISAT provided two wheeled tool carriers, with accessories, and power sprayers. Advice for laying out drainage channels to service the entire watershed, for survey of the watershed, and on pest and insect control, was given. Scientific and technical guidance were provided and scientists visited frequently. All inputs—such as fertilizers, seeds, pesticides, fuel, labor, bullocks—were provided by the cooperating farmers, either by themselves or through purchase on credit.

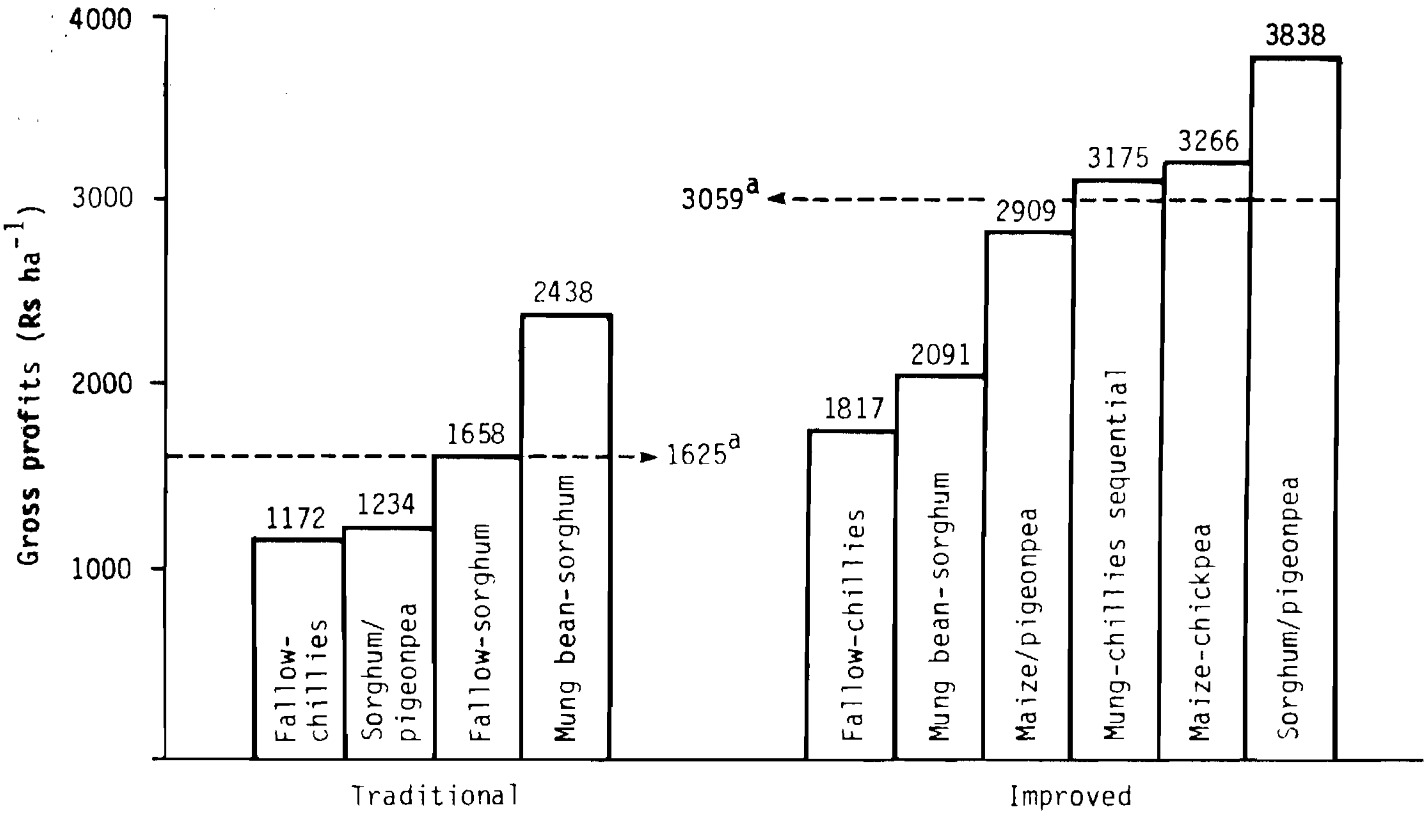
In February 1981, the area was surveyed and the watershed laid out without disturbing property lines. Then the farmers carried out land smoothing and made drainageways, using their own animals. Farmers quickly acquainted themselves with the wheeled tool carrier equipment. Although they had relatively small bullocks, and the soil was hard because harvest of crops had been delayed, the farmers were able to establish the broadbeds reasonably well. The total cost for developing the watershed was modest (Rs 254 ha^{-1}).

ICRISAT staff and other research agencies suggested what crops would be best, but farmers were allowed to make their own choices. As a result, nine cropping systems were tried. The rainy-season crops were planted in the dry soil ahead of the rains. The plant stand was good. In terms of crop production, as can be expected, some problems different from those encountered at ICRISAT Center did arise. These were: *Striga* weed on improved maize and the sorghum hybrids; inability of the farmers to cope with the harvest, threshing, and storage of the unconventional rainy-season crops (partly aggravated by the unusually wet conditions that year); and ineffective control measures against pod borer on the postrainy-season crops. Despite these problems, however, the improved technology performed remarkably well (Fig. 6). The average profit from the treated watershed was Rs 3059 ha^{-1}, 88% more than that obtained from the traditional system dominated by rainy-season fallow and postrainy-season sorghum. The improved system involved an additional operational expenditure of Rs 588 ha^{-1} but, interestingly, the rate of return on this added expenditure at 244% was close to that observed (254%) at ICRISAT Center. Sorghum/pigeonpea was the most profitable cropping system (Rs 3838 ha^{-1}), followed by the maize-chickpea sequential (Rs 3266 ha^{-1}).

Comparison of profits from sorghum/pigeonpea intercropping in the traditional and improved systems demonstrates that an improved cropping system in itself may be necessary, but it is not the only component that contributes to substantially higher profitability. Other practices—such as use of fertilizers, timely operations, pest management, and soil management—are necessary for deriving full benefits from the improved cropping systems.

In 1982/83 the on-farm test was repeated at Taddanpally and extended further to other Vertisol areas with problems different from those at ICRISAT Center (ICRISAT 1984). At two locations, Farhatabad (Karnataka) and Begumgunj (Madhya Pradesh), ICRISAT scientists directly supervised the tests, but at other locations they were conducted by the respective State Departments of Agriculture with advice from ICRISAT as required. Farhatabad has an average annual rainfall of 730 mm, and Begumgunj 1100 mm; early-season rains are much more assured at Begumgunj than at Farhatabad. Since some of the crops popular at these two ICRISAT-supervised sites were different from those tested at ICRISAT Center, cropping systems trials were conducted on the Government Seed Farms near these sites to evaluate locally recommended cropping systems and other options (Willey et al. 1989). The verification tests thus expanded to 22 locations in 1982/83, covering 1235 ha in four states. In these tests in the dependable-rainfall areas, the improved technology continued to perform well. The marginal rate of return on additional investment ranged from 26 to 381%, averaging about 240% (Table 5). Development costs for the watershed sites ranged from Rs 182 to Rs 1035 ha^{-1}; the highest cost was in Madhya Pradesh at Begumgunj where expenses for drain construction were high because of higher rainfall and the use of tractors instead of bullocks to develop the watershed.

The relative profitability of the improved technology (weighted over all the watershed cropping systems) was low at Begumgunj, compared with other locations, because of an unusual dry spell in late June and early July, followed by heavy rains leading to poor stand and inefficient weed control. Yet the



a. Weighted averages over all cropping systems.

Figure 6. Gross profits from major cropping systems in Taddanpally, 1981/82 (Source: ICRISAT 1983).

Table 5. Annual profitability (Rs ha^{-1}) of improved Vertisol management technology, compared to farmer's present practices in on-farm verification trials (1982/83) in four Indian villages.

Village District, State	Gross Profits (Rs ha^{-1})			Operational cost (Rs ha^{-1})			Marginal rate of return (%)
	Improved	Traditional	Difference	Improved	Traditional	Difference	
Taddanpally, Medak, Andhra Pradesh	3957	1722	2235	1035	448	587	381
Sultanpur, Medak, Andhra Pradesh	3576	1722	1854	1062	448	614	302
Farhatabad, Gulbarga, Karnataka	3323	2186	1137	1194	1142	52	-[1]
Begumgunj, Raisen, Madhya Pradesh	1172	786	386	2348	866	1482	26

Source: ICRISAT (1984).

1. Difference in operational costs was too small for meaningful comparison.

trial gave encouraging results, with the majority of farmers recognizing the potential of the system. Moreover, some cropping systems involving soybean, such as soybean/pigeonpea, emerged as the most promising (gross profit Rs 3535 ha^{-1}), followed by soybean-lentil (Rs 3215 ha^{-1}). The marginal rate of return calculated on the basis of these cropping systems was 175%. At Farhatabad, where the average rainfall is lower than at ICRISAT Center and less dependable, sole pigeonpea produced gross returns of Rs 4186 ha^{-1}, followed by mungbean-sorghum with Rs 4059 ha^{-1}. These were much better than the existing traditional system, a 2-year rotation of fallow-sorghum and pigeonpea, which gave only Rs 2186 ha^{-1}. At Taddanpally, where rainfall is similar to that at ICRISAT Center, the sorghum/pigeonpea intercrop produced the highest gross profits (Rs 4859 ha^{-1}).

In 1983/84 the on-farm verification trials were continued at Farhatabad and Begumgunj under the direct supervision of ICRISAT. At Farhatabad, rains started one month later than normally expected, resulting in the loss of viability in the dry-seeded crops and poor plant stand. However, waterlogging caused by subsequent continuous rains showed the importance of BBF in draining excess water. The cropping system that gave the highest gross profits was sesame/pigeonpea (Rs 7916 ha^{-1}), followed by sole pigeonpea (Rs 5228 ha^{-1}). The groundnut/pigeonpea intercrop (Rs 3524 ha^{-1}) gave higher returns than black gram/pigeonpea (Rs 2092 ha^{-1}). At Begumgunj, the improved technology performed well despite the occurrence of frost and fusarium wilt in pigeonpea.

Feedback from On-farm Verification

The multilocational on-farm testing has provided valuable information on the potential benefits of the technology for improved management of Vertisols and the regions of its adaptation, as well as its limitations; the testing has also raised questions that need further study. Given below are some of our experiences.

Not all components of the technology made a similar impact on farmers. While most farmers have realized the benefits of improved cropping systems, crop management, and fertilization, the BBF system appears to be needed only where waterlogging is a problem. Construction or improvement of surface drains was found to be important in most situations; neglect of this aspect caused ponding of water and crop damage (Fig. 7). Our experience shows that farmers are willing to construct the field drains required for good drainage within their fields, but they do not participate readily where drains are located outside their fields or involve drainage flows of many farmers. Policy guidelines and institutional arrangements for constructing community drains are required (Ryan and Sarin 1981).

Farmers have generally recognized the value of the wheeled tool carrier for making the broadbed-and-furrows, saving bullock power, and improving seed and fertilizer placement, and they were keen to use it. But in view of its high cost (Rs 8000 to 10000 each), very few are actually prepared to buy it.

Improved cereal genotypes will not be readily accepted by farmers unless they possess adequate tolerance to pests and diseases, and have good grain quality characteristics. Some of the new sorghum varieties (e.g., CSH 6, CSH 5) mature earlier than local sorghums and suffer from grain molds. These also showed greater susceptibility to *Striga*. Introduction of a new crop in an area should be viewed from the standpoint of fodder quality, availability of postharvest handling facilities, marketing, and pest susceptibility. Despite attractive profits from maize-based sequential systems, farmers in Taddanpally did not include it in the 2nd year of testing because, according to them, 1) cattle do not relish fodder of maize as much as that of sorghum, 2) maize suffered from *Striga* and nutritional disorders, and 3) shelling of maize is relatively costly (Sarin and Walker 1982).

Both on-station and on-farm work clearly showed the potential for using fertilizer in rainfed agriculture. Similarly, farmers fully realized the need for timely plant protection on pulse crops. Our experience shows that unless fertilizer and pesticides of the desired type are available within a short distance, dryland farmers will not use them. Moreover, since these inputs are costly, small farmers may not use them unless supported by institutional credit schemes.

Need for Agroclimatic Stratification

Probability analysis of rainfall and characterization of soil moisture variability of an environment help in deciding the applicability of new management approaches and for predicting further adjustments needed. Agroclimatic analysis in extending Vertisols

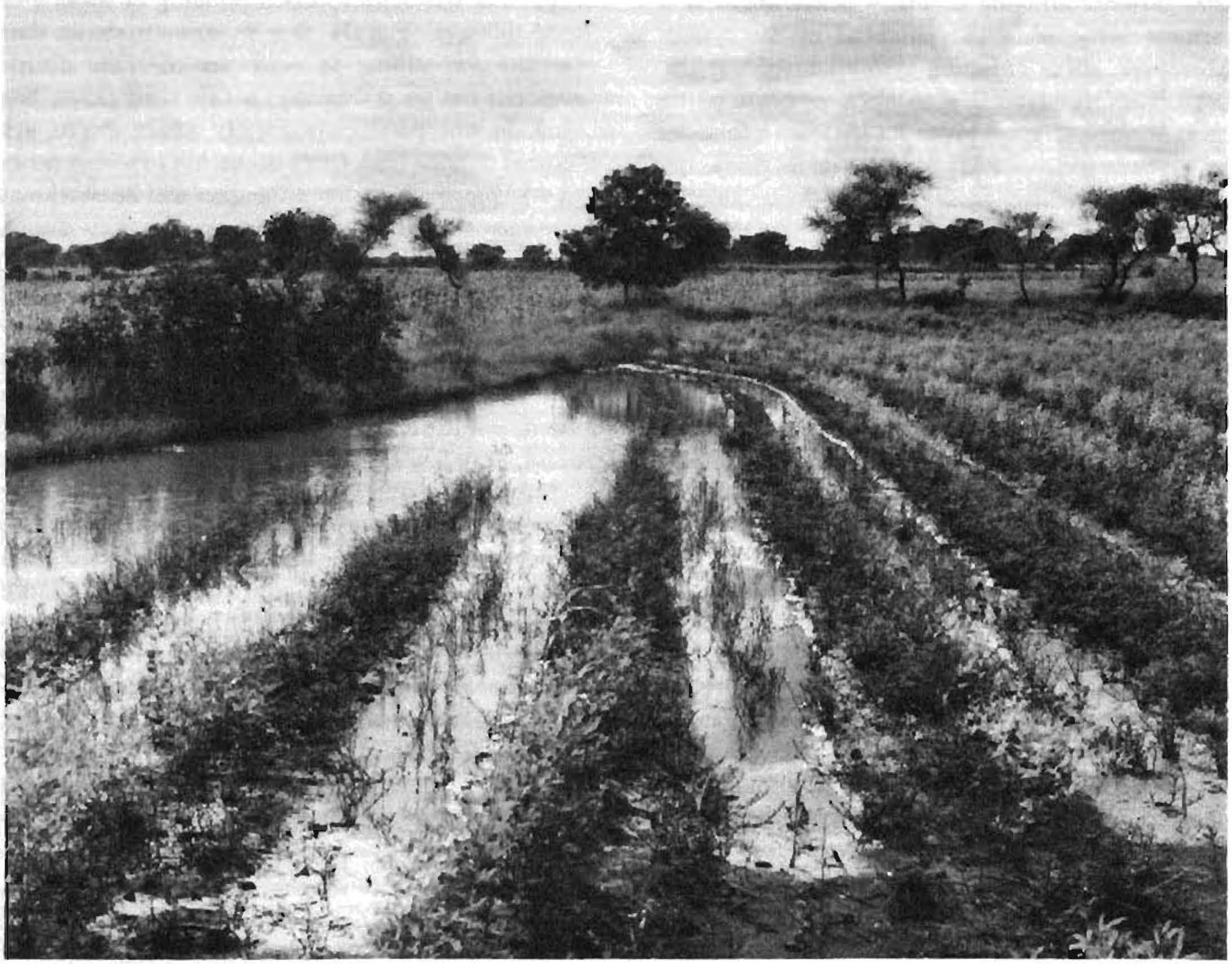


Figure 7. Water ponding in the lowest part of a farmer's field. Surface drains are necessary for efficient disposal of excess water.

technology is particularly important for the adoption of dry seeding of crops, and for determining the prospects for double cropping. Dry seeding is successful only in such places (e.g., Hyderabad) where rains commence abruptly and where early-season rainfall is dependable (> 70% probability); dry seeding is risky in places (e.g., Sholapur) where early-season rainfall is erratic (Virmani 1980). Double cropping is recommended for situations where the growing period is 23 weeks or longer. Quantification of the available soil moisture at the end of the rainy season is important for the success of the postrainy-season crop. Sequential cropping is recommended in areas where some rainfall is assured at the time of its sowing. Further work on classification of agroclimatic environments in Vertisol regions of the world is needed for predicting the success of alternative practices.

Concluding Comments

Vertisols are found in diverse agroecological environments. However, many of their qualities vary little. These are their high clay content, difficult water management, and gentle slopes. In India, differences in their management are primarily due to their location in a toposequence and prevailing agroclimatological regimes, which determine the choice of cropping systems.

The improved Vertisols technology developed at ICRISAT provides a framework for increasing crop yields on a sustained basis, while improving the land resource. Its components offer several options in each case. For instance, fertilizer levels can be varied according to targeted yields, available soil moisture, and soil nutrient levels; the design and layout of the surface drainage system can be varied according to amount and distribution of rainfall and topographical features of the land; and an array of cropping systems is available.

ICRISAT's experience in verification and transfer of the improved technology has shown that it has the potential to be highly productive in areas agroclimatically similar to ICRISAT Center. It must be recognized, however, that the improved technology requires to be fine-tuned for different environments. The principles and approaches followed at ICRISAT can be utilized for devising appropriate technologies for Vertisols in different agroclimates. Multilocational testing of various components and packages would lead to rapid identification of suitable technologies. Training of field staff and middle-level administrators has been found important for extending the technology, which can best be carried out by the coordinated effort of multidisciplinary teams involved in the development of technology.

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Discussion

Burnett: You referred to the storm runoff impounded in small runoff reservoirs and said it might be used for supplemental irrigation, but you did not show this application. Is the runoff water used to irrigate during stress periods?

Virmani: Experience showed that there was only a small increase in yield with supplemental irrigation in most years, and in some years no runoff water was available. Thus the profitability of reservoir development is doubtful.

Dudal: (1) The new ICRISAT technology has been worked out for deep Vertisols. What is the depth of these 'deep' soils, and what is being measured? (2) How is the response of the technology on shallower Vertisols? (3) What is the proportion of deep Vertisols in the study area that ICRISAT has covered?

Virmani: (1) Our experience has shown that the technology is applicable to those areas where the available water-holding capacity of the soil is at least 150 mm, which requires a soil depth of at least 80 cm or so.

Swindale: Vertisols have minimum depths of 50 cm, so we are really talking about a deeper phase than minimum.

Taimeh: (1) What was the method used to redistribute the harvested water, and what was the anticipated cost if sprinkler irrigation were used? (2) How did the farmers react to this new adopted technology, and was it hard to convince the farmers to adopt this technology?

Virmani: (1) In terms of the water harvesting, there are two issues: (i) if the water is used on the donor area, i.e., the area from which the water was harvested, the cost is quite high, as one has to use a pump to bring it back and apply it. (ii) If the water is used below the tank, it is easier and cheaper because gravity is used. In the Indian context, the costs worked out by Dr J. Ryan were about 25 Rs/cm/hectare of water application. We applied it by *gated* pipes in the furrows. We applied only 2–4 cm, but laying out the whole system makes the cost high. With high-value crops, such as tomatoes, it paid off, but not with arable crops, such as pigeonpea. (2) The new technology has to be demonstrated at the door-steps of the farmers, so that they can be convinced over a couple of years.

Blokhuis: You mentioned an available water-holding capacity of 220 mm in the upper 185-cm of the soil profile. If this figure is based on measurements in the laboratory, are you sure that all this water reached the 185-cm depth? In other words: is this a capacity only, or is this amount really available to the plant roots?

Virmani: The figure of 220 mm is the plant-extractable water in the 185-cm profile, determined from field measurements of maximum and minimum water contents of the soil. The maximum water content is obtained from an uncropped profile following cessation of drainage, after infiltration of water in excess of that required to fully recharge it. The minimum water content of the profile is obtained by measuring the water content of the soil profile after maturity of well-managed, deep-rooted, long-season crops grown in the postrainy season. This plant-extractable available water is less than that obtained from 15-bar and 1/3 bar moisture contents (determined in the laboratory), which result in an available water content for the 185-cm profile of 300 to 350 mm.

Swindale: The internal rate of return (IRR) at Begumganj was low because some of the farmer-suggested cropping systems were not suited to the technology. The ICRISAT-suggested cropping systems gave high IRRs.

Vertisols in Different Agroecological Zones

Vertisols of the Semi-Arid Tropics

W.A. Blokhuis[1]

Abstract

Vertisols, as classified at the highest category in Soil Taxonomy (USDA 1975) and in the French Classification System (CPCS 1967), are a remarkably homogeneous group of soils with a specific morphology, and with mineralogical, physical, and chemical properties that vary within a narrow range.

Optimum environmental conditions for their formation include a seasonally moist, tropical climate; restricted internal drainage; lack of runoff; and a parent material that contains, or yields on weathering, sufficient Si, Ca, Mg, and other ions that, under alkaline soil conditions, produce a smectitic clay. About 70% of all Vertisols occur in the semi-arid tropics.

The central concept of the order (in Soil Taxonomy) is a Typic Ustert belonging to the fine clayey, montmorillonitic, isohyperthermic family. The typical morphology of this soil is a structure profile that shows surface mulch, cracks, wedge-shaped peds with shiny faces in a multiple compound structure, and slickensides. Next to this central concept, arid, subhumid, and sodic variants can be conceptually defined.

The behavior of soil water has the greatest effect on agricultural use of Vertisols. Such behavior depends on climatic and site factors, infiltration rate, and hydraulic conductivity. The physical soil factors are difficult to measure in the laboratory and in the field, and this makes estimates of the available water-holding capacity less reliable. These factors are also affected by the nature and concentration of the soil solution and by the composition of the exchange complex. The relative saturation with Na, compared with that of Ca and Mg, more strongly influences shear strength, swelling pressure, plasticity index, and hydraulic conductivity.

Sodic Vertisols—those with an exchangeable sodium percentage (ESP) above 15—cover only a relatively small area in the semi-arid tropics. Identification of sodic Vertisols requires reliable data on ESP and CEC (cation-exchange capacity). The standard method for determining CEC (using ammonium acetate, NH_4OAc, at pH 7) may give faulty results when free carbonates are present; the use of a more recent method developed by Begheijn (1980) using LiEDTA and LiBaEDTA is suggested.

Résumé

Les Vertisols des tropiques semi-arides : *Les Vertisols, tels qu'ils sont classés dans la catégorie la plus élevée de la Taxonomie des sols (USDA 1975), ainsi que dans le Système français de classification (CPCS 1967), forment un groupe de sols remarquablement homogène ayant une morphologie spécifique, et avec des propriétés minéralogiques, physiques et chimiques qui varient peu.*

Les conditions du milieu optimal pour leur formation comprennent : un climat tropical avec une humidité saisonnière; un drainage restreint; une absence de ruissellement; et un matériau parental qui contient, ou qui produit par altération, assez de Si, Ca, Mg et d'autres ions, qui en conditions

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alcalines, produit de l'argile smectique. Environ 70% de tous les Vertisols se trouvent dans les tropiques semi-arides.

Le concept central de l'ordre (dans la Taxonomie des sols) est un Ustert Typique (Typic Ustert) qui appartient à la famille finement argileuse, montmorillonitique et isohyperthermique. La morphologie typique de ce sol est un profile à structures qui montre des paillis en surface, des fissures, des unités structurales en coin à faces brillantes dans une structure composée multiple et des faces de glissement. En plus de ce concept central, des définitions de variantes arides, subhumides et sodiques peuvent être conçues.

Le comportement de l'eau du sol est de la plus grande influence sur l'utilisation agricole des Vertisols. Un tel comportement dépend des facteurs climatologiques et du milieu, du taux d'infiltration et de la conductivité hydraulique. Les éléments physiques du sol sont difficiles à mesurer en laboratoire et sur le terrain, ce qui rend les évaluations de la capacité de rétention d'eau disponible moins fiables. Ces facteurs sont également affectés par la nature et la concentration de la solution du sol et par la composition du complexe d'échange. La saturation relative en Na, comparée avec celle en Ca et Mg, influent encore plus la structure cisaillée, la pression en gonflement, l'index de plasticité et la conductivité hydraulique.

Les Vertisols sodiques—ceux avec un pourcentage de sodium échangeable (exchangeable sodium percentage, ESP) supérieur à 15—couvrent une superficie relativement petite dans les tropiques semi-arides. L'identification des Vertisols sodiques requiert des données fiables sur ESP et CEC (capacité d'échange de cation). La méthode courante utilisée pour déterminer le CEC utilisant de l'acétate d'ammonium NH_4OAc au pH 7 peut donner des résultats inexacts lorsque des carbonates libres sont présents; l'utilisation d'une méthode plus récente développée par Begheijn (1980), employant LiEDTA et LiBaEDTA, est suggérée.

Introduction

In the last few years, attention has focused on Vertisols in a number of conferences, symposia, and workshops, including the following:

- Symposium on Vertisols at the 12th International Congress of Soil Science held at Delhi, March 1982 (ISSS 1982).
- Activities of ICOMERT and ICOMID at the 5th International Soil Classification Workshop, held in Sudan, November 1982 (Soil Survey Administration, 1985).
- 5th Meeting of the Eastern African Subcommittee for Soil Correlation and Land Evaluation and Management (theme: Vertisols), held in Sudan, December 1983 (FAO, 1985).
- Symposium on properties and utilization of cracking clay soils, held in Australia in 1981 (McGarity et al. 1984).
- Symposium on water and solute movement in heavy clay soils, held under the auspices of the International Soil Science Society in Wageningen, the Netherlands, August 1984 (Bouma and Raats 1984).

General introductory papers on Vertisols and a review of their properties were presented at the Delhi symposium and the two meetings in the Sudan. Therefore, in this paper I will concentrate on a few aspects of Vertisols that seem to be relevant to the topic of this Workshop. These are:

- concept and definition,
- environment,
- morphology, and
- soil properties.

Soil properties have a strong bearing on agricultural use, especially those relevant to the water regime and the available water-holding capacity. These include physicochemical factors, such as composition of the exchange complex, and concentration and composition of the soil solution.

Concept and Definition

Vertisols are a group of soils with a specific morphology, and their physical and chemical characteristics vary within rather narrow ranges. Morphology and properties are the consequence of both a smectitic (montmorillonitic) clay mineralogy and the location of these soils in regions with alternate wet and dry seasons. The most important aspect of soil formation in Vertisols is the alternation of water uptake and swelling in the wet season with water loss and shrinkage in the dry season.

Vertisols are classified at the highest level in multicategorical classification systems, such as Soil Taxonomy (USDA 1975) and CPCS (1967). Because Vertisols show greater uniformity in features and properties than do other groups of soils in the same categorical level, it is possible to make some interpretations for agricultural use and management for them at this highest level (Virmani and Swindale 1984).

In this paper, I will adhere to the definition of Vertisols in Soil Taxonomy that centers on three characteristics: more than 30% clay; wide and deep cracks at some time of the year; a specific morphology characterized by one or more of the following three criteria: gilgai microrelief, intersecting slickensides, and wedge-shaped structural aggregates. The first two of these criteria apply equally to vertic subgroups in other orders, which also require a high coefficient of linear extensibility (COLE). Pedons belonging to such vertic subgroups lack the Vertisol morphology, but as they have the appropriate soil material, such morphology easily develops when environmental conditions change (Blokhuis 1982). The third requirement refers to aspects of soil structure and surface morphology. A gilgai microrelief is not always present, but, when present, it is related to slickenside surfaces in the deeper solum; in addition, intersecting slickensides cut the soil mass into wedge-shaped peds. The latter requirement for the Vertisol order could thus be shortened to: have wedge-shaped peds with shiny surfaces.

Environment

Vertisols develop within climates that are warm to hot, with a seasonal rainfall that is both sufficiently high to substantially moisten the soil and sufficiently short to allow a strong desiccation in the dry season. High temperatures during the rainy season promote weathering of rocks and second-cycle weathering of young alluvial sediments.

The restricted length of the wet season prevents strong leaching of the products that result from weathering of rocks or sediment. Essential to the formation of smectite are the presence and availability of Si, Ca, and Mg and a pH above neutral. Leaching of soluble compounds is also hampered when there is slow internal drainage, which can be caused by an impermeable parent rock or parent material. When such material weathers, the permeability of the regolith will further decrease due to the neoformation of clay. In the semi-arid tropics, smectite is the first mineral to be formed as a result of rock weathering. Smectite may also be inherited when the parent material is a sediment, or it may develop when the sediment is subjected to continued weathering. Once smectite has formed, its stability is maintained by a high pH and the presence of free carbonates.

In short, optimum conditions for Vertisol formation are a semi-arid climate roughly equivalent to the ustic soil moisture regime basic parent materials, and landscapes of low relief. The central concept of the Vertisol order is probably a Typic Ustert, belonging to the fine clayey, montmorillonitic, isohyperthermic family. Perhaps one should add: this Vertisol has a surface mulch. The question whether this should be Chromustert or a Pellustert remains to be resolved (see also Comerma 1989).

The semi-arid tropics can be defined in different ways, but world climatic maps based on the various classifications pinpoint roughly the same regions as semi-arid. Comparing the semi-arid regions with the main Vertisol areas of the world (Beek et al. 1980) shows about a 70% overlap.

Morphology

A good understanding of the physical properties of Vertisols requires knowledge of their specific morphology, which is essentially a structure profile (described in detail by Krishna and Perumal 1948, Kaloga 1966, de Vos and Virgo 1969, Blokhuis 1982, and Ahmad 1983.)

In the dry season, the surface of Vertisols develops cracks (2-5 cm wide and 20-50 cm apart) that separate irregular, very coarse prismatic peds. Cracks can be traced to depths between 70 and 150 cm or more, depending upon rainfall (Soil Taxonomy requires that cracks are 1 cm wide at the 50 cm depth; such cracks should then be visible to depths of at least 70 cm.) The prisms have a subangular to angular substructure. Below 20 to 30 cm, but sometimes almost from the surface, the blocky peds acquire a flattened appearance, a feature that is increasingly more distinct with depth; at the same time, the size of the peds increases. Characteristic for Vertisols are these wedge-shaped or double wedge-shaped (described as bicuneate by de Vos and Virgo 1969) structural aggregates. Ped surfaces are shiny, and these have been described as shiny faces or pressure faces, and the larger ones as slickensides.

There is often a further subdivision of the wedge-shaped peds into increasingly smaller structural aggregates of the same shape; the smallest units have dimensions of 2-5 mm. With depth, the grade of this finest substructure decreases; it may show only as a fine lamination. If a structural aggregate showing this lamination is exposed to dry, it falls apart in these smallest units. Fox (1964) observed that when one side of an aggregate sample was ground smooth, water applied to the smooth side penetrated the aggregate along definite lines. From these lines, the soil was wetted laterally. The dimensions of the area between the lines were of the same order as those of the small aggregates that develop spontaneously when a large aggregate is air-dried. It is perhaps justifiable to consider these smallest aggregates as the basic structural units in Vertisols. They are most distinct at the surface, where the soil breaks apart into fine granular or crumb aggregates, forming what is known as a surface mulch. A well-developed mulch may block the entry to cracks, thereby preventing a further infilling. The mulch will also obscure part of the cracks at the surface.

The formation of this structure can be understood from the infilling of the cracks during the dry season by this mulch material. The mulch will then occupy, one could say, part of the volume that the moistened soil requires to accommodate its increased volume when it is wetted. Water uptake in a confined volume causes swelling pressures that result in the sliding of soil masses along each other. This shearing occurs when the shear stress, acting upon a section of the soil body, exceeds the shear strength of that soil body (White 1966, 1967; Yaalon and Kalmar 1978). The internal soil movements generate the bicuneate structure and the glossy nature of ped surfaces (Jewitt et.al. 1979). When shearing is strong, it may cause the development of a gilgai microrelief along pathways that are as yet not fully understood. Some Vertisols that do not develop a surface mulch will still show internal movement; uneven wetting of the soil causes stress and, ultimately, shearing.

The morphology as described above–with surface mulch, cracks, wedge-shaped peds in a multiple compound structure, shiny ped faces, and intersecting slickensides–is the "central concept" of the Vertisol morphology; this can be deduced from numerous descriptions of Vertisol pedons in the semi-arid tropics.

There are gradual changes in this morphology with differences in total annual rainfall and rainfall regime, and with differences in clay percentage, clay composition, saturating ions of the exchange complex, and composition and concentration of the soil solution. Schematically, next to the semi-arid central concept, one can distinguish three variants: arid, subhumid, and "intrazonal" sodic types.

1. **In arid regions**: The surface mulch is thick, 5 to 10 cm (Jewitt et.al. 1979), which is probably related to the occurrence of much finely divided lime in the soil matrix (Kaloga 1966). There is no gilgai microrelief. Cracks are relatively narrow and short. Sola are not deep. Sodicity and salinity may occur.
2. **In subhumid regions**: The surface mulch is thinner or absent (Jewitt et.al. 1979); there is less or no finely divided lime. Soil structure is coarser. Gilgai is distinct. Cracks are wider and deeper. Sola are deeper.
3. **In flooded areas**: Especially when these soils receive runoff water and solutes from surrounding higher ground, sodicity may occur. A soil is defined as sodic when the exchangeable sodium percentage (ESP) is greater than 15. As Na-montmorillonites have higher swelling pressures, a greater shear strength (Warkentin and Yong 1962), and a greater plasticity index than Ca-montmorillonites, both morphology and water regime are different for the two groups. Sodic Vertisols may occur in arid, semi-arid, and subhumid regions.

For both the arid and subhumid regions, there appears to be a correlation between content of finely divided lime and shear strength of the soil (Rimmer and Greenland 1976), and, through this, surface mulch formation and gilgai (Jewitt et al. 1979). This leads to a zonality in Vertisols that can be observed when large stretches of uniform clay plains extend over a wide range of rainfall, as, for example, in the Sudan. Finely divided lime in the soil matrix and a strong dominance of Ca in the exchange complex reduce both the shear and tensile strengths of the clay. Under these circumstances, rupture and shearing take place at relatively low tensile or shear stress.

In flooded areas, interesting observations have been made in the Lake Chad basin in North Central Africa on the occurrence of sodic Vertisols in combination with *solonetz solodisés* and with hydromorphic soils. The *solonetz solodisés* are classified according to Soil Taxonomy (USDA 1975) as Natralbolls, Natraqualfs, and Albic Natrargids. These soils occur together with Vertisols in a catenary succession on pediments and adjacent plains and in young river alluvia. The Vertisols occupy the lowest landscape positions. When the two soil groups occur in a gilgai pattern, the Vertisols occupy the highest positions, the microhighs, and the *Solonetz solodisés* the lowest positions, the microlows. These soils have been described by Bocquier (1973), and their mineralogical relationships by Paquet et al. (1966). The *solonetz solodisés* may represent a degraded Vertisol where clays have become mobile, resulting in the development of an albic and a natric horizon.

Soil Properties

Soil-water regime is the main property of Vertisols that affects their agricultural use. Climatological and site factors, as well as infiltration rate and hydraulic conductivity influence water regime. For crop growth, the available moisture-holding capacity is important. But physicochemical factors are relevant too: it is well-known that Na-saturated smectites have physical characteristics quite different from Ca-saturated smectites. The Na-smectite characteristics dominate when exchangeable sodium exceeds 15-20% (Shainberg et.al., 1971); such an ESP value is quite common in, for example, the Sudan Gezira. Even lower sodicity seems to cause changes in soil characteristics that are quite important for soil use. On the other hand, one may find high ESP values that hardly influence crop growth and soil structure.

Infiltration of rain or irrigation water is initially high in dry soil, reaching values of 50-80 mm h^{-1}, if the surface soil has a well-developed mulch or a fine tilth. Infiltration is very uneven: the surface soil is thoroughly wetted, whereas the subsoil receives water only through the cracks. Terminal infiltration rates, after the cracks have been sealed by swelling of the soil, can be extremely low, below 1.0 mm h^{-1} (Jewitt et al. 1979).

Hydraulic conductivity may be as low as 0.5 to 5.0 mm d^{-1}, and often the central parts of the soil bodies between wide cracks are not wetted before the cracks open again. Consequently, the wetting front never reaches these central parts (Lewis 1977). Indeed there may be no water movement at all when entrapped air fills the finest pores.

The total water-holding capacity of many Vertisols is high, but much water is held at wilting point, which makes the available moisture low. Data on available moisture, as given in the literature, show a wide range. Nevertheless, these soils are often stated to have high available water-holding capacity (e.g., Virmani and Swindale 1984). Reliance on estimates of available water, however, may be misleading in those instances where this capacity, e.g., in a 1-m deep profile, is never reached. The problem in some Vertisols is that water, even when given in unlimited quantity, does not reach the deeper parts of the solum. For instance, when the Gezira clays in the Sudan were kept flooded for several days to several weeks, moisture content in the upper 20 cm was 50-55% at field capacity (Farbrother 1972). Moisture content below 20 cm, measured midway between cracks, was entirely a function of crack diameter at the given depth—35-45% at 20-40 cm, and 30% at 40-60 cm—irrespective of duration of flooding. At a depth of 100 120 cm, moisture content did not increase appreciably above the permanent wilting point throughout the year. Farbrother concluded that, except for the surface soil, water penetrates only laterally from the crack surfaces and vertically from the bottom of the cracks. The Gezira clay would behave so differently from textbook soils in almost every respect that, quoting Farbrother, "the orthodox approach [for estimating irrigation requirements] via field capacity and available water, has failed entirely to provide a satisfactory understanding of what happens when water is supplied to a field in the Gezira." This statement may not apply to all Vertisols: the Gezira clay is slightly sodic, which may affect water intake and conductivity. Theoretically—and this is confirmed by some field observations—some sodic Vertisols develop fewer and wider cracks, and the substructure is weakly developed. Although this "sodic" structural pattern does not develop in the Gezira clay, probably due to the presence of finely divided lime and weak salinity, a rapid swelling and closure of cracks may be responsible for the very poor water penetration.

On the basis of the differences between Ca-saturated and Na-saturated smectites in hydrological and mechanical properties, we would expect self-mulching, carbonate-rich Vertisols (which have relatively fine structural aggregates and strongly intersecting slickensides) to have the most favorable fabric for optimum infiltration and movement of water down the profile. The matter does not seem clear, however: Smith (1959) and Sleeman (1963) found that carbonate-free Na-dominated clays developed a high intensity of fine cracks, and Ca-dominated clays fewer and wider cracks.

Sodicity of Vertisols and its effect on soil physical characteristics and plant growth is controversial. In several countries, good yields have been reported from Vertisols with measured ESPs greater than 40. Vertisols in the Sudan Gezira had ESPs of 40 to 80, but they were similar in morphology to nonsodic Vertisols in the same region and gave the same yields of cotton. The sodic soils, on the other hand, had high pH and were nonsaline (Buringh 1969). In arid regions, nonvertic sodic soils with very high ESP were found to contain the zeolite mineral analcime that, under field conditions, immobilizes part of the sodium (Schulz et al. 1964). We know this because certain extractants, including NH_4OAc, extract both this "zeolite sodium" and the sodium adsorbed on the active clay surfaces. However, zeolites have not been found in Sudan Vertisols, as far as I am aware.

Another possible explanation for the apparently little effect of high exchangeable sodium is that the crop benefits from the higher amount of available water in clays with high ESP (Jewitt 1955, Zein el Abedine et al. 1969). If sodicity is accompanied by salinity, the effect of the Na ion on the surface characteristics of the clay is counteracted e.g., hydraulic conductivity and degree of structural stability increase with increasing electrolyte concentration in the soil solution (Mukhtar et al. 1974, Pandey et al. 1974). Halitum et al. (1984) found that soil structure and water properties of Ca- and Mg-saturated smectites were only slightly modified by salt concentration, but a strong effect of salt concentration was found with Na-smectite.

One difficulty in assessing the effect of sodicity on crops is the lack of a suitable methodology for measuring exchangeable cations. The standard NH_4OAc method (at pH 7) for CEC-determination and extraction of exchangeable cations may give erroneous results when the soil contains finely divided lime, gypsum, or soluble salts. When salinity is suspected, the most acceptable procedure is to make separate determinations for water-soluble cations and subtract these from the soluble plus exchangeable cations (Hesse 1971), but this is cumbersome and not without analytical problems. In low-salinity, low-sodicity Vertisols from the Sudan, the CEC computed as a sum of cations greatly exceeded the CEC measured by the NH_4OAc method. These soils contain finely divided lime, and apparently some $CaCO_3$ is dissolved by the ammonium acetate and is, therefore, included in the exchangeable estimation. Naturally, in such cases where part or all of the figures for exchangeable cations are too high, a reliable ESP cannot be given.

A new method for the determination of CEC and exchangeable cations, described by Begheijn (1980), appears to be especially suited to calcareous, gypsiferous, and saline/sodic soils. It is a simple, single-step method using LiEDTA as extractant (or LiBaEDTA in gypsiferous soils). Extraction by LiEDTA removes all adsorbed Ca and Mg from the soil solution due to EDTA chelation; Na and K in nonsaline soils are removed by excess Li. In saline/sodic soils, replacement of Na is incomplete, but it was found that the Na/Li molar ratio in the extract equals that of the adsorption site. This permits correction for both CEC (+) and for exchangeable Na (+). Analysis of the extract provides data on Li (for CEC), Ca, Mg, Na, K (for exchangeable cations), CO_3, and Cl (for correction of dissolved NaCl and $CaCO_3$). For gypsiferous soils, LiBaEDTA is used. Gypsum is removed by simultaneous chelation of Ca (to the EDTA) and precipitation of SO_4 (as $BaSO_4$). Otherwise, the method is the same as with LiEDTA.

The overlap between sodic soils and Vertisols in world maps (Beck et al. 1980) is small and, therefore, sodicity may not be a great problem in Vertisols on a global scale. The relative saturation of the exchange sites with Ca and Na, however, appears to have important effects on the soils' physical characteristics and, consequently, on the water regime in Vertisols.

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Discussion

Bentley: You said hydraulic conductivity decreases with a decrease in the ESP of the soil. Is that correct and what you said?

Blokhuis: No, hydraulic conductivity will increase with a decrease in the ESP.

Hawando: In Vertisols in the semi-arid tropics, cracks may develop to as deep as 120 cm. If you put water in this soil or flood it, would not the bottom of the profile receive more water and wouldn't the lateral movement of water into the islands (between the cracks) cause more water to accumulate at the bottom of the profile than in the surface soil? This may not agree with the Sudanese data on water content after flooding.

Blokhuis: To some extent, yes, during the initial stages of infiltration; somewhat later, there will be the minimum water entry into the prismatic peds, at about the middle of the cracks' depth.

Sampath: It is suggested that Na-saturated clay soils tend to absorb more water than Ca- or K-saturated clay soils. Is it not true that since sodium is a deflocculating agent, the pore space gets clogged, which may lead to less pore space, thereby leading to less water storage in the soil as well as less infiltration by the Na-rich clay soils?

Blokhuis: Yes, but what is referred to is the micropore space and interlattice water-holding capacity of clay. More important, however, is the strongly hydrated nature of Na ions; its effective radius is greatly enlarged when enveloped by water molecules. Therefore, swelling—and repulsing of adjoining clay particles—is greatest with monovalent cations.

Vertisols in the Seasonally Dry Central Clay Plain in the Sudan

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Abstract

Vertisols cover a large area in the Sudan, almost 500 000 km², extending through latitudes 5 to 16° N and longitudes 28 to 36° E. This area forms an almost continuous clay plain of very low relief. Parent materials of the soils are smectitic clays derived either from Blue Nile sediments or from weathering of granitic, gneissic, and basaltic rocks. Most of the clay plain lies in the semi-arid tropics, but it stretches from the arid to the subhumid climates.

Soil properties change gradually with the rainfall gradient from north to south. Moisture variations in the dry environment (225-750 mm average annual rainfall) impose a certain degree of zonality in clay content, clay mineral dominance, chemical and physical properties, and the degree of expression of the vertic characters. Salinity and sodicity and the presence of gypsum are generally confined to the drier areas.

In the drier part of the environment (<400 mm average annual rainfall), vertic characters are weakly expressed, cracks are closely spaced, surface mulch is well developed, surface structure is slightly friable, soil peds have soft consistency, clay content is low (<50%), with smectite dominating (80% of clay) and chlorite present as an accessory mineral, and the soil matrix is calcareous. With increase in rainfall, a continuous change is observed in profile characteristics. In the wetter part of the dry tropics (>600 mm average annual rainfall), vertic characters become well expressed, cracks are more widely spaced, surface mulch is thin or absent, surface structure is massive and hard, structural peds have very hard consistency, clay content is more than 60% but contains less smectite (<60%), kaolinite is present as an accessory mineral, and the soil matrix is noncalcareous. A mixture of smectite, kaolinite, and chlorite and intermediate properties are seen in midzones.

Only two soil families, classified according to Soil Taxonomy, cover almost the entire semi-arid part of the Central Clay Plain, and this suggests a uniformity in aspects of soil management that does not really exist. Criteria relevant to agricultural use in the semi-arid tropics, therefore, need to be defined so that a more useful differentiation at the family level can be obtained.

Résumé

Les Vertisols de la plaine centrale argileuse à longue saison sèche au Soudan : *Les Vertisols couvrent presque 500 000 km² au Soudan. Ils s'étendent de 5 à 16° N et de 28 à 36° E. C'est une région dont la quasi-totalité consiste en une plaine argileuse à relief bas. La roche-mère des sols sont les argiles smectiques dérivées, soit des sédiments du Nil, soit de l'altération des roches granitiques, gneissiques et basaltiques. La plupart de la plaine argileuse se trouve dans les zones tropicales semi-arides, mais elle s'étend des climats aride à subhumide.*

Les propriétés du sol changent progressivement avec le gradient nord-sud de la pluviométrie. Les variations de l'humidité dans le milieu aride (225-750 mm de pluviométrie annuelle moyenne)

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imposent un certain degré de zonalité dans la teneur en argile, la dominance du minéral argileux, les propriétés chimiques et physiques, et le degré d'expression des caractères vertiques. La salinité, la sodicité et la présence du gypse sont, en général, limitées aux régions plus arides.

Dans la partie plus aride (>400 mm de pluviométrie annuelle moyenne), l'expression des caractères vertiques est faible, les fissures sont étroitement espacées, et le mulch de la surface est bien développé. La structure superficielle y est légèrement friable, les peds du sol ont une consistance tendre, la teneur en argile est faible (<50%), avec la dominance de l'argile smectique (80% de l'argile). Le chlorite est présent comme minéral accessoire et la roche-mère est calcaire. Au fur et à mesure que la pluviométrie augmente, il y a un changement continu dans les caractéristiques du profil.

Dans la partie plus humide des zones tropicales (>600 mm de pluviométrie annuelle moyenne), l'expression des caractères vertiques est forte, les fissures sont bien espacées, le mulch de la surface est presque absent. La structure de la surface y est dure et agglomérée, les peds structuraux ont une consistance dure et la teneur en argile est supérieure à 60% mais contient moins de smectite (<60%). La kaolinite est présente comme minéral accessoire et la roche-mère est non calcaire. Un mélange de smectite, de kaolinite et de chlorite ainsi que des propriétés intermédiaires se trouvent dans les zones intermédiaires.

Il n'y a que deux familles du sol, classifiées selon la "Taxonomie du sol", qui couvrent la plupart de la région semi-aride de la plaine centrale argileuse. Ceci laisse à croire une uniformité dans les aspects de la gestion qui n'existe pas vraiment. Les critères appropriés à l'utilisation agricole dans les tropiques semi-arides devraient être bien définis afin qu'on puisse obtenir une différentiation plus utile au niveau de la famille.

Introduction

Vertisols occur extensively in the monsoon and semi-arid climatic regions of the Sudan; patches of Vertisols are also found in the arid areas (Fig. 1). The landscape associated with Vertisols normally consists of gently undulating piedmont plains, flood plains, and deltaic plains. Parent materials are usually weathering products of basic metamorphic and igneous rocks, especially basalts, and acid igneous rocks.

Vertisols as a group are remarkably homogeneous and conform to a single process in soil genesis, which is dominated by the shrink-swell properties of the smectite clay minerals. Variations in this process are related to differences in clay content, climatic conditions, and soil drainage.

Soil structure is the most striking feature in Vertisol morphology. The structure profile shows variations with depth, but otherwise the formation of soil horizons is very weakly expressed. In the Sudan, structural development varies, as do a number of other characteristics, including clay mineralogy, carbonate and gypsum contents, and salinity. This paper focuses on the variations in the properties of Vertisols along the marked climatic gradient that occurs in a generally north-south direction. Climate appears to be the single factor that causes most variation. Discussion in this paper is confined almost entirely to the Central Clay Plain area, because this extends over a wide range of climate and is the area on which most previous research has been conducted.

Spatial Distribution

Vertisols have a wide global distribution, ranging from 45° S to 45° N. They occur extensively in tropical and warm temperate climates. In the Sudan, Vertisols occur on a large tract of land extending from 5 to 16° N and from 28 to 36° E. In western Sudan the clay cover does not extend north beyond the 500-mm annual rainfall isohyet, whereas in the east it extends north up to and just beyond the 200-mm annual rainfall isohyet.

Sudan's very large tract of Vertisols, totaling perhaps 50 million ha in area, is divided naturally into three separate areas: the Central Clay Plain, the Nuba Mountains Region, and the Southern Clay Plain. Vertisols in the Nuba Mountains Region occur on gently undulating plains and have better surface drainage than those in the extremely flat

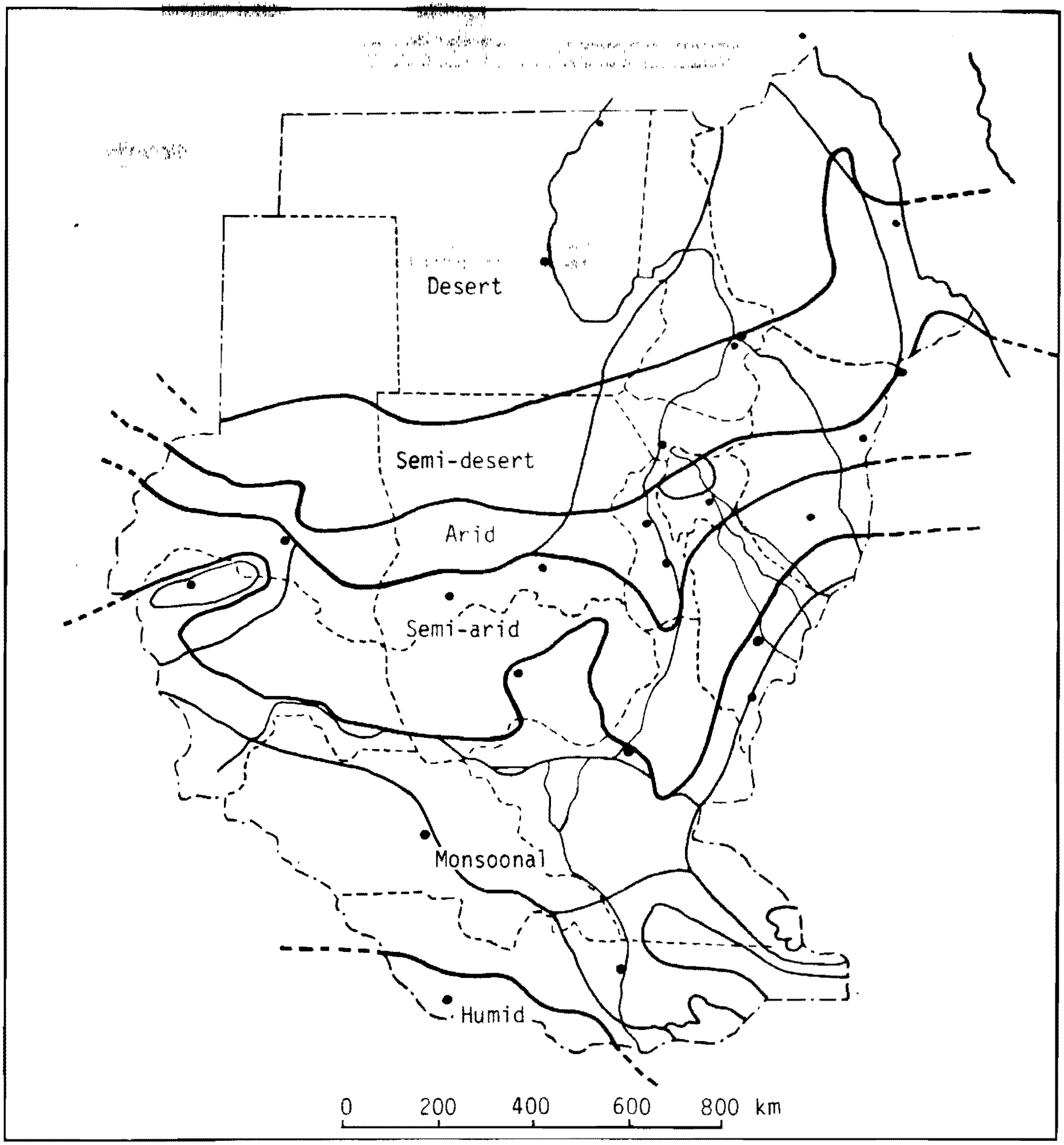

Figure 1. The climatic regions of Sudan.

landscape of the two Clay Plains. The Nuba Mountains Vertisols are considered to be derived from the underlying bedrock, whereas the Vertisols of the two Clay Plains are derived to a greater or lesser extent from alluvium deposited by the Blue and White Niles. The Central Clay Plain is the only area whose Vertisols have been examined in any detail; at present, it is by far the most important area for agricultural production.

The common features governing the distribution of Vertisols in the Central Clay Plain are discussed in the remainder of this paper.

Climate

In the arid region of the Sudan, temperatures are high, with maximum temperatures in the hottest month ranging between 40 and 45°C. There is no month in which average rainfall exceeds potential evapotranspiration; in at least 1 month, however, rainfall is 50% of the potential evapotranspiration. Average annual rainfall ranges from 225 to 400 mm. The soil moisture regime is torric, and the temperature regime is isohyperthermic. Under such an environment, the weathering reactions are restricted and the leaching processes limited. The vertic characteristics are rather weakly expressed.

Although temperatures are high in the semi-arid region of the Sudan, they are lower than those in the arid region. Maximum temperature in the hottest month is about 35–40° C. Average annual rainfall ranges between 350 and 750 mm and amounts to less than 44% of the annual evapotranspiration. In at least 1 month, the average rainfall exceeds potential evapotranspiration. Relative humidity is around 30–40% during most of the year, but rises to 70% during the rainy season. The soil moisture regime is ustic, and the temperature regime is isohyperthermic. Such an environment is more favorable to weathering reactions than is the arid region, and weathering proceeds to fairly advanced stages. Leaching processes have an impact on profile genesis, and depth of maximum salt accumulations depends on precipitation. Vertic characteristics are well expressed depending on precipitation. These general climatic effects may be influenced by variations in microtopography, which cause more arid or more humid conditions as a result of slope variations.

This is the principal environment where most of the Vertisols occur in the Sudan. In this environment, the most significant feature affecting Vertisol formation is the marked seasonality in the distribution of rainfall, which creates a seasonal, alternating wetting-and-drying in the soil.

Relief

Land form is an important factor contributing to Vertisol development. In the Central Clay Plain, the landscape is partly an alluvial plain formed from Blue Nile sediments (aggradational plain) and partly a gently undulating plain derived from weathering of granitic to gneissic rocks of the Basement Complex (degradational plain). Landscapes and soils are very similar in these geogenetically different regions, except for the presence of inselbergs in the degradational plains.

During its course from the Sudan border to Khartoum, the Blue Nile has an overall gradient of about 12.5 cm km^{-1}, whereas the White Nile has a gradient of only 1 cm km^{-1}. With a gradient of a few centimeters per kilometer and a low rainfall, water runoff from the Central Clay Plain seldom reaches the Blue or White Nile; the usually small amounts of runoff end in closed inland basins, locally known as 'Mayas.'

Parent Material

The Clay Plains owe their origin to a very complex series of tectonic, weathering, erosional, and depositional episodes. The clays have different sources. They are partly residual, partly alluvial, and partly paludal. The major geological formations from which the clays are derived are basic igneous and metamorphic rocks and sedimentary rocks, of the degradational plains.

In the aggradational plains, one finds great uniformity and great depth of the clay mantle. The lack of stratification or sorting indicates a long period of uniform climate, river regime, source materials, and depositional environment. Information on the mineralogy of the sediment is rather scanty. The mineralogy of the light sand fraction is dominated by quartz; potassium feldspar is the dominant weatherable mineral. The heavy mineral fraction of the sands is characterized by an association of hornblende, augite, and epidote, which indicates their origin as sediments in the Blue Nile. Minerals in the silt fraction are dominated by smectite, and similar minerals are dominant in the clay fraction. Kaolinite and chlorite have also been detected, but always to a lesser degree than smectite. The available data on the mineralogy strongly indicate that the smectite in these clays is inherited from the Blue Nile alluvium. However, circumstantial evidence also suggests the possibility of clay synthesis on these plains.

The Vertisol landscape in the Sudan extends over a wide range of rainfall and, with uniform topography and parent materials, some zonality in the clay mineralogy can be expected. Kaolinite is found as an accessory mineral in the wetter parts, and chlorite in the driest areas, whereas both kaolinite and chlorite are found in the intermediate zone. The relative abundance of smectite decreases with the increase in rainfall, from 80% to less than 60% of the clay fraction. The variations in clay mineralogy are expected to have an impact on profile morphology.

Profile Morphology

In Vertisols, profile morphology is generated by the forces that develop in the smectitic clay when it is subjected to alternate wetting and drying cycles. Several characteristic morphological features of Vertisols are common in the Vertisols of the Central Clay Plain of the Sudan. Variations in the degree of expression of these features are mainly a response to changes in the soil moisture regime, as affected by climate, topography, and clay content.

In the drier zone of the semi-arid region, the cracking pattern is closely spaced, the cracks are narrow (1–3 cm wide at the surface), and extend only to a shallow depth (50 cm). The cracks are covered with loose surface mulch up to 10 cm thick, consisting of fine-to-medium granular and subangular blocky aggregates. Immediately below the surface (10–20 cm), the soil has a slightly friable to slightly hard consistence. Wedge-shaped structural units are weakly developed, and slickensides are usually not seen in the upper 100 cm of the soil profile but are found below the 2-m depth. Black calcium carbonate nodules are found scattered on the surface; gilgai microrelief is a rare feature.

With an increase in average rainfall, a gradual change is observed in profile morphology. The strongest expression of vertic characteristics is encountered in the wetter parts of the semi-arid region (with 700 mm average annual rainfall). The clay content increases from 50% in the drier zone to as much as 80% in the wetter zone. In the wetter zone, the cracks are wider, extend to a greater depth, and are more widely spaced. In addition, the surface mulch becomes thinner and very often is replaced by a very hard compact surface. The soil peds are very dense when dry. Calcium carbonate concretions on the soil surface are rare or completely absent. Wedge-shaped structural units with polished faces (slickensides) are more strongly developed and at shallower depths. Large slickensides may be seen shallower than the 100-cm depth and commonly occur just below 25 cm.

Spatial variation in the dominant soil color is related to the soil moisture regime. In the drier parts of the semi-arid zone, pellic colors are very rarely encountered and only in depressions. The pellic colors are usually associated with receiving sites and chromic colors with shedding sites. The soil usually has a uniform color to a considerable depth. It is only in central Gezira that color contrasts are seen within the solum.

The colors are removable by treating the soil with alkaline extracts, i.e., sodium citrate or sodium bicarbonate. The efficiency of these extracts is greatly enhanced with reduction, i.e., when sodium dithionite is added. The pyrophosphate-extractable organic fraction in the chromic subgroup is dominated by fulvic acid (75%), whereas in the pellic subgroup, humic acids are dominant (75%).

Chemical Properties

Throughout the Vertisol landscape, there are gradual changes in soil properties, both laterally and in the profile. The lateral variation, apart from localized soil patchiness, is exhibited over the long tract of land where environmental conditions influence the soil properties. Gradual variations in the profile occur in the quantity of soluble salts, sodicity, gypsum, and calcium carbonate; these can be observed along the rainfall gradient in the Central Clay Plains.

Differences between profiles are related to the presence or absence and the depth of occurrence of saline and/or sodic horizons, gypsum crystals, and carbonate concretions. Vertisols in the Sudan are generally nonsaline within the top 50 cm. The electrical conductivity (EC) of the saturation extract is usually less than 0.1 S m^{-1}. In the northern limit of the landscape, where moisture is restricted, EC values of 0.5 S m^{-1} or more occur below 50 cm; further south, where precipitation is slightly higher, such values are found only below the 90-cm depth. In the higher rainfall zone of the semi-arid region, the profile is nonsaline throughout the depth of 2 m.

Sodicity is generally associated with salinity, with similar trends. But nonsaline soils with exchangeable sodium percentage (ESP) values of more than 15 within 75 cm of the soil surface are not uncommon. Sodicity occurs more widely than salinity. Although sodicity is less intense and less frequent under higher rainfall conditions, it does not generally seem to be closely associated with precipitation. Sodic soils with ESP values greater than 25 within the top 75-cm zone could occur in any locality of the central Sudan.

Gypsum is usually absent from the upper 2-m depth of Vertisols in higher rainfall areas (> 500 mm annually), but it may occur below 2 m. In the zone with low precipitation (< 500 mm), gypsum usually occurs in various amounts and at various depths within the top 75 cm. It sometimes occurs as acicular (needle-shaped) crystals, but more commonly it is lenticular.

There seems to be an interrelationship between average EC and ESP values in the top 50 cm and the presence and depth of occurrence of gypsum in the profile. When there is no gypsum within 2 m, a small increase of the EC brings about a large increase in ESP values. Such soils tend to exhibit high ESP at moderate EC values of about 0.1 S m^{-1}. When there is gypsum within the top 50 cm, the EC tends to be higher than 0.1 S m^{-1} and the ESP low, usually less than 15.

In addition to the presence of discrete hard carbonate glaebules, the soil matrix may be impregnated with finely divided free carbonates. The depth of occurrence of such a calcareous matrix is a function of rainfall. The Vertisols in the arid zone and the drier parts of the semi-arid zone (< 300 mm average annual rainfall) are impregnated with finely divided carbonate throughout the soil matrix; in the 500-800 mm rainfall areas, the soil matrix becomes calcareous below the 50-cm depth.

The soil reaction is generally alkaline. The pH generally increases with depth: it ranges from 8 to 9, rarely reaching 9.5 within the top 50 cm. High pH values are usually recorded in low-rainfall areas (< 400 mm) and in sodic Vertisols; with increasing precipitation, there is a progressive decrease in soil alkalinity. In the high-rainfall area (700–800 mm), pH becomes neutral to slightly acidic. Reactions of pH 6 or less are only found in Vertisols in the udic moisture regime, in the Southern Clay Plain, where the acidity is generally confined to the top 10–20 cm of the soil profile.

Classification

The prevailing climate over most of the Central Clay Plain is semi-arid. The soil moisture regime is ustic, the soil temperature regime is isohyperthermic. Usterts are by far the most extensive soils. Torrerts are found in the semi-desert and arid zone, usually confined to annually flooded alluvial basins along the Nile. Uderts occur in the wetter fringes of the ustic moisture regime in localities subjected to prolonged seasonal flooding, in the Southern Clay Plain. In the dry fringes of the ustic moisture regime, approaching the aridic moisture regime, vertic intergrades to Aridisols and Entisols (Vertic Camborthids, Vertic Ustifluvents, and Vertic Torrifluvents) occur. On coarser-textured sediments and in recent alluvium occurring within the Central Clay Plain, usually there occur Ustifluvents, Ustorthents, and Ustic Haplustalfs.

At the great group level, Chromusterts are by far the most dominant. In the wetter parts of the ustic regime, Pellusterts occupy slightly lower sites relative to the Chromusterts. The normal soil is the Typic Chromustert, generally occupying broad level plains, whereas Entic Chromusterts occur on shedding sites. There is a general tendency for entic colors to prevail in the drier northern parts of the Vertisol landscape.

At the family level, fine and very fine, mixed and montmorillonitic, isohyperthermic classes, as well as the calcareous and noncalcareous classes, are recorded.

A number of soil series have been recognized. A few that occupy sizeable tracts of land are listed in Table 1.

Soil Taxonomy, the system used for classifying Vertisols in the Sudan, has many favorable practical aspects, but it poses some difficulties, particularly for agrotechnology transfer. In the Central Clay Plain where the soil moisture regime is ustic, there are only two families: very fine and fine (of the isohyperthermic, montmorillonitic Typic Chromusterts). This apparent high degree of uniformity can be very misleading, especially for dryland farming. The separation at the suborder level, on the basis of soil moisture regimes, needs further categorization for the very wide range of the ustic regime. Although environmental parameters are very important in the classification, criteria used to separate families are noticeably deficient for the semi-arid environment. Features that have an impact on crop performance include: quantity and nature of the soluble salts, and their distribution within the soil profile; pH; air-dry consistence and air-dry density of the soil peds; and stability of the soil material when in contact with water (structure stability). The classification system might be improved if some of these criteria find a place in Soil Taxonomy. The intent of the soil family is to group together soils that are relatively homogeneous in properties important for plant growth. Consequently, all the soils in a family should have a common and predictable response to management practices, correlative input-output characteristics,

Table 1. Soil series and higher categories of Vertisols in the Sudan.

Series		Family	Subgroup/Great Group
1.	Seinat	Fine montmorillonitic isohyperthermic	Typic Chromusterts
2.	Dinder	Very fine mont. isohyp.	Typic Chromusterts
3.	Suleimi	Fine mont. isohyp.	Entic Chromusterts
4.	Roseires	Very fine mont. isohyp.	Entic Chromusterts
5.	Agadi	Very fine mont. isohyp.	Typic Pellusterts
6.	Tozi	Fine mont. isohyp.	Typic Pellusterts
7.	Hosh	Fine mont. isohyp.	Entic Pellusterts
8.	Abel	Very fine mont. isohyp.	Chromic Pellusterts
9.	Maxmum	Very fine mont. isohyp.	Chromic Pellusterts
10.	Kenana	Fine mont. isohyp.	Udorthentic Pellusterts

and similar crop-production potential.

The technology transfer hypothesis is based on the principle that the empirical agroproduction experience gained with a soil of a particular family can be transferred and extrapolated to all other members of that family, irrespective of their geographic occurrence. This hypothesis does not appear to be correct for the very fine, montmorillonitic, isohyperthermic family in the Vertisol soil landscape of the Central Clay Plain of the Sudan.

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Discussion

Virmani: What are the drainage characteristics of Vertisols in your country?

Abdulla: The drainage is very poor—permeability is very slow, with no internal drainage whatsoever. The only way that water is disposed of is through runoff and/or evaporation. The maximum depth for rainwater penetration is 90-120 cm. Irrigation water did not change the pattern of the moisture profile. The soil layers below 120 cm are permanently very slightly moist, both under irrigation and rainfall.

Mhiri: What is the distribution of natural vegetation on different types of Vertisols?

Abdulla: The distribution of the natural vegetation follows that of rainfall. The vegetation zones are as follows:
100-400 mm rainfall: Desert scrub 400-600 mm rainfall: *Acacia*/short-grass scrub
600-800 mm rainfall: *Acacia*/tall-grass forest
800-1200 mm rainfall: Broadleaf woodland forest
The dominant vegetation on the Vertisols is the *Acacia*/short-grass scrub in the drier areas, and the *Acacia* tall-grass forest in the wetter areas.

Hawando: Is the clay distribution in the Vertisol profile in wetter regions of the Sudan uniform throughout the profile?

Abdulla: In the Central Clay Plain, with rainfall in the region of 800 mm, the clay is very uniform throughout the solum. The CEC/clay ratio varies within very narrow limits, i.e., 0.8 or 0.9. In the southern parts of the Clay Plain under the same rainfall, the clays become heterogeneous and stratified as far as the CEC/clay ratio is concerned. The sequence could be 1, 0.5, 0.7, in successive layers with depth. This may indicate a difference in mineralogy.

Blokhuis: You made some interesting observations on the color change when organic matter (and other constituents) were removed using various extractants. Did you find any difference in dry-matter content and/or nature of the organic matter between Entic and Typic subgroups of Vertisols?

Abdulla: The test was limited to major categorizations at the great group level between Chromusterts and Pellusterts. There was no attempt to distinguish color at the subgroup level.

Comerma: Do you have critical levels for Na that affect water movement in Sudanese Vertisols?

Abdulla: There is no well-characterized limit for sodium as yet, but good yields of cotton can be obtained at ESP levels of 25. When the ESP reaches the level of 35, yields become low.

Hawando: Does deep plowing every 5 years in the Gezira scheme increase the EC and ESP in the surface soil by bringing up salt from the subsoil?

Abdulla: No deep plowing is practiced in the irrigated Gezira scheme. The normal tillage operation is ridging (15-20 cm of tillage). No sign of deterioration has been observed in Gezira after 60 years of irrigation. In fact, both EC and ESP values are less, and the depth of maximum salt accumulation is moving slightly down the profile.

Vertisols of Subhumid and Humid Zones

R. Dudal[1]

Abstract

It is estimated that Vertisols cover about 320 million ha of the world's land area. They developed under a very wide range of temperature and moisture regimes. Of these 320 million ha, stratified by temperature, 60% occur in the tropics, 30% in the subtropics, and 10% outside the tropical-subtropical belt. Stratified by moisture, 13% occur in the subhumid and humid zones, 65% in semi-arid areas, 18% in arid areas, and 4% under Mediterranean climatic conditions.

Vertisols in the subhumid and humid zones show several characteristics related to the overall climate. Other factors, such as texture, clay mineralogy, nature of the cation saturation, and amount of exchangeable sodium, however, have an equally important influence on soil morphology, so that a correlation with climate is difficult to establish. Physical constraints to tillage and crop growth—plasticity, crusting, waterlogging, and poor trafficability—are more pronounced in the humid zones; on the other hand, salinity, sodium saturation, and unreliable rainfall are less of a hazard. Vertisols in the subhumid and humid zones have been put to a wide range of land use; yet they offer considerable potential for the expansion and intensification of agriculture, subject to the application of technologies designed to meet the specific Vertisol management requirements in a humid environment.

Résumé

Les Vertisols des zones subhumides et humides : *On estime que les Vertisols couvrent environ 320 millions d'hectares de la superficie des terres du monde. Ils se sont développés dans une très grande gamme de régimes de températures et d'humidité. De ces 320 millions d'hectares, stratifiés sur base de température, 60% se trouvent dans les tropiques, 30% dans les régions subtropicales et 10% en dehors de la limite tropicale-subtropicale. Stratifiés sur base de l'humidité, 13% se trouvent dans les zones subhumides et humides, 65% dans les régions semi-arides, 18% dans les zones arides et 4% dans les conditions climatiques méditerranéennes.*

Dans les zones subhumides et humides, les Vertisols présentent quelques caractéristiques liées au climat global. D'autres facteurs, tels que la texture, la minéralogie de l'argile, la nature de la saturation en cations et la quantité de sodium échangeable, ont cependant une influence tout aussi importante sur la morphologie du sol, si bien qu'il est difficile d'établir une corrélation avec le climat. Des contraintes physiques au labour et à la croissance des récolte—plasticité, encroûtement, engorgement et un accès difficile en zones humides; d'autre part, la salinité, la saturation en sodium et les pluies irrégulières sont des contraintes moins prononcées. Dans les zones subhumides et humides, les Vertisols ont été utilisés de façon très variée; toutefois, ils offrent un énorme potentiel pour l'expansion et l'intensification de l'agriculture, à condition que l'on y applique des techniques adaptées aux exigences spécifiques de gestion des Vertisols en milieu humide.

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Introduction

Twenty years ago FAO published a review of the properties, distribution, and use of what were called "dark clay soils of tropical and subtropical regions" (Dudal 1965). This term covered soils of heavy texture that show marked tendencies to shrink and swell with changes in moisture content. In many parts of the world, these soils are known by various names, such as Regurs, Tirs, Gilgai soils, Black cotton soils, Black tropical soils, Black earths, Smonitzas, Cracking clays, and Grumusols. The Seventh Approximation of Soil Taxonomy (USDA 1960) coined the term "Vertisols" to group these soils in one order and under a common name.

Global Extent of Vertisols

In 1965, the "dark clay soils of tropical and subtropical regions" were estimated to cover 257 million ha. Although it was not possible to ascertain whether all these soils matched the definition of Vertisols, from available descriptions it was assumed that a majority corresponded to the Vertisol concept. "Dark clays" were found to occur in 76 countries, with the largest areas in Australia (70 million ha), India (60 million ha), and the Sudan (40 million ha). Since this first review, ongoing surveys and the preparation of the Soil Map of the World (FAO 1971-1981) have revealed additional or enlarged extensions of "dark clays" in Canada, China, Egypt, Ethiopia, India, Pakistan, Sri Lanka, the Sudan, Trinidad, the United States, the USSR, and Venezuela.

It is now estimated that "dark clays" extend over 320 million ha, or over 2.4% of the global land area of 13.2 billion ha. By eliminating permafrosted areas and mountain regions from the total land area, however, we find these soils occupy more sizable portion of the arable or potentially arable lands of the world. The accretions of Vertisols are the most important in Egypt (none in 1965 to 1 million ha by 1981), Ethiopia (from 10 to 13 million), India (from 60 to 79 million), the Sudan (from 40 to 50 million), the United States (from 5 to 9 million), and Venezuela (from 1 to 4.5 million).

The land surfaces mentioned in these accretions, however, are not entirely composed of Vertisols. In India, for instance, of the total 79 million ha in the "black soil region," 28 million are considered to be Vertisols, while the remaining surfaces are vertic subgroups of Ustropepts and Ustochrepts (Murthy et al. 1982). The proportion of Vertisols among the "dark clays" in Ethiopia, the Sudan, and the United States is likely to be much higher. For the U.S., for instance, the figure of 9 million ha might double if vertic subgroups were included (Nichols 1985). From a management point of view, the vertic subgroups present problems similar to those of the Vertisols and are, therefore, included in the discussion in this paper.

With these additions, Vertisols are now spread over a very wide range of temperature regimes, from isohyperthermic near the equator in Indonesia to frigid in the piedmonts of Montana in the United States. Nevertheless, we can still justify using the label "soils of tropical and subtropical areas," since 192 million ha (60%) of the Vertisols occur in the tropical belt, 96 million (30%) in the subtropics, and only 32 million (10%) outside the tropical and subtropical regions. Vertisols are estimated to cover nearly 4% of the total land area in the tropics, and, hence, occupy an important place in the developing world.

The 42 million ha of Vertisols estimated to occur in subhumid and humid areas—13% of the total Vertisols—are mainly located in India (25 million ha), Ethiopia (5 million ha), Argentina (3 million ha), the United States (3 million ha), Venezuela (1.5 million ha), and Indonesia (1 million ha). Other countries where they occur are Brazil, China, Ghana, Mozambique, Sri Lanka, Thailand, Trinidad, and a number of central European countries. It is worth noting that in Australia and the Sudan, where large areas of Vertisols occur, only a fraction of these soils are located in subhumid or humid zones.

Characteristics of Vertisols in Humid Environment

Moisture Regime

To ascertain the distribution of Vertisols in subhumid and humid zones, we have used the soil moisture regime, as defined by Soil Taxonomy (USDA 1975). Vertisols with an udic moisture regime are considered to be humid, and those with an udi-ustic. regime, subhumid.

On the basis of the udic and udi-ustic separation, it appears that 13% of the Vertisol areas occur under subhumid and humid conditions, 65% are semi-arid, 18% are arid, and 4% occur in Mediterranean climate conditions. In each of these zones, however, a common feature characterizes the moisture regime of Vertisols—namely, a distinct alternation of seasonal wetting and drying that results in a swelling and shrinking pattern.

The criteria in Soil Taxonomy that subdivide Vertisols according to moisture regimes include both the duration and pattern of soil cracking. In udic Vertisols, cracks do not remain open for as many as 90 cumulative days in most years, and do not remain open for as many as 60 consecutive days in the 90 days following the summer solstice in more than 7 out of 10 years. In some years, they may not crack at all. In udi-ustic Vertisols, cracks close once or twice during the year. The cracks are open from 90 to 150 cumulative days in most years, but remain closed for 60 consecutive days or more in most years when the soil temperature at a depth of 50 cm is continuously above 8°C.

One may wonder, though, if these cracking patterns fully reflect the climatic conditions under which these soils occur and which are important for management and land-use purposes. In addition to the overall climate, the following factors influence cracking:

- clay content (which in Vertisols ranges from 30 to 80%);
- clay mineralogy (it appears that Vertisols may crack with as little as 15% of smectite in the clay fraction);
- composition of the clay fraction, or the proportion of fine to coarse clay;
- saturation of the cation exchange sites (proportion of Ca, Mg, Na, and K);
- flood hazards;
- presence and type of gilgai; and
- rainfall pattern.

Gilgai may cover from 10 to 70% of the land surface. It appears that cracking is more frequent in the depressions than on the mounds, so that it may be difficult to average the duration of cracking over a certain landscape. When the rainy season begins with heavy downpours, cracks fill up with water and close entirely; however, if rain sets in with successive slight showers, cracks close only at the surface. As a result of the subsequent slow infiltration, cracks may remain open in the subsoil. It should be stressed that Vertisols very much develop their own soil climate, which is drier than the overall climate because of strong evaporation through cracks, and which is wetter than rainfall may suggest as a result of waterlogging and low infiltration rate when the cracks are sealed.

Moisture regimes of Vertisols may more approximately be characterized by the length of the growing period, as defined in the FAO agroecological zones project (FAO 1978). Humid zones have more than 270 days of growing period and correspond broadly to the udic moisture regime. The udi-ustic moisture regime corresponds to lengths of growing periods ranging from 210 to 270 days. Lengths of growing period of 180 to 210 days—partly typic-ustic—should probably also be considered as subhumid; otherwise, the semi-arid areas might be disproportionately extended. However, it is beyond the scope of this paper to lay down the limits defining the semi-arid and subhumid zones.

Morphology

Attempts have been made to identify morphological properties that characterize subhumid and humid Vertisols. In the Sudan, where Vertisols occur over a wide range of rainfall in level topography and have a relatively uniform parent material, we may observe soil morphological features that vary with varying climatic conditions (Jewitt et al. 1979, Blokhuis 1982). With increasing rainfall:

- cracks tend to be deeper and wider;
- the wedge-shaped soil structure is more distinct;
- surface mulch weakens and becomes thinner;
- crusting of the surface soil is more frequent;
- organic matter in the upper horizons is higher and color becomes darker;
- the content of soluble salts decreases;
- exchangeable sodium decreases or is absent;
- reliability of rainfall improves;
- hazards of flooding increase; and
- gilgais become more pronounced.

However, it does not appear feasible to use these characteristics to differentiate Vertisols in subhumid and humid areas from those occurring under more arid conditions. Indeed, as mentioned above, a number of factors other than climate influence the morphology of Vertisols.

Color

In Soil Taxonomy, Vertisols of the subhumid and humid areas are further subdivided, essentially on the basis of color of the surface horizons. The neutral, pellic chromas are meant to reflect less-favorable drainage conditions, while the higher chromas of the chromic subgroups are assumed to be characteristic of the better-drained Vertisols. Application of these criteria in soil surveys showed that these color differences were not generally correlated with drainage conditions. In humid areas, prolonged periods of flooding were not necessarily reflected by pellic colors of the soil surface. Other classification criteria are currently proposed (Comerma 1984), which will include seasonal "aquic" moisture regimes in Vertisols.

Other Properties Important to Management

The definition of Vertisols stresses cracking, pedoturbation, and movement within the soil mass (slickensides). From the point of view of management, however, other characteristics appear to be more important:

- hardness when dry;
- plasticity when wet;
- very low infiltration rate when the surface soil is sealed;
- very slow saturated hydraulic conductivity;
- compaction as a result of swelling;
- available water capacity;
- presence or absence of surface mulch;
- sodium saturation;
- possible salt content;
- rooting volume; and
- occurrence of permeable materials in the subsoil.

It is imperative that these characteristics be taken into account, if not in soil classification, at least for technical assessments aimed at evaluating the potential of these soils and at determining management practices.

In the Seventh Approximation of Soil Taxonomy (USDA 1960), a distinction was made at the great group level between "grumic" Vertisols that develop a loose, porous, surface mulch of discrete, very hard aggregates and the "mazic" ones, which, on the contrary, develop a platy or massive surface crust that has uncoated silt or sand grains and that persists after drying. This differentiation was subsequently abandoned as it was felt to be influenced by management and to vary from one year to another. In humid areas, however, the crusting phenomenon seems to be more frequent and is important for the water regime of the soils concerned: it causes less water intake, more hazards of waterlogging, difficult tillage, and poor seedbed conditions. The relationships between crusting in Vertisols and other soil-forming factors point to an intergrading toward Planosols (Dudal 1973). Where they have not been plowed, these soils may show a thin albic horizon overlying heavy clay.

While Vertisols make up a relatively homogenous order in a taxonomic sense, they show a great diversity in characteristics that are of paramount importance for their wetting and drying and, hence, for their suitability for plant growth. The effectiveness of precipitation on Vertisols is strongly influenced by factors that determine water entry, water retention, and removal of water when it occurs in excess of uptake capacity. The latter factor is of particular importance in subhumid and humid zones with special reference to tillage operations and soil aeration during the growing period.

Management Practices and Land Use

Management practices have been designed to overcome the physical problems of Vertisols. Since subsurface drainage is not feasible, as a result of very slow permeability, special attention has been given to surface drainage. Cambered beds, ridges and furrows, bunding, and broadbanks have been applied in a number of countries, including Ghana, India, Indonesia, Trinidad, the United States, and Venezuela. For the semi-arid tropics, ICRISAT (Kanwar et al. 1982) has developed a technology allowing Vertisols to be cropped in both the dry and wet seasons. This technology is conditioned by a certain soil depth and a quantity of stored available water, which covers the moisture requirements of the dry-season crop. A dependable rainfall is needed for dry seeding, prior to the onset of the rains. Elements of this technology might also be applicable in more humid areas where tillage in wet conditions offers particular difficulties. Soil depth and water-storage capacity are major factors in determining which components of this technology can be transferred.

Vertisols in subhumid and humid areas have been put to a wide range of land use. The larger part of these soils is still used as pasture since constraints to tillage have prevented their cultivation in a number of developing countries. Under rainfed conditions, depending on the temperature regime, Vertisols produce wheat, maize, sorghum, soybeans, cassava, groundnuts, and pigeonpeas; under irrigation, Vertisols grow rice, sugarcane, and cotton. Irrigation management has to be adjusted to an initially fast infiltration through cracks, and a subsequent very slow and rather shallow uptake of water when the cracks are closed. Weed control offers problems in these soils because of their plasticity and poor trafficability when wet. In the humid zones, Vertisols are also used for forestry, for instance, in Argentina, Ghana, Indonesia, and the United States.

Large areas of Vertisols are still unused and offer a potential for increased agricultural production. While difficulties of farming on Vertisols are real enough and deserve attention, their favorable features should be given equal emphasis: their high cation-exchange capacity, the high base saturation in a majority of these soils, the high water-holding capacity, a favorable seedbed in the "grumic" soils, a certain stability with regard to fertility status, and a resistance to salinity hazards owing to the self-mulching process. With appropriate technologies, additional areas of Vertisols can be put into cultivation, while those already used can be made to produce higher yields.

Conclusions

The great variability within Vertisols and the wide range of climatic conditions under which they occur have been pointed out. This variability should be fully considered when technologies or components thereof are to be successfully transferred. It should be stressed that socioeconomic issues, as well as the technical aspects, must be considered. Size of farms, kinds of cropping systems, availability of labor and draft-animal power, proximity of marketing facilities, and food habits are all factors that may determine the success or failure of a technological innovation. Although Vertisols in subhumid and humid areas represent only 13% of the global extent of these soils, experience gained in these zones is considerable and could contribute substantially to improving farming of these important soil resources.

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Discussion

Sahrawat: What causes the dark/black color of Vertisols?

Dudal: Several studies suggest that the dark color of Vertisols is due to the formation of clay/organic matter complexes in which the organic matter is absorbed on the clay surfaces or may even be chemically bound to it. The presence of iron sulfides and manganese may also induce dark colors.

Taimeh: The dark color might be due to a coating by manganese. This issue of black color is being investigated by R.C. Mackenzie (at the Macaulay Institute, in Aberdeen).

Hawando: (1) Could you relate subsoil slickenside expression to the surface gilgai expression? (2) Is the relationship between infiltration rate and water movement in cracks in the udic moisture regime due to lateral or vertical cracks in the profile?

Dudal: (1) Subsoil slickensides are frequently related to gilgai, as it is seen that they are often parallel to wavy horizon boundaries in the solum. (2) Water penetrating through cracks does indeed move laterally through connected fissures, at least if precipitation is sufficiently heavy to result in free water movement.

Vertisols in the Southeastern Mediterranean Region

Awni Y. Taimeh[1]

Abstract

This paper describes the Vertisols of the southeastern Mediterranean regions and their environments. The climate in the region is characterized by a cool, rainy winter and a hot, dry summer; mean annual precipitation ranges from 300 to 500 mm. The dominant minerals in the clay fraction are generally interstratified smectite, vermiculite, and illite, with some kaolinite. The clay content generally ranges from 60 to 80%.

The crops grown on Vertisols in this region are quite varied, ranging from staple foods, such as wheat, barley, chickpea, and lentils, to vegetables and fruits, such as tomato, watermelon, and grapes.

The major problems encountered in the use of these soils include low infiltration rate, high degree of compaction, high $CaCO_3$ concentration, low level of organic matter, and deficiencies of nutrients such as iron and zinc. Proper soil and water management is a prerequisite for achieving potential productivity on the Vertisols of this region.

Résumé

Les Vertisols dans la région sud-est du bassin méditerranéen : *Les Vertisols des régions sud-est du bassin méditerranéen et leurs environnements sont décrits. Le climat de cette région est caractérisé par un hiver frais et pluvieux et par un été chaud et sec; les précipitations annuelles moyennes varient de 300 à 500 mm. Les minéraux dominants dans la fraction argileuse sont généralement de la smectite, de la vermiculite et de l'illite inter-stratifiées avec une certaine quantité de kaolinite. Le pourcentage d'argile varie généralement de 60 à 80%.*

Dans cette région, l'utilisation des Vertisols est assez variée allant des aliments de base comme le blé, l'orge, le pois chiche et les lentilles, aux légumes et fruits comme la tomate, la pastèque et le raisin.

Les problèmes les plus importants rencontrés lors de l'utilisation de ces sols comprennent une infiltration très lente, le haut degré de compaction, la haute concentration de $CaCO_3$, une faible teneur en matière organique et les carences en d'autres éléments nutritifs tel que le fer et le zinc. Une gestion adéquate du sol et de l'eau est nécessaire afin d'atteindre le potentiel productif sur les Vertisols de cette région.

Distribution

The Mediterranean region is typically characterized by the extremes of a cool, rainy winter and a hot, dry summer and is defined as the xeric moisture regime according to Soil Taxonomy (USDA 1975). Vertisols occur within this moisture regime and also in the torric moisture regime in Egypt and Syria; they

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might occur, although they have never been reported, in the ustic moisture regime in the hyperthermic zone in Jordan.

There is no accurate estimate of the area occupied by different Vertisol great groups and subgroups because no systematic soil survey has yet been undertaken in the Mediterranean region; however, the following sections describe the Vertisols that have been identified in the southeastern countries of the region. All have fine to very fine texture.

1. Jordan

Most Vertisols in Jordan occur within the thermic temperature regime. The Xererts suborder is dominant, and it is represented mainly by only one of its two great groups, namely the Chromoxererts; some Pelloxererts have recently been identified in areas receiving more than 500 mm annual rainfall. The following subgroups were identified, listed in order of the area they occupy: Typic Chromoxererts, Entic Chromoxererts, and Palexerollic Chromoxererts. It is suspected that Vertisols might occur in the hyperthermic regime, but they have not yet been identified.

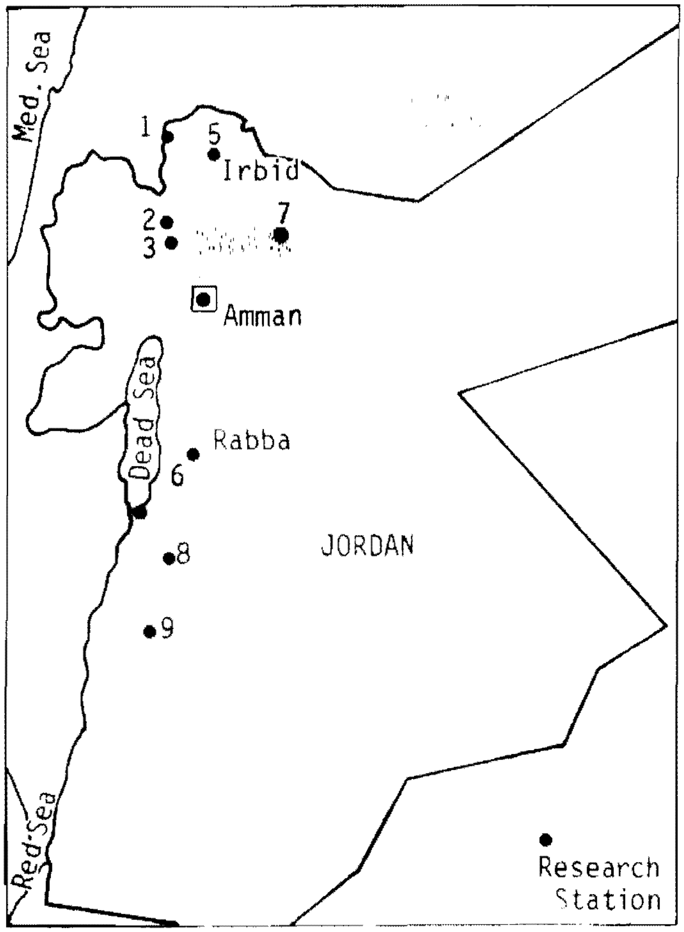

Figure 1. Locations of research stations in Jordan.

Figure 1 shows the research stations located in Jordan. Sites 5 (Irbid) and 6 (Rabba) are both on Vertisols, and it is soils at these sites that are described in this report.

2. Syria

In Syria, Chromoxererts are the dominant great group. Vertisols, however, occur under different temperature regimes: Mesic Xererts in the southwest, and Typic Torrerts in the northeast.

Chromoxererts occupy about 1% of the whole area, and prevail in the extreme northeast and northwest and in minor associations with Xerocrepts. Annual rainfall varies from 430 to 470 mm. The dominant subgroups, listed in descending order, are as follows: Entic Chromoxererts, Typic Chromoxererts, and Palexerollic Chromoxererts (Ilaiwi 1983, pp.207-211).

3. Egypt

Vertisols in Egypt occur on alluvium and within the torric temperature regime. The following subgroups are recognized, listed according to their dominance: Typic Torrerts, Salic Torrerts, Sodic Torrerts, and Mollic Torrerts.

Xererts and their Environment in Jordan

Generally, Xererts in Jordan have the following properties: high clay content, low organic carbon, low infiltration rate, high water-holding capacity, high cation-exchange capacity, low nitrogen content, high P-fixation capacity, and high calcium carbonate content (up to 30%). Severe iron and zinc deficiencies occur at many locations. Calcic horizons exist in some locations. The Xererts in Jordan are hard to very hard when dry and sticky when wet. The erosion potential by water is very high because of subsurface compaction. The cracks are wide (5-10 cm) and deeper than 150 cm in many cases. Strong slickensides may occur at depths greater than 100 cm; slickensides also occur at a shallower depth in many locations. There are no gilgai, which might be due to either cultivation processes or the young age of these Vertisols. The Appendix provides several profile descriptions that exemplify these properties.

Some properties noticed on these Vertisols worth mentioning are:

1. In almost all the Xererts studied, slickensides occurred only below a depth of 100 cm.
2. The slickensides were well-developed intersects and covered both sides of the ped when the structure was strong angular blocky. Further, when the structure was angular from the top of the subsurface downward, the slickensides were better expressed than when the dominant structure was prismatic structure breaking to blocky structure.
3. In some of these Vertisols, the cracks below a certain depth do not close as expected during wet spells.

Vegetation

The natural vegetation in the Vertisol areas of Jordan has been destroyed due to cultivation and human use. Most, if not all, the Vertisols are used to produce economic crops. However, the natural tree species bordering the Vertisol areas where cultivation is prohibited might include the following: *Pinus halepensis, Pistacia atlantica, P. terebinthus, Quercus calliprionos, Q. infectoria, Q. aegilops,* and *Acacia farnesiana.* Among the brushes the following species were also identified: *Pistacia lentiscus, Rhamnus palaestina, Poterium spinosum,* and *Cistus salvifolius.*

Climate

The dominant climate for Vertisols in Jordan is characterized by a cool, rainy winter, beginning in late October, with maximum rain falling in January and February. The rain recedes in May, and no rain falls in the hot, dry summer season (Fig. 2).

The Vertisols are located in the zone receiving 300-500 mm of precipitation annually. Mean annual potential evapotranspiration is 1550 mm. Elevation varies from 618 to 992 meters above mean sea level. Mean maximum and minimum air and soil temperatures for the stations representing the Vertisols are given in Table 1. The lowest mean air temperature occurs in January (7.9 and 9.2°C at Rabbi and Irbid, respectively), while the highest is in August (24.4 and 25.9°C). Mean measured soil temperature at the depth of 50 cm varies from 6.8 and 11.8°C in January to 26.0 and 27.4°C in August. Mean summer air temperature (June, July, and August) is 22.7 and 24.4°C; mean summer soil temperature at the 50-cm depth is 25.5 and 26.4°C. Mean winter air temperature (December, January, and February) is 8.9 and 10.1°C, while mean winter soil temperature at 50 cm is 11.5 and 12.7°C. Mean annual air temperature is 16.3 and 17.6°C. Mean annual soil temperature at 50 cm is 18.7 and 19.8°C.

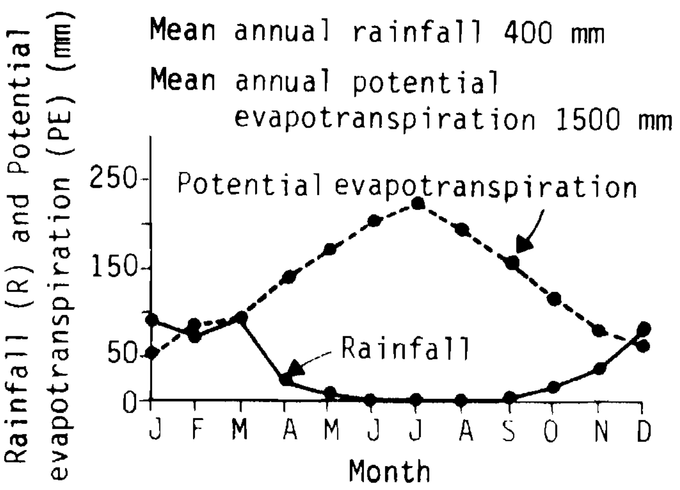

Figure 2. Average monthly rainfall and potential evapotranspiration at Irbid research station in Jordan.

Geology

Vertisols in Jordan are found on hard limestone from the lower Tertiary or upper Cretaceous Period, or on basalt from the undifferentiated Quaternary Period. Colluvium deposits, originating from these geological formations, developed the soil profiles described in the Appendix. They occur on flat, slightly undulating topography and were not identified on higher slopes. Accordingly, they did not develop *in situ*, and parent material does not exist in the C horizon of these profiles. The color of the Vertisols that developed on hard limestone is reddish, while those on basalt are dark reddish brown.

Mineralogy and Soil Formation

The dominant minerals in the clay fraction were found to be interstratified smectite, vermiculite, and

Table 1. Meteorological data for Irbid and Rabba stations, Jordan.

Research station	Elevation (m)	Annual rainfall (mm)	Period	Air temperature (°C)			Soil temperature at 50-cm depth (°C)
				Max	Min	Mean	
5.[1] Irbid[2]	618	410	May-Oct	28.8	17.2	23.1	25.1
			Nov-Apr	16.8	7.5	12.3	14.6
			Annual	22.8	12.3	17.6	19.8
			Summer (Jun-Aug)	30.2	18.6	24.4	26.4
			Winter (Dec-Feb)	13.9	5.7	10.1	12.7
6.[1] *Rabba*[3]	920	300	May-Oct	27.3	15.3	21.3	24.1
			Nov-Apr	15.6	6.9	11.2	13.5
			Annual	21.4	11.2	16.3	18.7
			Summer (Jun-Aug)	22.8	16.6	22.7	25.5
			Winter (Dec-Feb)	12.7	5.2	8.9	11.5

1. Number indicates location on Figure 1.
2. 32°33'N; 35°51'E.
3. 31°16'N; 35°16'E.

illite, with some kaolinite. There were no major differences in the composition of the minerals between Xererts that developed on hard limestone and those on basalt associated with limestone. The degree of interstratification of the smectite (with illite and vermiculite) in these soils was found to increase with depth.

X-ray analysis indicated the presence of several minerals in the silt fraction. Among these minerals was illite, whose abundance was higher in the surface. The occurrence of both illite and quartz was attributed to the aeolian activities. Moreover, the occurrence of the palygorskite and the plagioclase at the surface associated with the silt fraction was considered as a good evidence of the prevailing aridity during past ages. Quartz, plagioclase, and kaolinite were also uniformly distributed in the upper layers. Interlayered smectite or vermiculite were also identified in the silt fraction, and were found to be concentrated in the surface layers.

These soils have a very high clay content (60-80%). The variation of clay content with depth (Table 2) strongly suggests differential movement of clay within the soil profiles. To a great extent, this high clay content hinders the downward movement of clay, so the difference in clay between the surface and subsurface is not unexpected. In this respect, two hypotheses are advanced:

1. The fact that these Vertisols are located in a highly erodible zone (after the formation of the Rift Valley bordering these soils to the west) suggests that a large portion of the soil surface has been eroded. Thus, the large difference between the clay content of the surface and subsurface horizons was minimized.
2. In an independent study of the area where the Vertisols are located and which included some of the Vertisols reported here, it was found that the soils in these areas were subject to four different stages of soil formation under the following climates, which apparently began to affect the area during the Pleistocene Epoch (Taimeh 1984). The last two of these climatic changes were:
   a. During the early Pleistocene, humid climate, the soils developed a high clay content and features such as clay films, differential clay and carbonate distribution, calcic horizons located below 100 cm, and an abundance of secondary calcium carbonate concretions in many of them (Taimeh 1984).

   However, due to development of the shrinking and swelling potential later on, most of the features associated with the downward movement of clay were destroyed. The presence of these features was confirmed on soils occurring in association with Vertisols under almost the same conditions (Jamous 1984). Moreover, some of these Vertisols have a strong clay orientation at the bottom of the profile, which strongly suggests that the clay

Table 2. Distribution of sand, silt, and clay in the soil profile, before and after removal of carbonate, and distribution of carbonate in different particle-size fractions[1] of the soil (Xererts in Jordan).

			Particle-size distribution (%)						Carbonate distribution in fractions			
			Carbonate not removed			After removal of carbonate			(% of original soil)			
Profile No.[2]	Horizon	Depth (cm)	Sand	Silt	Clay	Sand	Silt	Clay	Sand	Silt	Clay	Total
3	Ap	0–40	5.7	42.4	51.9	4.0	37.9	58.1	2.5	12.7	5.1	20.3
	B21	40–90	6.8	34.3	58.9	3.1	33.6	63.3	4.4	8.6	9.6	22.6
	B22	90–130	7.7	34.4	57.9	2.9	36.1	61.0	5.5	6.3	10.4	22.2
	B23Ca	130–161	7.2	23.0	69.8	3.7	23.9	72.4	4.6	6.9	20.8	32.4
6	Ap	0–10	4.8	32.9	62.0	2.8	31.2	66.0	2.2	5.3	1.6	9.1
	B21	10–50	4.2	27.4	72.3	2.4	25.4	72.3	2.1	5.7	1.0	8.7
	B22	50–80	3.4	29.7	71.9	2.1	26.0	71.9	1.6	4.8	1.8	8.2
	B23	80–155	5.7	23.4	77.8	2.4	19.8	77.8	4.6	4.5	1.9	10.0
	B24Ca	>155	10.1	21.6	76.9	3.3	19.9	75.9	7.4	6.1	1.3	14.8
7	Ap	0–21	6.3	35.9	57.8	3.2	29.8	67.1	4.0	13.6	9.3	27.0
	B21	21–85	5.1	27.5	67.4	2.9	24.0	73.1	3.0	7.7	15.4	26.1
	B22	85–133	7.5	22.2	70.3	4.1	22.7	73.2	4.5	5.9	16.6	27.0
	B23	133–175	8.6	20.2	71.2	2.5	16.5	81.0	6.9	8.2	15.2	30.3
8	Ap	0–10	6.9	30.7	62.4	3.4	28.0	68.6	3.9	4.1	1.6	9.6
	B21	10–70	5.0	30.1	65.6	3.6	24.1	72.2	1.7	7.2	1.1	10.0
	B22	70–130	6.3	26.9	66.8	2.8	24.2	73.0	3.8	4.5	1.3	9.6
	B23	130–180	9.3	27.2	63.6	4.2	24.2	71.7	5.7	5.2	1.4	12.2
	IIB24	>180	11.7	29.7	59.6	5.4	17.1	77.5	6.7	16.7	1.8	25.2

1. Particle-size fractions: sand, >0.05 mm; silt, 0.05-0.002 mm; clay, <0.002 mm.
2. Source: Jamous (1984). For a description of each profile, see Appendix.

had moved downward.

b. After this humid period, the climate became drier. It is estimated that this change began about 5000–1000 B.C. and is still continuing. During this episode, and due to wind erosion, the calcareous silt began to accumulate at the surface (see Table 2).

At the same time as the last episode, the soil's reaction became more basic, and the content of the swelling type of minerals increased. The increase in shrinking and swelling and the enrichment of carbonate, in addition to the desiccation, have aided in the destruction of many of the pedological features associated with the downward movements of different soil components. With this in mind, we might wonder whether leaching really takes place in Vertisols, as suggested by the data in Table 2. Except for those soils with calcic horizons, Vertisols show a uniform distribution of total carbonate, but if we consider the carbonate associated with the clay, then we could say that this pattern has resulted from leaching. The questions that then arise are: At what time did leaching occur? Is it due to the past or present climates? If it is due to past climate, did it have any effect on soil behavior important to soil management? Consequently, does it have to be reflected in the classification at some level? If this leaching pattern is attributed to the current climate, bearing in mind that the existing water balance does not greatly support the occurrence of the calcic horizon at that great depth, it is probably better to redefine the parameters for determining the moisture regime in Vertisols.

Land Use of Vertisols in Jordan

Field Crops

Field crops grown on Vertisols are:

- Winter crops: wheat, barley, lentils, vetches

- Summer crops: tomato, watermelon, chickpeas
- Trees: olives, grapes, etc.

Farming Systems

Rainfall distribution and its great variability has precluded introduction of a sound farming system into the Jordan Vertisols. However, some advancements have been achieved in the last years, with the use of modern machines and the addition of fertilizers. Soil-conservation measures, such as stone or earth terracing to control water erosion or for soil-moisture conservation, have been carried out sporadically in some areas. On farms, a disk plow or moldboard plow has been used for seedbed preparation. Seeding is done by seed drill. Sometimes a disk-harrow is used before the first rain, usually in October, to incorporate plant residues and to increase infiltration. However, not much of the plant residue is left in the field because it is usually fed to animals. Nitrogen fertilizer is added, and a small number of farmers add phosphorus, but no potassium. Fertilizer usually is added only to winter crops, due to the occurrence of rains then.

The major problems experienced in managing these soils can be summarized as follows:

1. Low infiltration rate, which increases the runoff and decreases the water stored, especially during heavy storms.
2. High compaction, which greatly affects root distribution and development.
3. High calcium carbonate, and, thus, a high capacity for P-fixation.
4. Very deep cracks, which greatly affect the summer vegetables or the trees grown on them.
5. Iron and zinc deficiency (other micronutrients have not been investigated in detail).
6. Low organic matter and, consequently, low nitrogen content.
7. High water-holding capacity, but low availability of water, in addition to low rainfall in the zone where these soils occur (Taimeh 1984, Ilaiwi 1983, Jamous 1984).

Acknowledgment

The tables on particle-size distribution and the profile distribution were taken from a thesis completed by M. Jamous under the supervision of the author.

Appendix

Profile No.3

General information

Classification: Very fine, smectitic, thermic, Typic Chromoxererts

Location: 32° 33′N; 35° 51′E

Present land use: Summer, winter crops

Time of sampling: July 1981

Relief: Level site through undulating area, 1–3% slope.

Parent material: Limestone associated with ba-salt-derived colluvium material.

Climatic data: Potential evapotranspiration is 1600 mm a^{-1}. The annual precipitation is 300 mm. The average air temperature during January is about 10°C., and during June 24–26°C.

Remarks: Colors are for moist soils unless otherwise noted. Depth of cracks is 160 cm. Width at the surface 7–10 cm.

Profile description

A 0–40 cm: Dark reddish brown (5YR3/4), clay, large clods that break to weak coarse subangular blocky, v. hard, friable to s. firm, s. plastic, common to many fine roots, some angular limestone gravels, small rounded basalt fragments, clear boundary.

B21 40–90 cm: Dark reddish brown (5YR3/4), clay, strong very coarse prismatic breaks to angular blocky, extremely hard, s. firm, sticky, plastic, few to common fine roots, distinct very few medium white carbonate concretions, clay and oxide coatings (not prominent), vertical pressure face of about 70 cm, diffuse boundary.

B22 90–130 cm: Reddish brown (5YR4/4), clay, strong, very coarse prismatic, breaks to angular blocky, extremely hard, s. firm; sticky, plastic, few to common fine roots, distinct few to common coarse white carbonate concretions, clay and oxide coatings (not prominent), gradual boundary.

B23Ca 130-161 cm: Yellowish red (5YR4/6), clay, strong, very coarse prismatic breaks to angular blocky, v. hard, s. firm, sticky, plastic, few fine roots, many coarse white carbonate concretions (prominent secondary carbonate accumulation), prominent clay and oxide coatings, faint organic matter coatings, oblique intersecting slickensides.

Profile No.6

General information

Classification: Very fine, smectitic, thermic, Typic Chromoxererts.

Location: 32° 33'N; 35° 51'E

Present land use: Summer, winter crops

Time of sampling: July 1981

Relief: Extensive flat plain, 1-2% slope.

Parent material: Colluvium material derived from limestone associated with basalt.

Climatic data: The average annual precipitation is about 300-400 mm. The average air temperature during January is about 10°C, and during June about 24°C. Potential evapotranspiration is 1600 mm a^{-1}, and mean annual air temperature 17-18°C.

Remarks: Colors are for moist soils unless otherwise noted.

Profile description

A 0-10 cm: Dark reddish brown (5YR3/4), clay, moderate medium subangular blocky, extremely hard, friable, sticky, plastic, few fine black concretions, oxide and organic matter coatings, clear boundary.

B21 10-50 cm: Dark reddish brown (5YR3/4), clay, very strong very coarse angular blocky, extremely hard, friable, sticky, plastic, few fine black concretions, oxide and organic matter coatings, diffuse boundary.

B22 50-80 cm: Dark reddish brown (5YR3/4), clay, very strong very coarse angular blocky, extremely hard, friable, sticky, plastic, few fine black concretions, oxide and organic matter coatings, many 10 mm in diameter, hard limestone gravels, diffuse boundary.

B23 80-155 cm: Dark reddish brown (5YR3/4), clay, very strong very coarse angular blocky, extremely hard, friable, sticky, plastic, few coarse white carbonate soft concretions, few fine black concretions, oxide and organic matter coatings, a lot of limestone and flint gravels, slickensides and pressure faces, abrupt boundary.

B24Ca >155 cm: Dark reddish brown (5YR3/4), clay, strong medium angular blocky, extremely hard, s. firm, sticky, plastic, common medium to coarse white soft carbonate concretions, few fine black concretions, oxide and organic matter coatings, some flint gravels, many slickensides.

Profile No.7

General information

Classification: Very fine, smectitic, thermic, Typic Chromoxererts

Location: 32° 31'N; 35° 51'E

Present land use: Summer, winter crops

Time of sampling: July 1981

Relief: Level-undulating with hilly surroundings, 1-2% slope.

Parent material: Colluvium material derived from hard limestone.

Climatic data: The average annual precipitation is about 300-400 mm. Potential evapotranspiration is 1600 mm a^{-1}, and mean annual air temperature 17-18°C. The average air temperature during January is about 10°C, and during June about 24-26°C.

Remarks: Colors are for moist soils unless otherwise noted. Cracks on 10cm wide and 120 cm deep.

Profile description

A 0-21 cm: Yellowish red (5YR4/6), clay, moderate medium subanglar blocky breaks to granular, hard to v. hard, friable to firm, sticky, plastic, common to many fine to medium roots, clear boundary.

B21 21-85 cm: Dark reddish brown (5YR3/4), clay, very strong very coarse prismatic breaks to angular blocky, extremely hard, v. firm, sticky, plastic, common fine roots, very few fine white carbonate concretions, thin carbonate filaments, chert and limestone round-edged gravels, oxide and organic matter coatings, gradual to diffuse boundary.

B22 85-133 cm: Dark reddish brown (5YR3/4), clay, very strong very coarse angular blocky, extremely hard, very firm, sticky, plastic, common fine roots, few coarse white carbonate concretions, few coarse black concretions, many small fragments of chert, limestone and shell, oxide and organic matter coatings, 40 cm oblique intersecting slickensides at 115 cm and pressure faces, diffuse boundary.

B23 133-175 cm: Dark reddish brown (5YR3/4), clay, very strong very coarse angular blocky, extremely hard, v. firm, sticky plastic, common fine roots, common coarse white carbonate concretions, common coarse black concretions, clay, oxide and organic matter coatings.

Profile No.8

General information

Classification: Very fine, smectitic, thermic, Typic Chromoxererts

Location: Northwest of the industrial city of Irbid

Present land use: Summer, winter crops

Time of sampling: July 1981

Relief: Flat-gentle sloping, 1-3% slope.

Parent material: Colluvium material derived from limestone associated with basalt.

Climatic data: The average annual precipitation is about 300-400 mm. The average air temperature during January is about 10° C, and during June 24°C. Evapotranspiration is 1600 mm a^{-1}. Mean annual air temperature is 18-20°C.

Remarks: Cracks 7 cm wide at surface and 80 cm deep. Colors are for moist soils unless otherwise noted.

Profile description

A 0 10 cm: Dark reddish brown (5YR3/4), clay, moderate medium subangular blocky breaks to granular, v. hard, firm, sticky, plastic, few to common fine to medium roots, clear boundary.

B21 10-70 cm: Dark reddish brown (5YR3/4), clay, strong very coarse prismatic breaks to subangular blocky, extremely hard, v. firm, sticky, plastic, some chert and limestone gravels, diffuse boundary.

B22 70-130 cm: Dark reddish brown (5YR3/4), clay, very strong very coarse prismatic breaks to angular blocky, extremely hard, v. firm, sticky, plastic, few fine roots, few fine white carbonate concretions, few fine black concretions, organic matter coatings, gradual boundary.

B23 130-180 cm: Dark reddish brown (5YR3/4), clay, very strong very coarse angular blocky, extremely hard, v. firm, sticky, plastic, few fine roots, common coarse white and black concretions, carbonate concretions are prominently distinct, slickensides are oblique covering both sides of the ped, oxide and organic matter coatings, abrupt boundary.

IIB24 > 180 cm: Dark reddish brown (2.5YR3/4), clay, strong coarse angular blocky, v. hard, v. firm, sticky, plastic, few fine roots, many coarse white and black concretions, oxides and organic matter coatings, oblique 40 cm slickensides on both faces of the ped, flint and limestone gravels, basalt boulders are present.

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Discussion

Dudal: Is it common that xeric Vertisols are reddish, as it appeared from the photographs you showed?

Taimeh: Mostly yes, if they had developed on hard limestone. But if they had developed from basalt as the main parent material, the color would be dark-reddish brown.

Comerma: Do you have any suggestion on how to improve the definition of moisture regimes in the case of Vertisols?

Taimeh: At the moment, no. But I think some Vertisols exhibit some properties that are not in harmony with the laboratory measurements since they represent point estimates and, in many cases, the presence of cracks are not taken into consideration. Real measurements of some kind should be conducted in the field for a better approximation of the moisture variation and movement.

Hong: In your presentation, you mentioned that in some soils, fixation of P is very high. You also mentioned that only a few farmers use P fertilizers. If the soil's P-fixation capacity is very high, without application of P fertilizer (at a reasonably high level), crop performance should be very poor.

Taimeh: What I said was that we are trying to estimate the maximum P-fixation for various kinds of soils, and Vertisols are one of them. This is a laboratory test, but in the field P-fixation is not very fast due to immobility and low moisture contents. The laboratory measurements indicate that the moment P contacts moist soil, fixation processes occur rapidly. Our Vertisols do have a high P-fixation capacity.

Research Needs and Constraints

Behavior and Microstructure of Clay Water Systems

Daniel Tessier[1]

Abstract

The clay-water relationship during desiccation and hydration is examined, and the organization of clay materials at different hydration stages is investigated, using pressure techniques. Scanning electron microscopy (SEM) and transmission electron microscopy (TEM) observations were conducted, together with measurements such as low-angle X-ray scattering. Special attention is given to 2:1 clays, especially Ca-smectites and Na-smectites. These clay materials show a quasi-crystal internal structure, which is affected by rehydration after the initial desiccation, and pores of about 1 µm size are a constant feature. Comparisons are made with kaolinite, which has a crystallite structure, and illites, which form crystallite aggregates. In the latter case, much smaller pores were observed. Therefore, the swelling and hydration properties of a clay material depend not only on its internal organization but also on its history and on stress conditions of the climatic origin.

Résumé

Comportement et microstructure du rapport argile/eau : *L'article examine le rapport argile/eau pendant le dessèchement et l'hydratation ainsi que l'organisation des matériaux argileux à différents stades de l'hydratation en utilisant des techniques de pression. Des observations par la microscopie électronique à balayage (SEM) et la microscopie électronique de transmission (TEM) ont été faites avec des mesures telles que la diffusion des rayons × à angle bas. On a accordé une attention spéciale aux argiles 2:1, en particulier aux Ca-smectites et Na-smectites. Ces argiles ont une structure interne quasi-crystale, qui est affectée par la réhydratation à la suite du dessèchement initial et sont toujours caractérisées par des interstices de 1 environ. Elles sont comparées à la kaolinite qui a une structure cristallitique et aux illites qui forment des aggrégats cristallitiques. Dans le dernier cas, les interstices étaient plus petits. Les caractéristiques de gonflement et d'hydratation des matériaux argileux dépendent donc non seulement de leur organisation interne, mais aussi de leur histoire et des conditions de stress d'origine climatique.*

Introduction

One of the major needs in soil science today, and one which goes beyond the sphere of agriculture as such, is a better understanding of the genesis and functioning of specific structures of clay soils, both from a pedological and agronomic point of view. Some basic information that would help to achieve this goal could be provided by a study of the evolution of clay material during desiccation and rehydration, using well-defined clay materials that make it possible to isolate and modify parameters and to show the effect of each parameter on the system.

It is first necessary to state why we need to study

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ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1989. Management of Vertisols for improved agricultural production: proceedings of an IBSRAM Inaugural Workshop, 18-22 February 1985, ICRISAT Center, India. Patancheru, A.P. 502 324, India: ICRISAT.

clay materials. Clays occur as very small particles. Their nature at the structural unit level is relatively well known today, but their organization at a more microscopic scale, and when subject to more intense hydration, is still poorly understood. By identifying the various levels of the organization of clay material, a better knowledge of the system in operation in this type of material can be developed. Secondly, it is difficult to fully control the energy factors in the system when they involve very small stresses compatible with the natural development of the soil structure and with biological activity in general.

Further, when studying clay organization, it is of primary importance to consider the essential parameters of clay-water behavior. Clays need to be classified according to a coherent system, and the two criteria for making this classification are the type of layer and the electric charge it gives. It is well known that for a given clay, the type of cation which saturates the exchange capacity plays an essential role in the behavior of the clay towards water. The four main basic cations occurring in soils are Mg, Ca, K, and Na. The salt concentration of the interstitial solution must be allowed to vary since concentration exerts a significant effect on the behavior of some clay materials with water.

Secondly, the problem in dealing with high water contents is how much water fills up the interlayer space and how much of it fills the space between the particles that are not necessarily primary particles, especially in the case of smectites and illites (Schofield, 1934; Mering, 1946; Norrish, 1954; van Olphen, 1962; Quirk, 1968, Henin, 1971). Characterizing the system organization at various levels is therefore essential for a more thorough understanding of the clay hydration mechanism. Consequently two different methods are used, namely Scanning Electron Microscopy (SEM) and Transmission Electron Microscopy (TEM), for observing samples and methods of measurement, such as low-angle X-ray scattering, to follow the evolution of the crystalline structure and clay particle size.

In discussing the initial desiccation and subsequent rehydration of clays to determine the hydration swelling and mechanism of structure formation, we shall first describe the experimental procedure and underline the conditions under which materials can be compared with each other. Then we shall present the overall results on clay-water behavior and the evolution of the bulk volume and, finally, we shall consider the organization aspects of the clay's evolution.

Experimental Design

Stress Problem

Earlier physiocochemical and crystallochemical studies were conducted under conditions where the equilibrium frequently did not reflect the normal environment of clays in the soil. Soils should be regarded as strongly hydrated environments containing weakly bound water. The normal environment of soils corresponds to an equilibrium relative humidity (RH) exceeding 95% or even 98% (pF 4.5 and above). Such an equilibrium cannot be successfully obtained by attempting to control the samples exposed to vapor tensions and, consequently, pressure techniques are required. Table 1 shows equivalence between pF water activity and air pressure applied to the samples.

In other words, a sample subjected to a given gas pressure provides evidence for the state of the water in the system. Besides desiccation and rehydration cycles—within a very small range of stresses—can be reproduced by subjecting the samples to increasing and decreasing gas pressures.

The Use of Pressure Techniques

In the range of high water contents, the sample size changes with the water content at equilibrium, and

Table 1. Levels of energy and ways of expressing various states of water in the soil, in relation to the external pressure applied and the maximum size of the corresponding pores.

Gass pressure applied (bar)	pF	Chemical potential of the water (J kg^{-1})	Water activity	Maximum size of the pores filled with water (μm)
0.010	1	- 1	0.999993	150
0.100	2	- 10	0.999927	15
1	3	- 100	0.99927	1.5
10	4	- 1000	0.9927	0.15
15.8	4.2	- 1580	0.9888	0.092
100	5	- 10000	0.927	0.015
500	5.7	- 50000	0.695	0.0029
1000	6	- 100000	0.484	0.0015
Heated to 105°C	= 7	-	= 0	-

hydration increases as the sample size decreases. Further, it should be noted that experimental hydration conditions are also a major factor. Thus, different water contents are found, depending on whether the sample is hydrated progressively or suddenly.

Adequate time should be allowed for equilibrium to be reached, taking account of the fact that this time varies with the pressure (Fig. 1). As a result, considering the state of the water in a clay-water system is not sufficient. It is also necessary to control the conditions leading to such a water content.

Comparing Clay Materials

Clays are known to differ not only in their structural type but also in their composition of the crystallochemical. In dioctahedral 2:1 clays, the trivalent cations filling octahedral cavities are essentially Fe and Al. The volumic mass of a dioctahedral clay like montmorillonite, which is an Al smectite, is 2.65 g cm^{-3} vs 3.20 g cm^{-3} for nontronite.

Consequently, for a given solid mass, the two clays develop a different surface area:

800 m^2 g^{-1} for montmorillonite,

650 m^2 g^{-1} for nontronite

When comparing results from various clay samples, reference to solid weight or mass is inadequate because the volume occupied by the solid phase differs from one sample to another. On the other hand, if we relate the results to the volume of solids (V_S), using the void ratio for the volume of voids and the water ratio for the volume of water, we obtain realistic results.

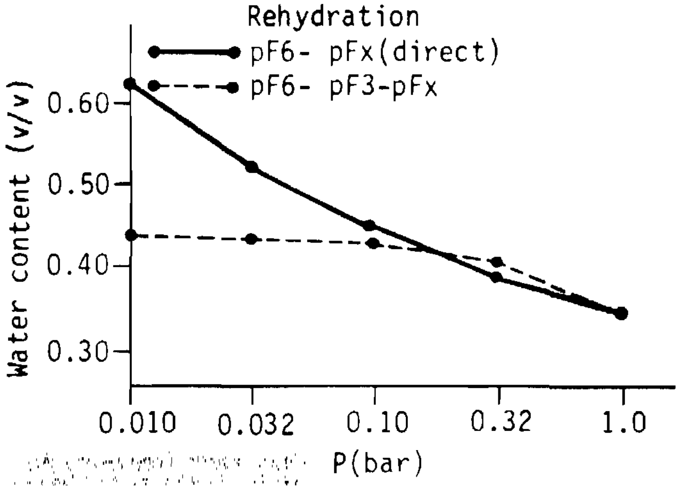

Figure 1. Change in the water content of Be'thonvilliers clay material during rehydration.

Experimental Results

Clay-water behavior and evolution of the bulk volume of clay materials

Desiccation

The results show the parallel evolution of the water ratio and void ratio. They were obtained on <2 μm clay made homoionic in the presence of a given salt concentration. Initially samples were prepared as mechanically agitated pastes, and they were compared at constant V_S. The stress was plotted on the abcissa, and the ratios used for the major clay types were plotted on the ordinate.

At P = 0.0010 bar, the Na-smectites prepared with a diluted solution were the most hydrated clays. The water content decreased in the following order:

Na and K smectites > illites > kaolinites

At P = 1000 bars the boid volume of the samples was smaller as the clay was initially more hybrid. Finally, the samples were water-saturated at 0.010 bar. At higher pressures, however, the stress at which the air penetrates into the samples was smaller as the clay was initially less hydrated.

The parallel evolution of void volume and water content for the major types of clay was represented by shrinkage curves. The minimum values obtained were significantly different, ranging from e = 1.1 to e = 0.35 for St-Austell kaolinite and Wyoming smectite, respectively. It may be concluded that clays not only differ in their maximum water content but also in the minimum volume that they can acquire.

It will be noticed that changing the compensating cation or increasing the salt concentration has virtually no effect on the maximum volume characteristics of kaolinites and illites. For smectites however it is necessary to consider all parameters. Thus, the water ratio obtained at P = 0.032 bar strongly decreases as the electric layer charge increases (see Fig. 2). For Na-smectites prepared with NaCl 10^{-3}M solution, the water ratio drops from 45 to about 10 as the layer charge rises from 0.30 to 0.60. Consequently the layer charge is a major component of the behavior of smectite water systems.

It can be further noticed that the difference in water content persists within a very wide range of stresses, especially at $P < 25$ bars. Besides the nature of the exchangeable cation is also involved. For example, the water content in Bethonvilliers smectites decreases in the following order: Na > K > Mg > Ca. Renewed emphasis should be given to the fact

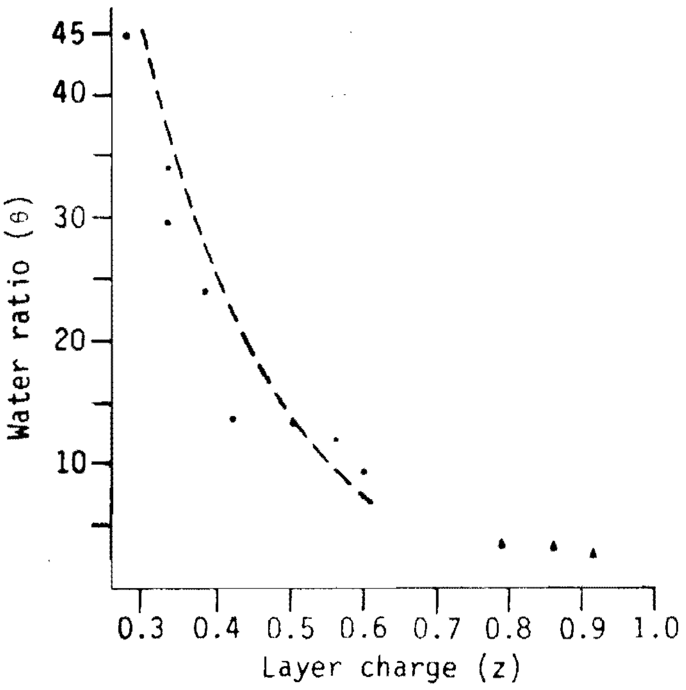

Figure 2. Water ratio (V-w/V-s) as a function of total electric charge of the layer for sodium clays, 10^{-3} molar NaCl at 0.032 bar suction.

that differences in clay behavior are most significant at pressures <10 bars.

Rehydration

After examining the results obtained during initial clay desiccation, a phenomenon which occurs in nature (e.g., consolidation of a sediment or a mud), we shall now consider the second stage, namely rehydration, and first we shall examine the behavior of illite. After extreme initial desiccation corresponding to a pressure of 10 and 1000 bar (to which the materials may be exposed in nature depending on the climatic conditions and depth in the soil), the materials were rehydrated. After initial desiccation, it appears that the material does not totally recover its original water content as only 30% of the water removed during desiccation was reabsorbed. Thus one single desiccation causes an irreversible change in the system.

However, the results in each case were not obtained under similar conditions since the first desiccation occurred after mechanical agitation, whereas during rehydration hydration forces were the main active components. It should, therefore, be emphasized that mechanical agitation following the preparation of a paste has a major effect on the water content of a clay material. Differences in water content upon desiccation and rehydration occur because a certain amount of energy is provided to the system through mechanical agitation. Similar behavior was observed for all kaolinites and illites, whatever the exchangeable cation happened to be.

For smectites, however, it is necessay to distinguish the various kinds of preparations used. In Greek Na-montmorillonite 10^{-3}M NaCl, nearly the same water content was found after rehydration as during initial dessication. Thus mechanical stirring seems to play a more limited role in this case than it does in the case of illite.

Ca-smectites, such as Wyoming montmorillonite, show a significantly different behavior from Na-smectites. Firstly, the sample is more dehydrated and so absorbs less water; and secondly, the initial water content is not regained. A similar behavior was observed in all Ca and Mg smectites. Thus the behavior of Ca and Mg smectites with water depends in particular on the initial level of desiccation, and one single desiccation produced an irreversible change in the system.

Now that the essential lines of clay-water behavior have been described, the simultaneous evolution of organization and clay-water behavior, as shown by smectites and other clays, will be examined.

Evolution of Smectite: Organization in Relation to Clay-water Behavior

Ca-smectites

Clay-water samples can be characterized at the general organization level by using SEM, but they cannot be observed in the wet state unless the system is preserved. From an undisturbed sample, it is possible to gradually replace water by methanol and then by liquid CO_2 that has been brought to such a temperature and pressure that the critical point is exceeded. Since the liquid and the gas have similar physical properties, there is no interface between them, and CO_2 can be extracted by maintaining the temperature above the critical threshold. After extracting the CO_2 the classical SEM procedure can be adopted. In this way, a kind of isotropic three-dimensional network, which bounds pores about 2 μm in size, will be found.

Small samples of the same clay were freeze-dried by cooling with freon, which is itself cooled with liquid nitrogen. After freezing, which is the most important phase, the network is observed to be oriented at P = 1 bar. At P = 1000 bars, however, the network collapses totally, yielding a perfect face-to-face contact between the network constituents.

In order to observe smectites under TEM, water was progressively replaced by methanol, and then by Spurr's resin. The exchange occurred in a liquid medium so any variation in the bulk volume of the sample could be prevented. After hardening and ultramicrotomy, the lattice images that correspond to each layer can be observed under TEM. At P = 0.032 bar, about 40 layers were found for a Ca-Greek montmorillonite. Evidence of internal discontinuities were also noted. Nevertheless, it should be borne in mind that such organization is characteristic of the quasi-crystal as defined by Aylmore and Quirk (1971).

Low-angle X-ray scattering, by means of the X-ray synchroton at LURE in Orsay (Pons et.al. 1981), was used to characterize the system more accurately. This technique provided information on two levels of the clay-water system organization, the internal particle structure and the particle size. Figure 3 shows the theoretical curves representing clay particles made up of 20-layer and 400-layer stacks.

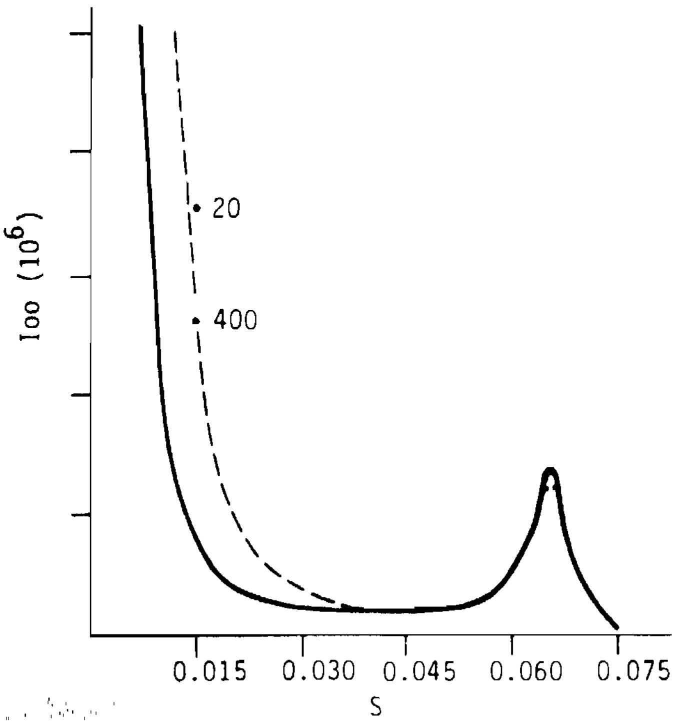

Figure 3. Theoretical intensities expressed in electronic units corresponding to disordered particles made up to 20-layer and 400-layer stacks (Pons 1980).

This figure shows that the central part of the diagram (which scatters at small angles) depends on the number of layers making up a particle. However, as previously observed by Pons (1980), reflection 001 reacts to both the disturbed layer stacks and the number of layers. This is not a turbostratic disorder related to layer translation along the a-b plane. Rather it results from a translation of the defects in the direction normal to the layer plane.

From a practical point of view, adjusting a theoretical model to the experimental curve allows the number of layers of quasi-crystals and the translation defects in the direction normal to the layer plane to be determined in both cases.

Initial Drying

In the pF range 1.5–4.0 (0.032 bar–10 bars) for a Wyoming Ca montmorillonite, the interlayer space with the highest probability is 1.86 nm. This corresponds to interlayer spaces separated by 3 monomolecular water layers. 1.56 nm occurs only at pF 6.0, corresponding to 2 water layers (d). Thus, in the stress range < 10 bars (pF 4.0), montmorillonite occurs as a stable hydrate.

On the other hand, X-rays show that the internal structure of the quasi-crystal is composed of sub-stacks of 7–8 layers separated by wider spaces (3–4 nm), which are visible in TEM. This internal structure of the quasi-crystal is a distinctive feature of Ca-smectites, and it has been confirmed by the methods used here. However, the evolution in size of quasi-crystals remains steady in the range of pF 1.5 to 3.0, and it reaches 225 layers at pF 4.0 and 400 layers at pF 6.0. Thus, the essential component involved in the evolution of the water Ca-montmorillonite system is the size of the quasi-crystal, whereas the internal structure develops only at a pressure exceeding about 50 bars (RH < 95%).

Rehydration

First we will consider the evolution of the general organization of the system dehydrated at pF 4.0 and at pF 6.0, and then rehydrated at pF 1.5. In the case of Wyoming Ca-montmorillonite, the sample absorbs less water because it has been more dehydrated (see Fig. 4).

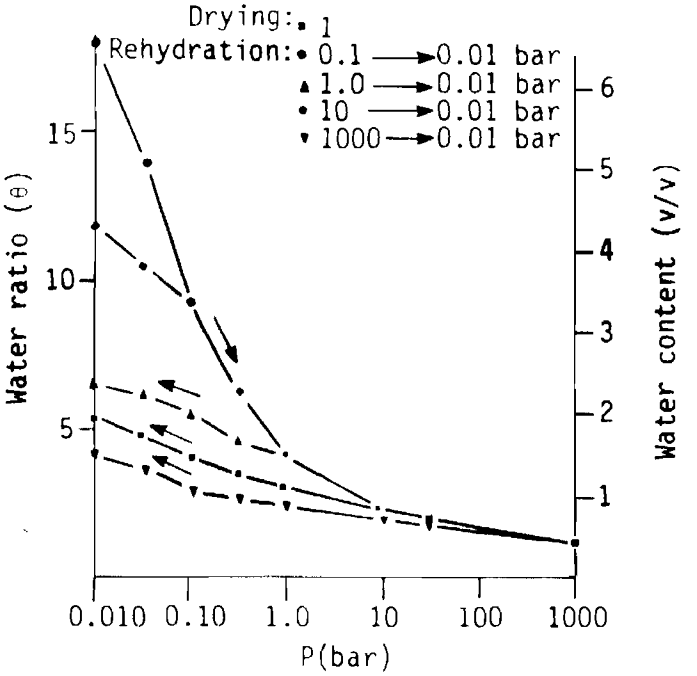

Figure 4. Effect of drying on the water retention curves of a calcium smectite (Wyoming Bentonite), 10^{-3} molar $CaCl_2$.

The organization of this clay is different from that obtained during the initial drying. The isotropic organization that was present in the initial drying does not occur, and the network remains oriented. Besides, the network obtained seems more rectilinear and thicker as the clay has been more dehydrated; but the pore size remains close to 1 μm when the clay is fully rehydrated.

Similar behavior was obtained with Bethonvilliers smectite because the network is strongly aggregated (about 5 particles) at pF 6.0 to pF 1.0. Therefore, the pore size is quite constant (close to 1 μm) when clay is rehydrated at very low pressure. When observing the system change under low-angle X-ray scattering, d_{d} remains constant at 1.86 nm from pF 4.0, which means that the absorption of water occurs without any change in the interlayer hydration state that keeps 3 layers of water.

Similarly, after drying at pF 6.0, the 3-layer hydration state occurs again at pF 4.0 and remains constant. But here again, evolution of the system is essentially reflected by the number of layers of the quasi-crystals. After desiccation at pF 6.0, we find 90 layers at pF 1.5, which is about twice as much as at pF 1.5 during initial desiccation. Thus, for Ca- and Mg-smectites, the evolution of the water content during rehydration should be related not only to an irreversible change in orientation but also (and essentially) to the increased thickness of the quasi-crystals following the application of a very strong stress.

In the case of smectites, we can observe a genuine structural aggregation. The use of X-rays shows that the internal structure of the quasicrystals does not change during initial drying as it does in rehydration. However, quasi-crystal size and, hence, the surface exposed to pore water, is altered. Nevertheless, pore size remains more or less constant (about 1 μm at pF 1).

Na-smectites

Next we will consider the evolution of Na-smectites. For this we will first examine Na-smectites in NaCl 10^{-3} molar diluted medium and then the 1 molar preparation. During initial drying, the general organization of smectites can be examined in relation to the electric charge. Greek smectites under SEM display an isotropic organization similar to that of Ca-montmorillonite, and the same is true of other smectites. Indeed such network-based organization is characteristic of all smectites under SEM.

Low-angle X-ray scattering yields the most accurate picture of the water-Na-montmorillonite NaCl 10^{-3} molar system. The data relating to the evolution of the major parameters of the system were collected during initial drying and rehydration of Wyoming Na-montmorillonite in 10^{-3} molar NaCl.

First $d_{\max}$ was found to occur in the range 1–4 nm, depending on whether the mineral was undergoing drying or rehydration. From other reports in the literature, the distance appears to be characteristic of the formation of a diffuse layer. Although the interlayer space changes considerably during rehydration as compared to initial drying, the number of layers making up the network was found to rise from 8 at pF 3.0 (first drying) to 20 at pF 6.0, indicating that one of the major variables in a clay-water system is the number of clay layers forming one particle. This was confirmed by TEM.

Thus the use of TEM allows us to count the number of layers making up the walls of the network in Greek Na-montmorillonite NaCl 10^{-3} molar and hectorite. There are about 10 layers in Greek montmorillonite and about 5 in hectorite. This finding confirms the results obtained by low-angle X-ray scattering because the number of layers is maintained. However, for 10^{-3} molar preparations, the interlayer space drops to 1.55 nm. The salt concentration parameter has not been considered here, but it is known that in the presence of a high salt concentration the water content of Na-smectite becomes similar to that of Ca-smectites.

SEM examination showed the simultaneous changes in the water content and the organization of Greek Na-montmorillonite NaCl 1 molar during drying. This evolution is similar to that for the same clay's Ca-montmorillonite. TEM shows that increasing salt concentration causes the number of layers making up the network to rise from 10 to about 30–40. These results are in agreement with low-angle X-ray scattering data, which further show that $d_{\max}$ is equal to 1.86 nm and, therefore, is similar to that of Ca-montmorillonite for $P < 10$ bars.

Organization of Other Clays—Macroscopic Implications

In St-Austell kaolinite, the organization of the system during drying appears to be based on crystallites. At P = 0.032 bar, the distance between crystallites is approximately 1 μm. From P = 1 bar the crystallites are closer to each other (see Fig. 5).

During rehydration from pF 6.0 to 1.5, the system has the same compact state at pF 1.0 as at pF 3.0. It may thus be concluded that the system does not reorganize very much during rehydration, and this is confirmed by bulk volume measurements.

In Ca-kaolinite only one organization level, corresponding to the crystallites, can be demonstrated. The pores between crystallites remain very small in comparison with those of Ca-smectites. Besides, crystallites are the smallest particles that can be isolated from the system in this kaolinite, which is not the case for illite or glauconite. TEM examination of glauconite, for example, shows that the smallest particle that can be extracted is a crystallite aggregate known as microdomain. In a similar system, say illite from Puy en Velay during rehydration, some macroscopic discontinuities representing domains can be observed under certain conditions due notably to the formation of fracture planes, which are similar to shearing planes during rehydration. No pores 1 μm in size form in illite.

Domains may form in $MgCl_2$, $CaCl_2$, and NaCl 1 molar-smectites and this is clearly visible in $CaCl_2$ and NaCl 1 molar-montmorillonite. It seems that true shearing planes, which bound domains, form in clays having $CaCl_2$, $MgCl_2$, and NaCl 1 molar-charged basal surfaces (Tessier, unpublished data). In kaolinites (zero charge) and in Na-smectites prepared with a diluted solution (i.e., in the presence of a diffuse double layers), shearing planes do not form. So it would appear that the macroscopic behavior of clays depends largely on the clay organization at the first level, that is, at the crystalline level.

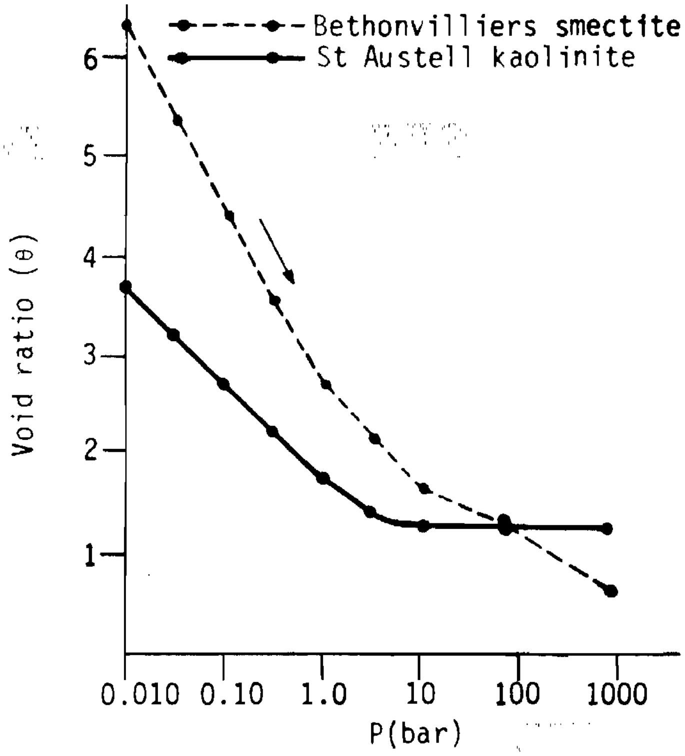

Figure 5. Shrinkage curves for Be'thonvilliers smectite and St. Austell kaolinite.

However, considering the parameters related to crystalline structure alone is not sufficient. Vermiculite, for example, is an oriented network similar to that of Ca-smectites. Considering that the water content is very high (water ratio = 10) in Palabora vermiculite, it is clear that the strongest hydrations in clays are due to either the presence of one diffuse double layer between the layers (e.g., in Na and K smectites prepared with a dilute solution) or to existence of particles having a wide lateral extension in the a-b plane, as is the case in $CaCl_2$, $MgCl_2$, NaCl 1 molar-smectites, or in Palabora vermiculite.

There is, however, a basic difference between smectites and macrocrystalline vermiculite. The network-based system forms spontaneously again only in smectites when the layer charge is low enough. For this reason, a network-based organization is mainly characteristic of smectites. The quasi-crystals are then sufficiently flexible so that pores approximately 1 μm in size can form. We may say that the major result of this work was to provide evidence that pores of approximately 1 μm can form during clay rehydration. However, such an organization cannot occur in kaolinites or illites due to insufficient extension in the a-b plane. The particles become so rigid that curving is prevented.

It is thus clear that, in the range of high water contents, macroscopic behavior cannot be examined without considering the properties of the system at the crystalline level. Therefore, we have examined the clay-water behavior and changes in organization for each major clay material during drying and rehydration, in relation to the parameters that are actively involved in such systems.

Conclusion

The initial purpose of this work was to obtain the basic information required to make a rational interpretation of the behavior of clay materials in soils. First we need to define the behavior towards water of the major types of clay materials and their macroscopic swelling properties. Then we have to relate the behavior of such materials to some crystallochemical and geochemical parameters and to the action of stresses.

Some continuity should be established between the various organization levels from the structural unit up to the macroscopic organization of the material. The specific action of each parameter on the characteristics of the system should be determined. The results obtained with various methods point to the overall coherence of various data provided by low-angle X-ray scattering, SEM and TEM observations, macroscopic examination, etc. All these data finally appear to be complementary, and they contribute to a better definition of the clay materials.

However, a clay material cannot be adequately defined unless the structural unit of the layer aggregation and the major types of particles that characterize this system are taken into account. Clays may have the following structures: crystallites (kaolinites), crystallite aggregates (domains in illites), or quasi-crystals (smectites), which means that we are dealing with particles of variable size, depending on all the environmental parameters.

The evolution of the water content of a clay material actually reflects organizational changes, which may occur at 3 levels:

arrangement (orientation-disorientation);
particle size (following the a, b, and c planes);
internal particle structure (variable in interlayer space distribution).

Under conditions compatible with biological activity, the arrangement and size of the particles are the parameters most likely to evolve. Thus in most soils an evolution of the water content does not cause significant modification in the interlayer space.

On the other hand, the swelling and hydration properties of the clay materials are closely related to their "history", i.e., to the various successive stresses to which they have been previously subjected. In other words, clay behavior should not be identified exclusively on the basis of the nature of the clay or of its geochemical environment. It is also necessary to evaluate accurately the stress conditions, and these may be of climatic origin (as examined in this paper) or mechanical origin (requiring further study). This means that various mineralogical, geochemical, and physical parameters need to be considered simultaneously in order to determine accurately the genesis, behavior, and functioning of a clay soil. Only by considering all the parameters involved can an overall strategy be developed for the study of clay soils or any other kind of soils.

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Vertisols: Some Research Avenues for their Management

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Abstract

Recent research in soil science has shown that (i) the soil mantle is an organized, dynamic system, and (ii) soil characterization must take into account the three spatial dimensions and the time dimension.

A review of the literature on Vertisols reveals that few works address these points. However, two major studies in West Africa have shown that Vertisols can originate under either (i) an arid or semi-arid climate by direct differentiation on basic rocks, or (ii) a semi-arid climate by clay illuviation in the lowlands. These differences in origin have to be considered in soil management of Vertisols, and should be investigated thoroughly in other soil systems.

Résumé

Vertisols—certaines possibilités de recherche pour leur gestion : *Les recherches conduites récemment sur la science du sol ont montré que (i) l'enveloppe du sol est un système organisé et dynamique, et (ii) la caractérisation du sol doit tenir compte des trois dimensions spatiales et la dimension du temps.*

Une revue de la bibliographie sur les Vertisols révèle qu'il y a très peu d'ouvrages qui abordent ces points. Cependant, deux principales études en Afrique de l'Ouest ont montré que les Vertisols peuvent être dérivés dans les climats soit (i) aride ou semi-aride par la différentiation directe sur les roches ignées, ou (ii) semi-aride par l'illuviation argileuse dans les bas-fonds. Ces différences dans l'origine doivent être prises en considération dans la gestion des Vertisols ainsi que dans d'autres systèmes du sol.

Introduction

Soil, a constituent of the earth's crust located at the lithosphere-atmosphere interface, results from phenomena that generally occur over a very long period of time. Its dynamic characteristics are based on transformations and transfers of matter, resulting from biological activity and fluid movement produced by hydric and thermal conditions. Hence, soil has a spatial extension and there is linkage between its various elements.

Apart from a few specific cases, the transition between one type of soil and neighboring soils is usually progressive and nonuniform. This means that studying the soil in the landscape should go beyond considering the soil unit, described according to its reference soil profile, to investigating the distribution and succession of the horizons constituting the tridimensional soil mantle.

Two basic pedological concepts were recently developed as a result of research in this area, namely:

- The soil mantle is an organized, dynamic system. Its originality, as compared to other mineral or biological systems, consists in its specific organization and dynamics.
- The characteristics of a soil are determined by

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three spatial dimensions and one time dimension, the latter being the age of its constituents.

Soil as an Organized and Dynamic System

The soil mantle (which includes the mineral and organic constituents and also the liquid and gaseous phases) is an organized system. This means that its components are not put together randomly, but are arranged both vertically and laterally, which gives the soil its morphology. This morphology can be observed and described from an ultramicroscopic scale to landscape dimensions. One of the main features of a soil is determined by the arrangement of the porosity within its constituents. Porosity plays a major role in the dynamic properties of the soil—infiltration, gas diffusion, and solute transfer—and consequently in the behavior of a soil in relation to plants.

Since variations in the soil are continuous, it would at first appear difficult to study it by examining a succession of soil profiles, which might give the impression of artificial discontinuities. Soil does have a number of nonhomogenous as well as homogeneous zones, and a thorough examination of the soil should first aim at identifying and describing both types of zone and at establishing their geometrical relationships.

Finally soil is a dynamic material and continuously undergoes changes with regard to eluviation, illuviation, biological transformations, and the chemical and physical modifications of its constituents.

Soil as a Four-Dimensional System

In its spatial dimension, soil organization (basic assemblages and horizon assemblages) can be related at all levels of the landscape, and often over great distances. These relationships result from the vertical and lateral transfer of matter within the soil mantle, and they relate the genesis of the different soil assemblages to their dynamic properties. The observed lateral and vertical differentiation is mainly linked to the landscape (upland or lowland) and gives rise to what is usually called a toposequence.

Soil organization is also related to time, which means that in the same site very different features may occur from one period to the next. For example, the various soil features observed along a geologically homogenous toposequence can, in fact, be the stages of a single evolution. Therefore, it is essential to try to understand the spatial and historical relationships that exist between the soil organizations of a particular area, since these relationships define the soil units of the area. These units are not characterized by a "soil type" or by several related soil types, but by variations in the soil organization and structure of the soil mantle.

Applications to Vertisols

Numerous soil studies have been carried out on Vertisols, as well as on the vertic subgroups of other orders. These include:

- Morphological description of the soils and of their distribution in the landscape, as related to environmental factors such as climate, rocks, and vegetation.
- Investigations of the constituents of the soils, and in particular of the clay materials.
- Chemical, physical, and mechanical characterization of various types of Vertisols and of vertic horizons.
- Characterization of the moisture regime in relation to the structural properties (e.g. swelling and stability).

The following observations can be made from a review of the literature on Vertisols:

- In most cases, studies on Vertisols and vertic soils have been conducted on soil profiles or pedons. Very little work has been carried out on the spatial and historical differentiation of Vertisols, or on the relations between Vertisols and other soil types within a particular landscape.
- Although Vertisols have been adequately described and measured at the macroscopic and microscopic scales, few studies have been conducted at the ultramicroscopic scale, which is the scale at which most constituents of Vertisols, and in particular clay minerals, can be observed.
- Finally, much remains to be done to achieve a better understanding of the dynamic properties of Vertisol systems.

From this review, it can be seen that studies on Vertisols, which relate to their spatial and historical differentiation, their ultramicroscopic organization, or the dynamic properties of their systems, should be enhanced in soil research programs. The type of results that can be obtained are indicated in two examples of work on toposequences, including Vertisols, recently conducted in Africa.

Two major types of toposequences have been identified:

- Toposequences where illuvial clay horizons are minimal whatever the topographical position (Boulet 1974) and clay minerals are found throughout. The Vertisols are well differentiated and occur in the lower part of the landscape, while the vertic subgroups develop on the higher part of the slopes. They are found in the driest zones of Africa, mainly in the Sahel, or on basic rocks which are mostly basalts. In these sequences, fersiallitic or eutrophic brown soils (Eutropepts, Ustropepts, Tropaqualfs, and Haplustalfs) are related to Vertisols and vertic soils. These sequences are known not only in tropical and mediterranean Africa but also in Australia, Brazil, and other parts of the world. In this context, within geologically homogenous landscape units, Vertisols and vertic soils can occur in different topographic positions. However, the normal evolution of these systems is the development of vertic features, and the different soils encountered on the toposequences represent various evolutionary stages of the systems.
- Very differentiated toposequences relating highland and bleached soils, solodized solonetz, to lowland Vertisols. Two such sequences have been studied in detail in Chad (Bocquier 1971), where the following features have been noted:
  - the high parts of the sequences are characterized by bleached upper horizons and by clay eluviation;
  - the lower part of the sequence is marked by an accumulation of illuvial clay, which accumulates from the lower part upward.
  - the illuvial zone corresponds to the ionic neoformation of montmorillonite, with local alkalization or the formation of calcareous nodules.
  - usually the differentiation in the catena goes through the following steps:
    - clay eluviated soils (Haplustalfs);
    - hydromorphic clay eluviated soils (Aqualfs);
    - Solodized Solonetz (Natraqualfs); and
    - Vertisols

These two types of toposequences show that Vertisols do not have a single origin, and it is questionable whether Vertisols of different origin can be considered equivalent, or even whether they can be used in a similar way. The answer is affirmative if merely the morphological and physicochemical features of the soil profiles are considered. However, if the issue is soil management and the relation between the soil characteristics and land use, a more comprehensive study of the soil sequence may be needed, from a microscopic scale to landscape dimensions.

Conclusion

Vertisols and vertic soils of different origins have different organizational structure and dynamic properties, which may affect their potential uses. Consequently, research should be carried out in accordance with the following guidelines:

- Survey the various types of landscape and toposequences that exhibit Vertisol features.
- Make detailed studies, at all scales, of the transitional zones between the Vertisols and other soils, and of the water movements in these transitional zones.
- Make detailed studies, at all scales, of the similarities and differences that exist as regards the morphology of Vertisols belonging to different landscapes and toposequences, and of their behavior in relation to plant growth.

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Soil Physical Research for Improved Dryland Crop Production on Vertisols in Queensland, Australia

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Abstract

Physical processes in Vertisols influence the ease and success of farming, but they have not been extensively studied in traditional soil science. Large areas of Vertisols occur in Queensland, Australia. Crop production on these soils is mainly between 20 and 29°S, and between the 500-mm and 700-mm rainfall isohyets. Rainfall is dominant in the summer and highly variable. Wheat (in winter) and sorghum (in summer) are the major crops. Farmers traditionally fallow to store water in the soil prior to planting, but there is an increasing trend toward opportunity cropping.

The Queensland environment may be less favorable for agriculture than are the Vertisol regions of India. Constraints to crop production are divided between those due to deterioration through land use (erosion, salinization, compaction, organic matter decline) and those due to preexisting soil characteristics (surface sealing and crusting, excessive cloddiness, low plant-available water capacity, restrictions to root growth, subsoil salinity, surface waterlogging). Research should aim to improve the understanding of physical processes to assist soil management, especially to improve plant-available water, rainfall-use efficiency, and structure management and to reduce soil erosion.

Résumé

Recherche physique des sols pour l'amélioration de la production agricole en régions arides sur les Vertisols au Queensland, en Australie : *Les processus physiques des Vertisols influent sur la facilité et le succès de l'exploitation agricole, mais ils n'ont pas été étudiés de façon approfondie dans la science des sols traditionnelle. De grandes surfaces de Vertisols se trouvent au Queensland. Sur ces sols, la production agricole se situe essentiellement entre 20 et 29°S latitudes et entre les isohyètes de précipitations de 500 et 700 mm. Les précipitations prédominent en été et sont très variables. Le blé (en hiver) et le sorgo (en été) sont les principales cultures. Traditionnellement, les agriculteurs laissent les terres en jachère afin d'établir une réserve d'eau dans le sol avant de planter, mais il y a une tendance croissante vers le défrichage occasionnel.*

L'environnement du Queensland est peut-être moins favorable à l'agriculture que les régions de Vertisols en Inde. Les contraintes à la production agricole se partagent entre celles dues à l'usage des terres (érosion, salinisation, compaction et appauvrissement de la matière organique) et celles dues aux caractéristiques préexistantes du sol (battance et encroûtement de la surface, formation excessive de mottes de terre, faible capacité d'eau disponible pour les plantes, restrictions à la croissance des racines, salinité du sous-sol, engorgement d'eau en surface). La recherche devrait tendre à améliorer la compréhension des processus physiques afin d'appuyer la gestion des sols, surtout afin

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ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1989. Management of Vertisols for imporoved agricultural production: proceedings of an IBSRAM Inaugural Workshop, 18-22 February 1985, ICRISAT Center, India. Patancheru, A.P. 502 324, India: ICRISAT.

d'améliorer la quantité d'eau disponible pour les plantes, l'efficacité de l'usage des précipitations ainsi que l'aménagement des structures et de réduire l'erosion des sols.

Introduction

Interest in Vertisols in Queensland arises from the predominance of these soils in the major cropping areas. Hubble et al. (1983) show (Fig. 1) that Vertisols cover more than one-quarter of the Queensland land surface—some 45 million ha; this amounts to about three-fifths (60%) of the total Vertisols in Australia and about one-fifth (20%) of the total area of Vertisols in the world (Hubble 1984). In comparison, India has an estimated 73 million ha of Vertisols and associated vertic soils (Venkateswarlu 1984).

The unique physical properties of Vertisols can be either an advantage or a disadvantage for farming. These are listed by Smith et al. (1984), who also provide background information on climate, crop production, and soil physical processes important in management of Queensland Vertisols. Despite progress in soil physics research, information is still inadequate for the development of integrated soil-and-crop management systems, which can improve production in the short term while also maintaining long-term productivity.

This paper discusses areas where research can lead to improved management systems. To understand the need for such research, we also consider present land use and soil management, and the major constraints to improved crop production.

Present Land Use and Soil Management

Land Use

Many of the Vertisols in Queensland are too dry for cropping, as annual rainfall is less than 500 mm (see Fig. 1). The main cropping area lies between 20 and 29° S, and between the 500-mm and 700-mm rainfall isohyets. In this area, rainfall is summer-dominant and highly variable; pan evaporation exceeds rainfall in all months.

Weston et al. (1981) estimated that mapping units with Vertisols as the principal profile form covered an area of 50 million ha. They summarized land use in this area as follows:

- Irrigated cropping = 0.05 million ha
- Dryland cropping = 1.20 million ha
- Land presently uncropped with:
  potential for dryland cropping = 6.00 million ha; and
  suitable only for grazing = 43.00 million ha.

The large proportion used for livestock production (extensive grazing of native grass pastures) reflects the occurrence of very large areas of Vertisols in low-rainfall regions. Although there is concern for soil degradation by erosion and salinization in some areas under livestock production, economic considerations limit the potential for improved pasture and soil management.

Despite problems of crop establishment, waterlogging, and salinity control in some soils, Vertisols are commonly irrigated in Queensland; although the total area of irrigated Vertisols is relatively small, it is highly valued. Soil scientists and farmers have developed considerable expertise in the management of Vertisols under irrigation (Shaw and Yule 1978, Smith and McShane 1981, Gardner and Coughlan 1982, Smith et al. 1984).

This paper describes dryland (rainfed) use of Vertisols in Queensland, where the greatest constraint to crop production is lack of water. Traditionally, dryland farmers in Queensland try to grow one crop each year, in either the rainy or postrainy season, with fallow in the alternate season. The major winter crop is wheat, and the major summer crop is sorghum. Although rainfall is dominant in summer (October-March), wheat is the main cereal crop in the southern areas, particularly toward the west (e.g., Roma), where rainfall is lower and less reliable. The extent of summer dominance increases towards the north; the ratio of summer:winter rainfall is 2:1 at 29° S, and >3:1 at 20° S. The average area planted annually to each crop in four of the Queensland Government's statistical regions is shown in Table 1.

Soil Management

Dryland crop management includes a degree of physical manipulation of the soil, mainly during cultivation and planting. The objectives of these operations are:

- To enhance water storage during fallow. This is achieved both by killing weeds and by using crop stubble and surface structure to maximize infil-

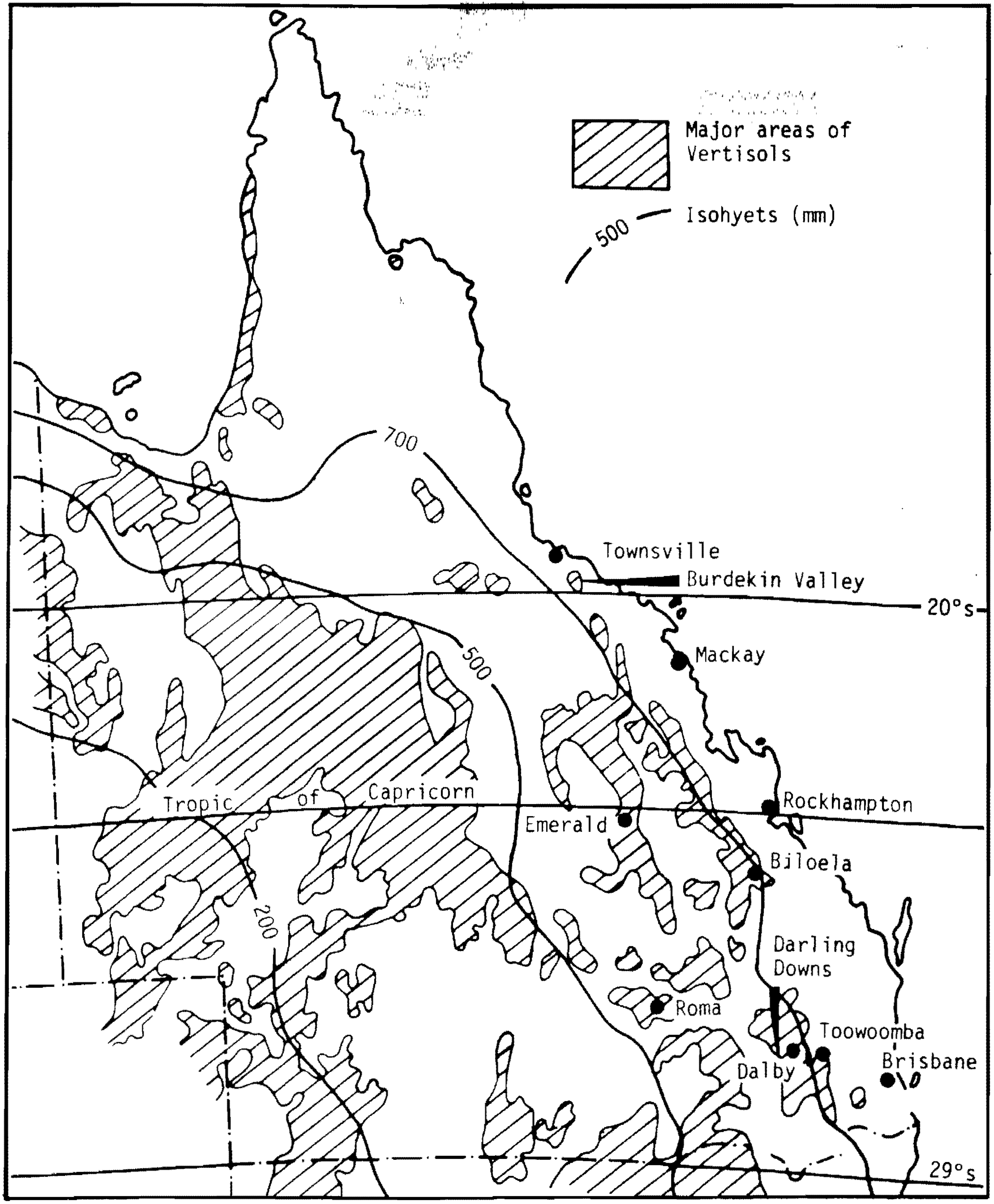

Figure 1. Distribution of Vertisols in Queensland. (Sources: Hubble et al. 1983, Smith et al. 1984).

Table 1. Average annual area (1978-83) planted to sorghum and wheat for four regions of Queensland.

Region	Sorghum ('000 ha)	Wheat ('000 ha)
Mackay (21-23°S approx.)	37	4
Rockhampton (23-25°S approx.)	152	91
Darling Downs (25-27°S approx.) (East)	191	570
Roma (25-27°S approx.)(West)	10	99

Source: Compiled from data provided by Australian Bureau of Statistics.

tration and minimize runoff and evaporation.

- To prepare a suitable seedbed.
- To establish a crop, often using special equipment such as presswheels.
- To minimize soil erosion, by constructing contour banks, thus facilitating contour tillage, and maintaining crop stubble on the soil surface.

In manipulating the surface structure of Vertisols, the most important principle is to work with and not against the considerable natural phenomena that operate in these soils. Structure is largely determined by forces generated by wetting and drying. Management should aim to supplement these forces by careful timing of tillage as regards wetting and drying. A good example of this is the management system developed at ICRISAT (Swindale and Miranda 1984), in which the difficulty of preparing a good seedbed with animal-drawn implements is minimized by commencing primary cultivation immediately after the harvest of the second crop. In contrast, the Australian farmer has large holdings, and timeliness of operations is essential; he needs access to considerable mechanized power. The disadvantage of this system is that it may allow the farmer to carry out operations under less ideal moisture conditions, thus risking structural damage to the soil.

The level of management applied on an individual farm depends on a number of factors, including climate, soil type, crop to be grown, available knowledge, and machinery and labor inputs. The influence of social and cultural norms on farming practice is not considered in this paper.

If we compare Queensland with India, we can note the obvious differences in the effect of climate and machinery and labor inputs on crop production.

Climate

Mean annual rainfall at representative towns within the Queensland grain-growing area (see Fig. 1) is 594 mm at Roma, 634 mm at Emerald, 673 mm at Dalby, and 702 mm at Biloela. All these areas fall within a "low" rainfall region, on the basis of the simple classification used in India by Venkateswarlu (1984): high, > 900 mm; medium, 700-900 mm; and low, <700 mm.

Australia not only is the driest continent, but also has very variable rainfall. This is reflected in the variability of crop yields. Russell (1984) analyzed wheat yields in 13 countries and found that coefficients of annual variation of wheat yields in Australia (18.9%) were exceeded only in Algeria (22.2%) and Morocco (24.0%). Other values were 10.3% for India, and 8.0% for the United States. Analysis of figures for Australian states over a longer period showed annual yields in Queensland to be most variable, with a coefficient of annual variation of 35.3%.

Because of the low reliability of rainfall, farmers must maximize the water available to a crop by ensuring maximum storage of water in the soil prior to planting. This is attempted by bare-fallowing, but the efficiency of water storage under fallow is low. Table 2 compares summer (rainy-season) fallow water-balance components at ICRISAT with those on the Darling Downs (location shown on Fig. 1). Major differences are the comparatively low percentage of rainfall stored in the soil and the predomi-

Table 2. Comparison of water-balance components in the rainy-season fallow at ICRISAT Center, India, and on the Darling Downs, Australia.

	ICRISAT Center	Darling Downs (Greenmount)	
Water balance components[1]	Bare fallow	Bare fallow	Stubble mulched
Runoff	25	17	10
Evaporation	25		
Deep percolation	10	65	66
Soil storage	40	18	24

[1] Figures are % of rainfall during the fallow.

Source: For ICRISAT Center, Venkateswarlu (1984); for Darling Downs, pers. comm., D. Freebairn, Queensland Wheat Research Institute, Toowoomba, Queensland.

nance of evaporation as a cause of water loss in the Darling Downs environment. At ICRISAT, soil storage was higher. However, there are insufficient data available for tropical and subtropical areas to explain these differences in terms of environmental and soil hydrologic processes.

The importance of soil water in determining grain yields under dryland agriculture is illustrated by the analysis of Nix and Fitzpatrick (1969). In Central Queensland, 60 to 83% of annual variability in sorghum and wheat yields could be accounted for by an index based on available water in the root zone at peak anthesis and subsequent potential evaporation.

Because of the low and variable rainfall, there are two soil-water management options for dryland cropping in the Queensland climate:

1. Fallow to allow recharge of the soil-water profile. However, recharge during summer fallow may not be sufficient to ensure good crop yield. In this respect, Queensland differs from India, where even in rainfall-deficient rainy (kharif) seasons, the soil moisture may be fully replenished in areas with a rainfall greater than about 800 mm a^{-1} (Hodnett and Bell 1981).
2. Opportunity cropping, which involves planting after a "sufficient" rainfall event (30-50 mm, depending on the amount of water stored in the subsoil). Success depends on the amount and distribution over time of subsequent rainfall.

Dryland cropping normally involves a combination of these options, and models predicting the success of various option combinations are available (e.g., Berndt and White 1976).

Machinery and Labor Inputs

In Australia, labor rather than land is the primary limiting factor. A wheat farm in Queensland commonly has 200-2000 cultivated ha, compared with 3.7-7.5 ha in India (Venkateswarlu 1984). For this reason, large machinery is required for cultivation and harvesting; the farms are usually owner-operated with the use of labor assistance or contractors during planting and harvest. Particularly in the more marginal areas, average grain yield is low (e.g., 1 t ha^{-1}), average profit per unit area is low, and annual financial return is variable. The cultivation of very large areas, which require large total capital outlay on machinery but low management input per unit area, reflects the farmers' realistic response to a high land:labor ratio. The general level of soil management is less than that in ICRISAT's improved system, and probably less than that practiced in most less developed countries (LDCs). Farmers in LDCs may be better placed to take advantage of a knowledge of soil processes, because farms are smaller and more labor-intensive, and they probably allow more flexibility in relation to cropping and other decisions. Small farmers may be able to give more attention to the soil structure and soil-water consequences of management decisions. For this reason, our knowledge of soil physical processes in Vertisols may be of more value to scientists and farmers in LDCs than our soil-management system.

Soil Physical Constraints to Improved Crop Production

The existence of soil physical constraints increases the risk of crop failure, the impact of unfavorable weather events, and the cost and difficulty of implementing good soil management practices. Soils with a greater number of constraints increase the difficulties encountered by farm managers in making the correct management decisions, thus increasing the probabilities of decreased yields and crop failures due to poorer crop establishment, persistence, or productivity. The constraints and their consequences include:

- surface waterlogging (in some cases associated with gilgai microrelief)—causing poor growth and persistence;
- surface sealing—causing increased runoff and erosion;
- coarse surface aggregates—making timing of cultivation and seedbed preparation difficult;
- low plant-available water capacity (PAWC) associated with limited root penetration—restricting yield; and
- subsoil salinity—affecting yield and plant persistence.

Some or all of these problems often occur in combination and appear to be related to the unsaturated hydraulic conductivity of the soil. A model to explain the interaction of these properties has been proposed (Fig. 2, from Coughlan 1984, Coughlan and Loch 1984).

Our studies also suggest that a number of soil properties are associated with the constraints listed above. These properties include clay content in the range of 40-60%, lower smectite and higher kaoli-

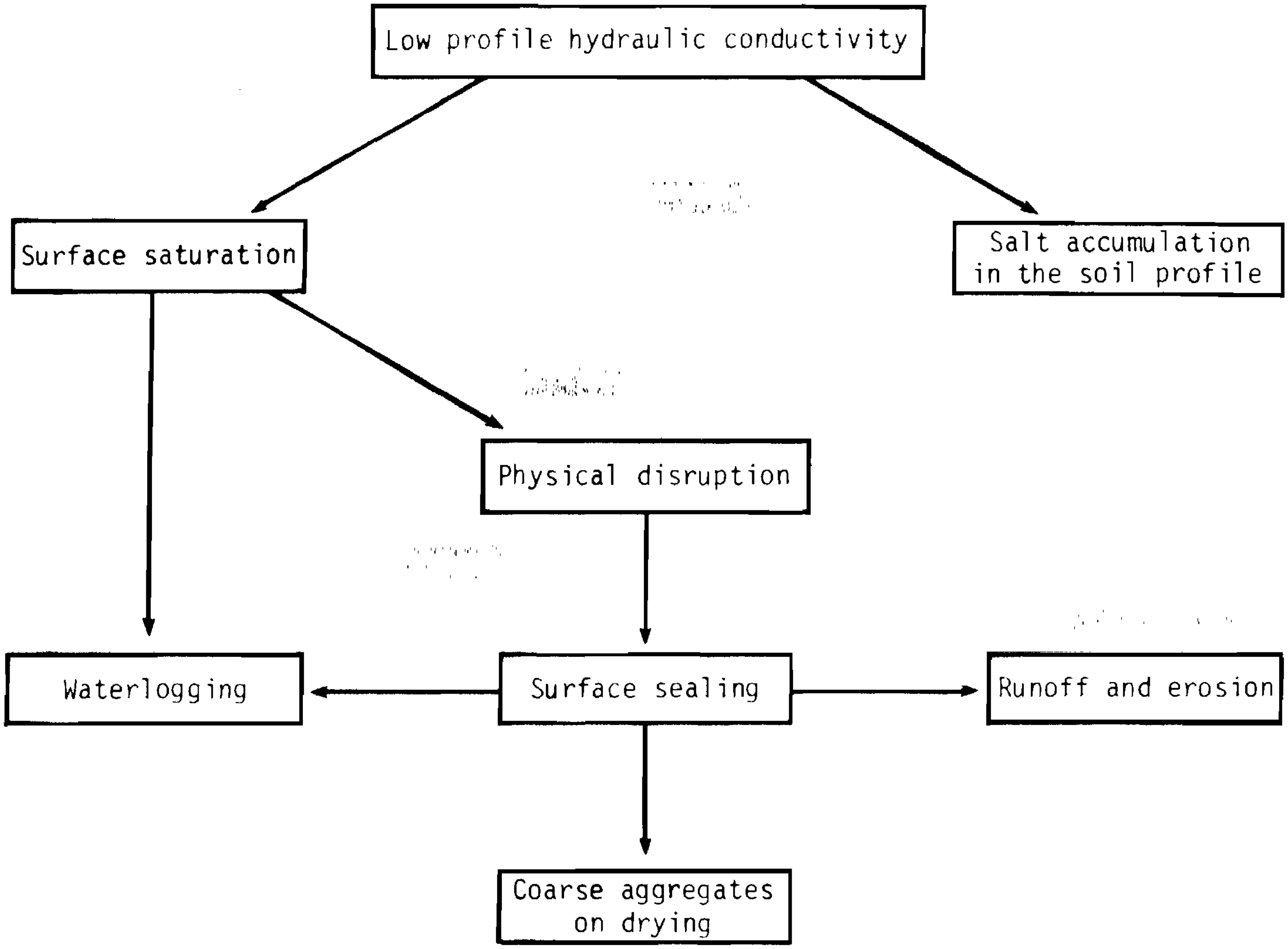

Figure 2. A conceptual model describing the function of coarse dry aggregates in Vertisols (Coughlan 1984).

nite contents, and higher ESP (exchangeable sodium percentage) of the surface soil. One of these relationships, between soil properties and coarse surface aggregates, is shown in Figure 3. In this study, coarse dry aggregates in the surface were also associated with higher salt levels at 60–90 cm (Coughlan and Loch 1984).

Depth of root penetration is an important factor in PAWC, but the factors limiting root penetration are not known. It is commonly found that the depth of rooting is associated with the depth at which salt accumulates (Shaw and Yule 1978, Gardner and Coughlan 1982). Figure 4 shows chloride profiles and depth of root penetration (as indicated by water extraction) for irrigated fodder sorghum on three Mollic Torrerts at Emerald. In a study of soils in the Burdekin Valley, Gardner and Coughlan (1982) also found that, although the depth of salt accumulation was a fair estimate of rooting depth, salt concentrations in a number of soils were insufficient to markedly reduce root growth. Hence, it is uncertain whether salinity limits rooting depth.

Despite this, there is ample evidence to suggest that the salt profile is a good indicator of water fluxes in the soil profile. Examples of this evidence are:

- Salt content (at 60–90 cm) in Vertisols is related to rainfall and a number of soil factors that may influence water movement, e.g., clay content, clay type, and ESP (Shaw and Thorburn 1985).
- Wetting depth can be predicted from the salt profile (Mullins 1981).
- Salts can be leached by irrigating (Smith and McShane 1981, Gardner and Coughlan 1982) or by changing management systems (Loch and Coughlan 1984).

These results support the use of the salt profile as a surrogate measure of soil physical constraints in Vertisols. Further studies on interpretation of salt profiles are warranted.

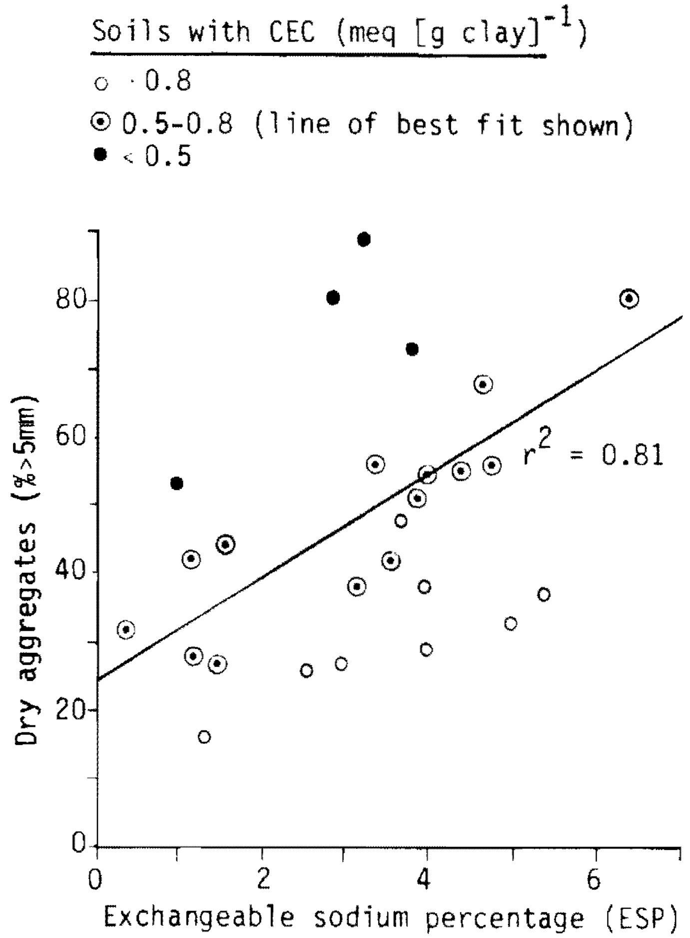

Figure 3. Relationship between percentage of dry aggregates (>5 mm) and exchangeable sodium percentage of Queensland Vertisols.

Erosion, salinization, compaction, and organic-matter decline tend to reduce productivity. As pointed out by Smith et al. (1984), soil erosion and reduction in organic matter (and associated nutrients) have been legacies of traditional farming systems, which in some areas are close to exploitative monoculture. More recent farming systems retain crop stubble on the surface and minimize soil disturbance by cultivation. They offer an increase in soil organic matter, particularly if nitrogen fertilizer is used, and thus the potential to reduce erosion. As seen from Table 2, such management systems may also result in an increase in the efficiency of soil-water storage during the period under fallow.

Development of innovative cropping systems and fallow-management techniques to maintain soil fertility, decrease erosion, and optimize soil-water use represents a major direction for future research. Some research options within the area of fallow-management techniques will be considered next in this paper.

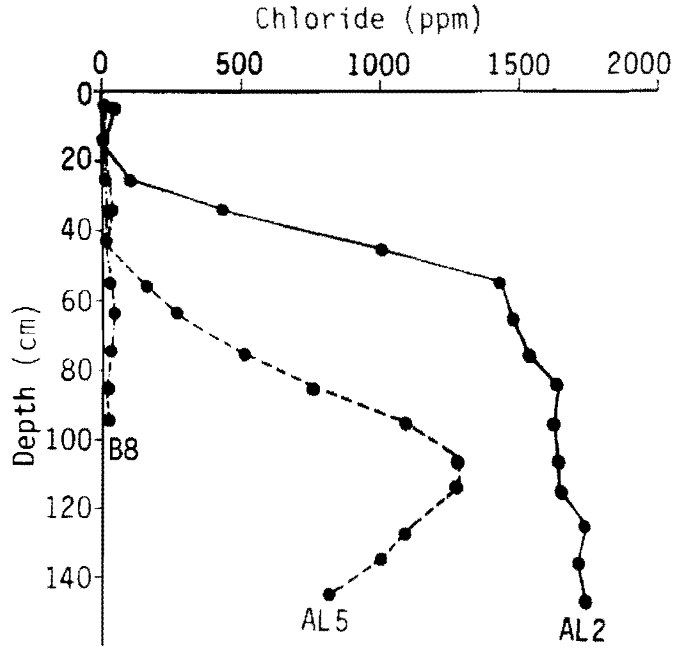

Figure 4. Chloride profile in three Mollic Torrerts at Emerald, Queensland; depth of water extraction by irrigated sorghum is shown by the arrow for each soil (from Shaw and Yule 1978).

Research Options for Improved Dryland Crop Production

Four priority areas for soil physical research can be identified, and they are discussed in this section:

1. identifying and modifying the plant-available water capacity;
2. improving the management of the surface soil structure;
3. improving rainfall-use efficiency; and
4. increasing soil-erosion studies.

The research approaches suggested here are not technology based, but aim to provide information on those properties of Vertisols that will allow appropriate management systems to be developed. As mentioned previously, the development of conservative management systems for various combinations of soil, climate, and technology input is a critical endpoint in this type of research. One prerequisite is a method of classifying Vertisols (preferably related to crop performance) to allow satisfactory transfer of information on soil physical processes for incorporation into management systems. Such a classification is not presently available.

Plant-Available Water Capacity (PAWC)

PAWC is defined as the amount of water that can be extracted from an initially fully wet soil by a crop before a chosen stress symptom is observed. This definition assumes an initially fully wet profile. Although this is normally the case under irrigation, PAW under dryland conditions is often less than PAWC because the soil profile is not fully wet. (Profile wetting under fallow is considered later in this section).

PAWC is a very important soil property in a semi-arid dryland environment. The pattern and amount of rainfall in Queensland is such that high water storage during fallow increases the probability of obtaining high grain yields. The effect of PAWC on dryland pasture yields has been illustrated by Williams and Probert (1984).

Our own experience is that sensible values of PAWC in Vertisols can only be obtained in the field under crop and drying conditions appropriate for the intended use of the derived value. The wet profile, or Upper Storage Limit (USL), plus the Lower Storage Limit (LSL) should be determined under realistic field conditions. As pointed out by Smith et al. (1984), the USL may be grossly overestimated by laboratory measurement; LSL water contents are often less than the 1500 KPa water content (although it is uncertain whether this is due to evaporation from cracks or to transpiration), and rooting depth is sufficiently variable to make generalization inappropriate.

Variation in PAWC can occur due to crop type, crop age, soil type, and pattern of water stress on the crop. Evidence suggests that the type of crop has only a secondary effect on PAWC (Mason et al. 1983) under irrigated (low stress) conditions. Also under irrigated conditions, Shaw and Yule (1978) and Gardner and Coughlan (1982) found that PAWC for fodder sorghum on a range of Vertisols varied from 8 to 14 cm, with maximum depths of significant water use varying from 60 to 120 cm for different soils.

Gardner and Coughlan (1982) measured PAWC under both irrigated and dryland sorghum crops on a range of soils in the Burdekin Valley (Table 3). Under dryland conditions, with a much more severe drying cycle and associated drought-hardening effects on crops, there is a large increase in the PAWC of some soils, due to both increased depth and degree of subsoil drying (Gardner et al. 1984). The largest increase was associated with soils with relatively low ESP in the clay subsoil (Table 3). The range of PAWC (8–22) cm in Queensland Vertisols is shown in Figure 5.

Table 3. PAWC[1] under irrigated and dryland conditions and ESP[2] at 50–60 cm for five soils in the Burdekin Valley, Queensland (Source: Gardner and Coughlan 1982).

Soil	ESP (50–60 cm)	PAWC (cm) Irrigated	PAWC (cm) Dryland
Alfisol 1	1	10.4	19
Vertisol 1	5	11.9	30
Vertisol 2	10	11.4	22
Vertisol 3	21	10.4	14
Alfisol 2 (Typic Natrustalf)	36	7.2	8.8

1. PAWC = Plant-available water capacity.
2. ESP = Exchangeable sodium percentage.

Our data suggest that PAWC is limited by rooting depth rather than by PAWC per unit depth. For the zone of maximum root density (< 30 cm), differences in PAWC per unit depth of soil are relatively small (0.16–0.21 cm cm^{-1}. A number of factors may

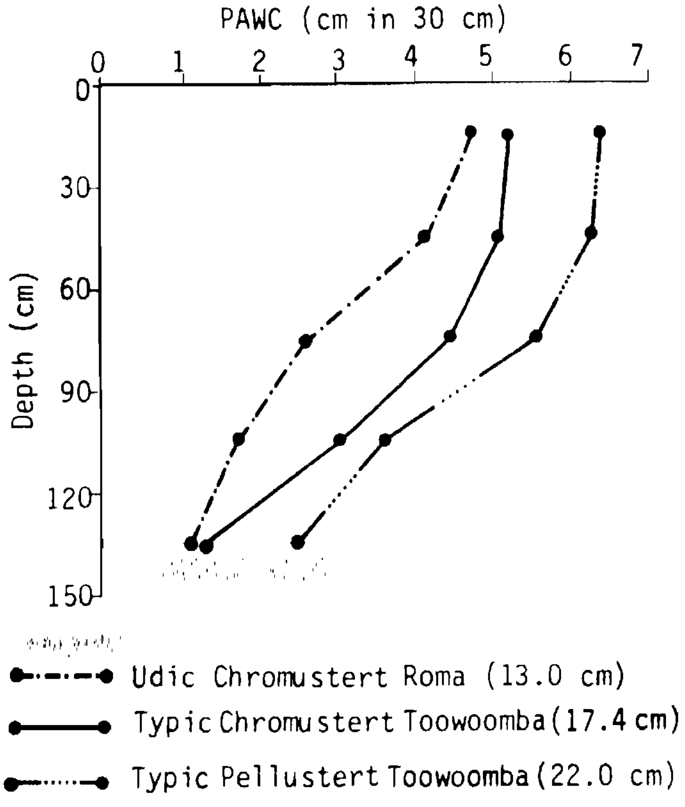

Figure 5. Plant-available water capacity profile for three Queensland Vertisols.

limit rooting depth, including soil strength (which is often related to lack of wetting), soil salinity, and subsoil structure (which may determine aeration, drainage, and root ramification). Gardner and Coughlan (1982) found no definite evidence on which factor was the most important limitation to root growth. However, it is a common observation that deeper and more prolific root systems are developed on Vertisols with a more strongly developed lenticular structure (and smaller primary peds) in the subsoil. As suggested by Greacen and Gardner (1982), relationships between morphological subsoil structure and root growth are worthy of quantitative field investigation.

There are several specific options for research on PAWC:

PAWC prediction. The major information required is PAWC under field conditions for a range of Vertisols. More specifically, the need is for information on USL (after ponding or heavy rainfall), LSL after dryland cropping, and -15 bar water content. Soil properties such as cation-exchange capacity, -15 bar water content, and the salt profile have been used to predict USL, LSL, rooting depth, and hence PAWC (Shaw and Yule 1978). More information, both in Australia and in other countries, would improve the prediction of PAWC for crop modeling purposes.

Root development and function. Information is also required on root length, density, and water extraction with reference to depth in Vertisols. Relationships with morphological subsoil structure may then allow the constraints to root growth in Vertisols to be quantified.

Modification of PAWC. In some soils, low PAWC (possibly related to surface structural problems, such as crusting and waterlogging) imposes unacceptable risks on dryland crop production. In these cases, amelioration techniques such as gypsum application and deep ripping (subsoiling) may be cost effective. Information is required for Vertisols on the relationship between soil properties (e.g., soil structure, exchangeable cations), climate, and economic response to gypsum or deep ripping.

Management of Surface Soil Structure

To allow effective management of soil structure, we need information on a number of processes.

Stability under rain. Soil structure in the surface of Vertisols commonly collapses under rain (Hodnett and Bell 1981, Smith et al. 1984, Venkateswarlu 1984). The resulting surface sealing causes runoff. If cracks are open, the runoff directly recharges the subsoil. If cracks are not open, soil-water storage is reduced, and runoff and erosion are increased. It is well known that cover on the soil protects against structure breakdown by rain. Cover often is not available and intrinsic soil properties then influence the degree of breakdown under rain.

The key soil properties that influence aggregate stability are not well defined, nor are the long-term effects of farmer management practices known. To overcome these deficiencies, a research project is under way to develop a simple laboratory test to measure structural stability to rain. The test will be evaluated on a range of Vertisols, using laboratory and field rainfall simulators. It is expected that the eventual technique would be useful on Vertisols in any tropical or subtropical environment. The test could be validated on a wider range of soils by expanding the project to include soils from other countries.

Structure development by tillage and wetting and drying. Queensland farmers use tillage to control weeds in fallows, to break crusts (to improve water entry), to increase surface roughness (to assist water storage), and to prepare seedbeds. There is a trend toward less tillage because of (1) rising energy and labor costs, (2) increasing acceptance of chemical weed control, and (3) concern about possible adverse effects of excessive tillage on soil structure; in addition, new methods of crop establishment (e.g., presswheels) make seedbed conditions less critical. If tillage can be reduced without detriment to yield, the principles employed will be acceptable in any country. In Vertisols there is some scope to use wetting and drying (the self-mulching tendency) to generate a suitable structure for water entry and crop establishment, and to use tillage to complement this structure-generation process. In order to fully exploit the forces associated with wetting and drying, we need to know more about the interactions between crop type, soil constituents, wetting and drying conditions, and the effects on aggregate size, strength, and density.

Structure requirements for seedbeds. Crop establishment is commonly a major problem on Vertisols. Inadequate soil moisture can prevent germination, and soil structure can restrict seedling emergence (Leslie 1965). Presswheels can, in some cases, greatly improve emergence (Smith et al. 1984). However, the range of soil structure and moisture characteristics adequate for satisfactory seedbeds is not known. Basic research covering a range of soils, crops, planting conditions, and climates is needed to determine what constitutes a suitable seedbed. This would improve productivity, reduce risks of crop failure, eliminate unnecessary tillage operations, and ensure more timely planting.

Rainfall-Use Efficiency

It is important to minimize soil-water losses by runoff, evaporation, and deep percolation and to maximize soil-water storage during fallow and crop-water use during cropping. Some relevant research areas for Vertisols are given below.

Manipulation of crack configuration and surface microrelief. In comparison with ligher textured soils, Vertisols are relatively inefficient in the storage of light rainfalls. The quantity of water required to raise soil-moisture potential from air dry to -15 bar is of the same order as the amount held in the available water range. Effective recharge, below the zone of rapid evaporation loss, only occurs with substantial rainfalls or movement of runoff down cracks. To enhance recharge of the soil water store, it may be possible to create surface microrelief (in the form of ridges and microdepressions) to pond water and enhance flow of water into cracks. About two-thirds of the soil-water deficit can be stored directly in cracks, should heavy rainfall or runon occur. Cracks are known to form in interrow spacings (Swartz 1966), but little is known about the pattern of cracking in fallow soil with ridged microrelief or about the effect of ridges on evaporation.

Efficient water use. Systems of alternating bare fallow and a crop have been traditional for dryland grain production in Queensland. Stored soil water at planting is essential to provide an initial water supply to the crop, due to the high variability and low effectiveness of rainfall. It should be possible to define probabilities of successful cropping for various levels of stored soil water. Due to the crop options available to the farmer and the variable rainfall throughout the year, the necessary combination of adequate soil-water storage and a "planting" rain could occur in any month of the year. This is recognized by an increased tendency toward opportunity cropping. Good long-term weather records are needed to forecast probabilities of crop success. If these are not available, conservative estimates may be adequate. It may be possible to considerably increase the efficiency of rainfall use by better understanding soil hydrology, seasonal weather probabilities, and crop requirements.

Infiltration. Although it is a very important process, infiltration in dryland Vertisols is not well understood. At a relatively gross level, infiltration parameters can be inferred from runoff measurements on small catchments. We are currently conducting studies of runoff and soil loss from contour bays on a range of soil types and climates, measuring the response to crop type and fallow management (tillage by stubble interaction). We expect these studies to delineate the dominant factors in the infiltration process—for instance, which aspect plays the major role: cracks, surface, cover, antecedent water content (and profile distribution), surface tilth, subsurface flow, plow pans, soil structure, or any other factor? In parallel with these large field studies, we have process-oriented research into field infiltration under a rainfall simulator. This research aims to quantitatively define the effects of the variables listed. These studies are directed to the fallow and crop-establishment periods, since in our environment little runoff occurs from well-grown crops. In summary, the future research areas are process and field studies of infiltration and the effects of variables that may be "managed."

Soil evaporation. With our low rainfall, soil evaporation is undoubtedly the major loss mechanism affecting rainfall-use efficiency (see Table 2). We are, therefore, interested in the effects of surface cover and tillage on soil evaporation. A small pilot study has been conducted using wheat stubble as a surface cover and we plan major studies across a range of environments. These studies will measure not only soil-water loss but also the resulting soil-water profile. Consequently the data will be useful for predicting planting opportunities and options (depth, etc.) and for coordinating with the infiltration research by predicting the antecedent soil-water profile for subsequent rainfall.

Soil-Erosion Studies

Research on both management of soil structure and the soil-water balance aim to provide methods of reducing soil erosion. Soil erosion is seen as a major threat to agriculture on Vertisols in Queensland. A number of aspects are being studied in the field (Smith et al. 1984). The eventual aim is to derive physically based process models able to forecast the effects of cropping system and management on crops and soils.

The effect of crop or stubble and tillage on hydrology and soil loss is being monitored near Toowoomba, Roma, Emerald, and Biloela. Automatic instruments monitor rainfall and runoff on contour bay catchments 1-15 ha in area. These studies have shown that management practices can have significant effects on fallow efficiency and soil loss.

Rainfall simulators are also being used to study the effects of rainfall, soil and sediment properties, surface tilth, stubble cover, and slope length on runoff and erosion processes. These studies of the erosion process are integrated with the field-scale management studies.

Conclusion

Vertisols occur largely in tropical regions and in less-developed countries. Traditional agriculture of temperate countries and associated soil research has, therefore, been carried out on other soil types. As pointed out by Coughlan (1984), extrapolation of results and management systems from other soil types to Vertisols is inappropriate. Thus, few technology-based farming systems have been developed for Vertisols, nor is there a satisfactory understanding of soil physical processes.

Australia is the only one of 49 countries in which farming on Vertisols is carried out in the semi-arid tropics that is not classified as an LDC. For this reason, Australia, with its advanced technological base, is a logical venue for field and laboratory research into fundamental processes in Vertisols.

Our role should be to perform strategic research aimed at understanding soil physical processes. Once the principles are understood, they could be used in the development of soil and crop management techniques for field testing in appropriate environments in other countries.

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Discussion

Virmani: I believe the apparent difference in rainfall water balance observed at ICRISAT and Darling Downs may be due to geology and rainfall distribution.

Coughlan: I don't think that it is due to geology. Our clays are normally deep, while rainfall distribution and soil hydraulic conductivity would suggest that deep percolation losses would be small. The high evaporation loss in the Queensland situation is probably due to rainfall distribution and amount.

Sagua: Is sorghum grown in the summer with or without irrigation?

Coughlan: Sorghum is grown both with and without irrigation.

Saunders: What data do you have on the differing effects of disc versus tine or sweep tillage, and depth of cultivation on moisture infiltration and storage?

Coughlan: We are doing work on both frequency and type of cultivation. However, our data are not yet available. We have been using sweep tillage to maintain stubble on the soil surface for erosion control.

Blokhuis: You mentioned salinity, but not sodicity. Is there no sodicity accompanying the salinity?

Coughlan: The salts accumulating in the subsoil of Queensland Vertisols are sodium-rich. In the 1-10 cm layer, ESP can range up to 7-8% (see Fig. 3), while in the subsoil, values up to 40% can be measured.

Hawando: Three highly different PAWC values were shown on three different Vertisols. Do you think that research results, or a only production technology, obtained in one of these soils in relation to PAWC, can be predictably applied to the other Vertisols with highly varying PAWC? Is direct application of transfer of technology from one region to another possible without testing it first to determine if it could work?

Coughlan: This would be true if the technology depended on PAWC. In this case, agrometeorological models could be useful for predicting the effectiveness of technology transfer.

Srivastava: (1) I would like to know more about your experience on zero-tillage practice on Vertisols in Queensland. I am particularly curious to know about long-term effects and economics. (2) Do you have any experiments on 'fixed traffic zone' and 'crop production zone'?

Coughlan: (1) We have included zero-tillage in a number of our small contour catchment studies. We are also doing work on application at a commercial scale. Zero-tillage reduces soil loss and, in some cases, runoff. However, because of the cost of chemicals, the profitability of zero tillage is marginal. A paper in the Australian Journal of Soil Research in 1984 considered changes in soil properties. (2) No.

Limited-Irrigation/Dryland Farming Systems for Efficient Water Management in Semi-Arid Environments

B.A. Stewart[1]

Abstract

Much of the increase in world food production in recent years has been due to increased irrigation. Expansion of irrigation will continue, but future development will become increasingly more difficult and costly. This fact highlights the need for more attention to be given to increasing crop production under rainfed conditions.

Food production can be increased substantially in the semi-arid tropics under rainfed conditions, but improved technologies and changes in traditional systems will be required. In many cases, traditional agriculture evolved to reduce the risk of losses in dry years. Although this approach is an absolute necessity in some cases, such a system often fails to take advantage of wet years. The key to successful dryland farming in semi-arid regions is using systems and practices that can take advantage of the favorable years.

In many situations, runoff water from rainfed agricultural systems can be feasibly harvested, stored in ponds, and then used for supplemental irrigation. The efficient use of such water requires a good understanding of the relationships of transpiration and evapotranspiration to dry-matter and grain yields, and to water application rates. Data presented herein clearly show that limited amounts of irrigation water can be used more efficiently on grain sorghum by applying small amounts to more land than by fully irrigating less land. However, the extent of benefits and the economics of such a practice depend on many factors, particularly the cost of irrigation and the value of the crop. In general, when irrigation cost is low and the value of the crop is high, net return is enhanced by spreading the limited amount of water over a larger area. However, if irrigation costs are high and crop value is low, net return is greatest when less crop area is irrigated sufficiently to obtain near-maximum yields. Curves presented in the paper show these relationships.

Résumé

Systèmes de production pluviale avec irrigation limitée visant une gestion efficace de l'eau en milieux semi-arides : *La plus grande partie de l'augmentation de la production agricole du monde de ces dernières années est due au redoublement de l'irrigation. L'expansion de l'irrigation continuera, mais les développements futurs deviendront de plus en plus difficiles et onéreux. Cela met en relief la nécessité de prêter une attention particulière à la production agricole pluviale.*

La production alimentaire peut être accrue de façon considérable dans les zones tropicales semi-arides en régime pluvial, mais des techniques améliorées et des modifications des systèmes traditionnels seront nécessaires. Dans de nombreux cas, l'agriculture traditionnelle a tenté de réduire le risque de pertes pendant les années de sécheresse. Bien que cette approche soit une nécessité absolue dans certains cas, un tel système réduit souvent les bénéfices à tirer des années pluvieuses.

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Afin que les cultures pluviales réussissent en régions semi-arides, il faut utiliser des systèmes et des pratiques qui puissent bénéficier des années favorables.

En général, l'eau qui s'écoule des systèmes agricoles pluviaux peut probablement être récupérée, retenue dans des étangs et ensuite utilisée pour une irrigation supplémentaire. L'usage efficace de cette eau nécessite une bonne compréhension des rapports entre la transpiration et l'évapotranspiration, la matière sèche et les rendements en grain, et les taux d'application de l'eau. Les données présentées ici montrent clairement que des quantités limitées d'eau d'irrigation peuvent être utilisées de façon plus efficace pour le sorgho en apportant de faibles quantités d'eau à une plus grande superficie de terre qu'en irrigant complètement une plus petite superficie. Néanmoins, l'importance des bénéfices et la rentabilité d'une telle méthode, dépendent de plusieurs facteurs, en particulier du coût de l'irrigation et de la valeur de la récolte. En général, lorsque le coût de l'irrigation est faible et la valeur de la récolte élevée, le bénéfice net est accru en répandant une quantité limitée d'eau sur une large surface. Cependant, si le coût de l'irrigation est élevé et la valeur de la récolte faible, le bénéfice net est plus élevé lorsque une surface cultivée est suffisament irriguée afin d'obtenir des rendements presque optimum. Des courbes sont présentées qui démontrent les rapports décrits ci-dessus.

Introduction

In 1979 the Food and Agriculture Organization (FAO) of the United Nations estimated that irrigated agriculture represented only 13% of global arable land; however, the value of crop production from this area represented 34% of the world total (FAO 1979). This indicates the tremendous effect of irrigation on food production, and the potential of continued efforts to develop additional irrigated land.

Earlier, FAO (1977) estimated that the total global irrigated area of 223 million ha would increase to about 273 million by 1990. Buringh et al. (1975) estimated that, of the 3419 million ha of potential agricultural land in the world, 470 million could be irrigated. Although it is technically possible to expand the amount of irrigated land, future expansion will be more difficult than it was in the past. The capital expenditures required for development and the high energy costs for pumping will increasingly affect the feasibility of irrigation projects. The most easily developed land and water resources have already been utilized, and further development will become increasingly more difficult and costly. Therefore, additional emphasis must be placed on increasing food and fiber production on nonirrigated lands.

Swindale (1982) concluded that food production can be increased substantially in the semi-arid tropics through rainfed, arable farming without recourse to costly, large irrigation schemes. He pointed out that traditional agriculture in the semi-arid tropics has evolved to reduce the risk of losses in dry years because such losses can be very severe. The benefits that could accrue in good years are then also usually lost. Much of the effort to create new or improved technology for the region is designed to provide opportunities to invest safely in anticipation of good years. This necessitates a change in production strategy before substantial increases can be made in rainfed agriculture. Kanwar (1982) also discussed the need for making better use of the environment for food production. Both Kanwar and Swindale called for increased attention to using supplemental irrigation as a means of reducing risk and improving production. They proposed that runoff water from rainfed agricultural systems, in many situations, could be feasibly harvested, stored in ponds, and then used for supplemental irrigation. There are also situations where small supplies of groundwater are available, which can be used for supplemental irrigation. El-Swaify et al. (1985) describe a watershed-based farm design for improved land and water management that includes supplemental irrigation of Vertisols in India.

The Great Plains of the United States is a major dryland agricultural region. The rainfall in this area is highly variable, and the lack of water limits crop production in nearly all years. The key to successful dryland farming is using systems and practices that can take advantage of the favorable years. There is also a substantial part of the Great Plains that is irrigated, but there is much more land suited for irrigation than there is water available. Also, the primary source of irrigation water is groundwater from the Ogallala aquifer, which is being depleted (Gutentag et al. 1984). This is particularly true in the southern portion of the Ogallala aquifer area, where some of the previously irrigated land has been returned to dryland systems. In other cases, only limited amounts of irrigation water are used. These limited supplies are used in various ways, ranging from preplant irrigation only to application at critical growth stages.

This paper assesses the likely increases that can result from supplemental irrigation and presents some strategies for applying limited amounts of irrigation water. The discussion is limited to grain sorghum [*Sorghum bicolor* (L.) Moench]. The work reported from the USDA Conservation and Production Research Laboratory, Bushland, Texas, was carried out on a Pullman clay loam, a member of the fine, mixed, thermic family of the Torrertic Paleustolls. Although the soil is not a Vertisol, it is similar in many ways with reference to management.

Problems of Water Management under Dryland Conditions

Some established relationships have been shown to affect water management under semi-arid, dryland conditions. These include the effects of evapotranspiration, applied water, and water-use efficiency on yields, as discussed below.

Relationship between Yield and Evapotranspiration

When yields are limited by transpiration, strong correlations usually occur between cumulative seasonal dry matter and cumulative seasonal transpiration (de Wit 1958, Arkley 1963): de Wit showed that for dry, high-radiation climates, yield and transpiration were related as

$Y/T = m/T_{max}$,

where Y = total dry matter mass per area, T = total transpiration per area during growth to harvest, and T = mean daily "free water evaporation" for the same period. The "constant" m is governed mainly by species and is largely independent of soil nutrition and water availability, unless it is seriously nutrition-limited, or unless soil water is too high, causing lack of aeration or leaching of nutrients.

Since transpiration is difficult to separate from evaporation from the soil surface, the total "evapotranspiration" is most often measured. Many studies have shown that transpiration and evapotranspiration are closely correlated, and particularly so after a plant canopy has formed. A representation of dry-matter yield as a function of evapotranspiration is shown in Figure 1. The intercept along the evapotranspiration axis presumably represents evaporation from the soil surface. Also, for crops that have a relatively constant harvest index, the harvestable portion of the crop can be substituted in the relationship. For grain sorghum, the yield of grain can be used on the Y axis.

Figure 2 shows a compilation of data from the USDA Conservation and Production Research Laboratory, Bushland, Texas, for grain sorghum. The data of Jones (O.R. Jones, personal communication of unpublished results, 1958–1983) represents 26 years of dryland grain sorghum production. The data from Stewart et al. (1983) were collected in 1979–1981 and from Musick and Dusek (1971) during 1963–1965. There is a very good linear relationship between grain yield and evapotranspiration, showing that 15.5 kg ha^{-1} of grain were produced for each mm (1.55 kg m^{-3}) of evapotranspiration above the threshold value of 126 mm.

Figure 3 shows a similar relationship, but, in addition to the Bushland, Texas, data used in Figure 2, there are data from California, Kansas, and College Station, Texas, of the United States, and from Israel and several locations in India. All these data showed that 15 kg ha^{-1} of grain were produced for each millimeter (1.50 kg m^{-3}) of evapotranspiration above

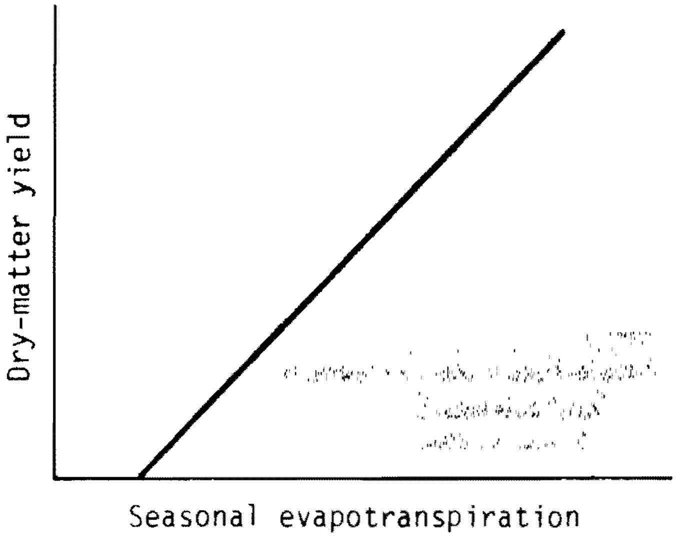

Figure 1. Schematic diagram of the effect of seasonal evapotranspiration on dry-matter yield.

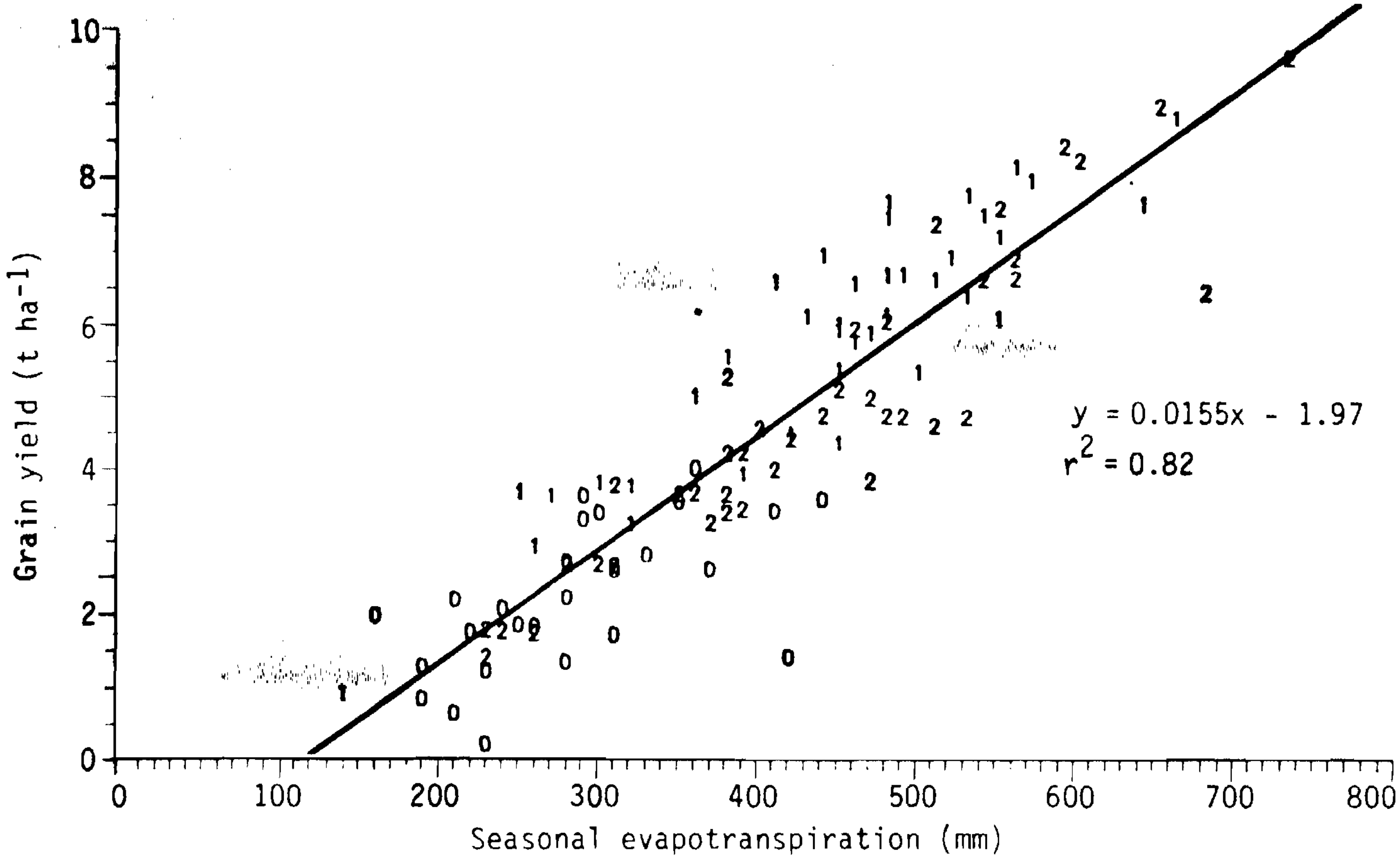

Figure 2. Effect of seasonal evapotranspiration on yield of grain sorghum at the USDA Conservation and Production Research Laboratory, Bushland, Texas (O = unpublished data, O.R. Jones; 1 = Musick and Dusek 1971; 2 = Stewart et al. 1983).

a threshold value of 94 mm. The relationship was surprisingly good, considering that such diverse data were used. There is a tendency for more of the Bushland, Texas, and Israel data points to be below the line and more of the India, Kansas, and College Station, Texas, data points to be above the line. This is probably because vapor-pressure deficits over the growing season are generally greater for the Bushland, Texas, and Israel locations. As vapor-pressure deficit increases, maximum evapotranspiration increases, and it requires a greater evapotranspiration level to maintain a given yield level. Tanner and Sinclair (1983) present a thorough discussion of the climatic effect on the relationship between yield and evapotranspiration. The purpose of presenting the data in Figure 3 is to suggest that, as a "first approximation," this relationship can be used to estimate the benefit that can be expected from supplemental irrigation of adapted hybrid grain sorghum in semi-arid regions of the world. Certainly, the actual yield increase for any specific location and year will vary, but this relationship can serve as a guideline until data for specific conditions are obtained.

The data in Figures 2 and 3 represent a variety of conditions, with reference to the amount of water supplied by rainfall or irrigation and regarding the time of water application. Although grain sorghum shows a remarkable ability to compensate and adjust to stress conditions, some growth stages are more critical than others. Based on a large number of irrigation studies in the Southern High Plains of the United States, Musick (1984) concluded that good yield responses and efficient use of water are achieved when water is applied at the midboot and flowering stages, and a much lower response and efficiency result when water is applied at the 6- to 8-leaf stage and at the milk to soft-dough stage. Doorenbos and Kassam (1979) reached similar conclusions. They stated that where rainfall is not sufficient and irrigation water is limited, irrigation should be based on avoiding water deficits during the periods of peak water use from flowering to the early yield-formation period. The timing of irrigation or rainfall can certainly influence where particu-

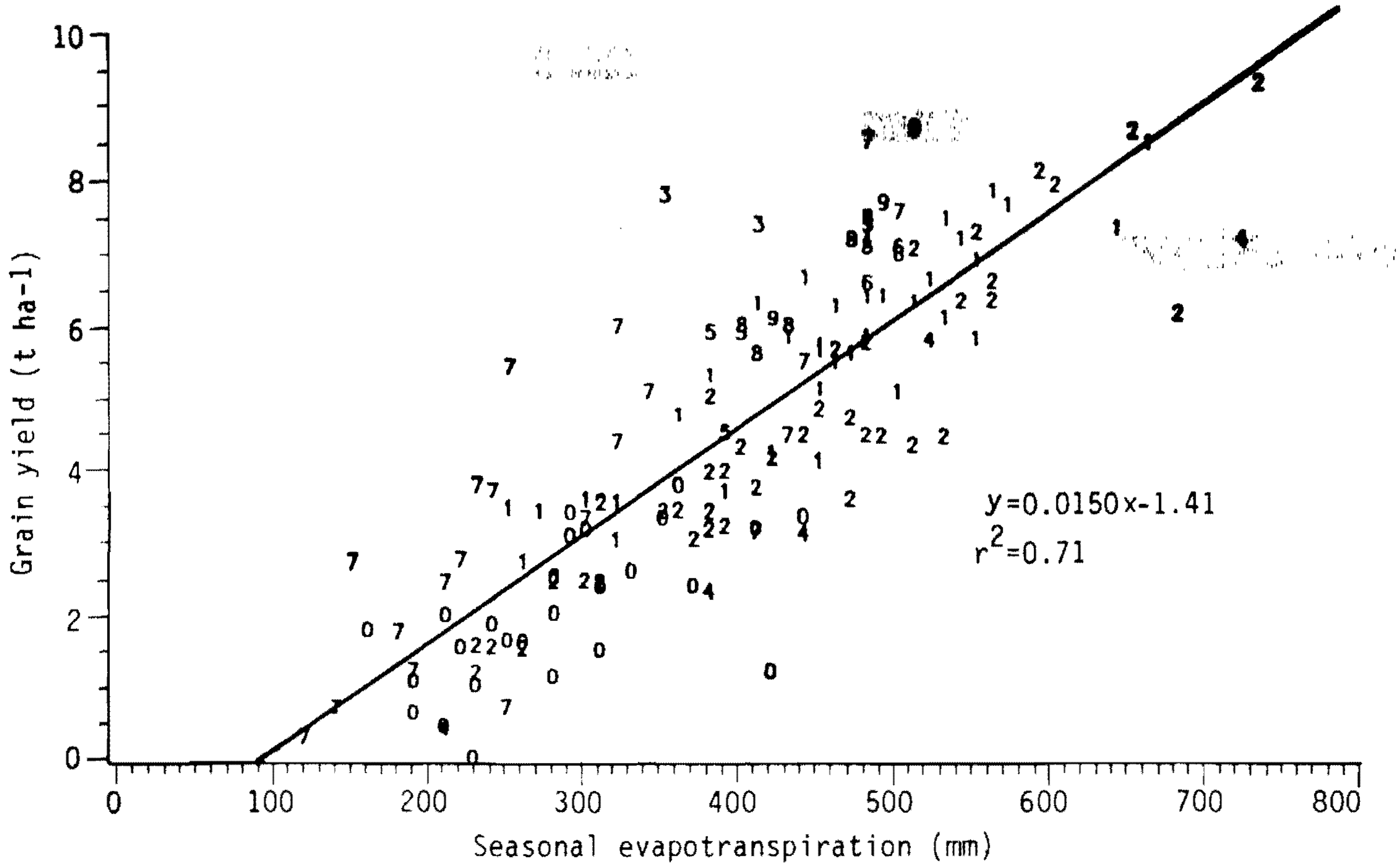

Figure 3. Effect of seasonal evapotranspiration on yield of grain sorghum at various locations (0 = unpublished data, O.R. Jones, Texas, 1 = Musick and Dusek 1971, Texas, USA; 2 = Stewart et al. 1983, Texas, USA; 3 = Owonubi and Kanemasu 1982, Kansas, USA; 4 = Bielorai et al. 1964, Israel; 5 = Howell and Hiler 1975, Texas, USA; 6 = Stewart et al. 1975, California, USA; 7 = Seetharama et al. 1984, compilation of Indian studies; 8 = Stone et al. 1978, Kansas, USA; 9 = Chaudhuri and Kanemasu 1982, Kansas, USA).

lar data points fall when plotted, as shown in Figures 2 and 3. Timely additions will result in points above the fitted line, while untimely additions will result in lower than predicted efficiencies.

Relationship between Evapotranspiration and Water Applied

Although the relationship between yield and seasonal evapotranspiration is linear, relationship between evapotranspiration and water applied is generally not linear. The general effect of water applied (which can be rainfall, irrigation water, or a combination of the two sources) on evapotranspiration (Y axis) is shown in Figure 4. The amount left of zero on the X axis represents the amount of stored soil water used by the crop during the growing season. When water is added during the growing season from either rainfall or irrigation, some of it may be lost as runoff or deep percolation, or some may remain in the soil at the end of the growing season. Runoff and deep percolation represent inefficiencies. Also, small amounts of water added early in the growing season will mainly result in evaporation and may not benefit transpiration and thereby increase yield.

The extent that the curve in Figure 4 deviates from a 1:1 line indicates the extent of losses as runoff and percolation plus the amount of applied water that remains in the soil at harvest time. While it may be beneficial in some situations to have considerable quantities of soil water remaining at harvest, it often lowers water-use efficiency because the storage efficiency of rainfall during the fallow periods will be reduced if the profile is already partially charged. Musick (1970) showed a significant negative relationship between antecedent soil water after harvest

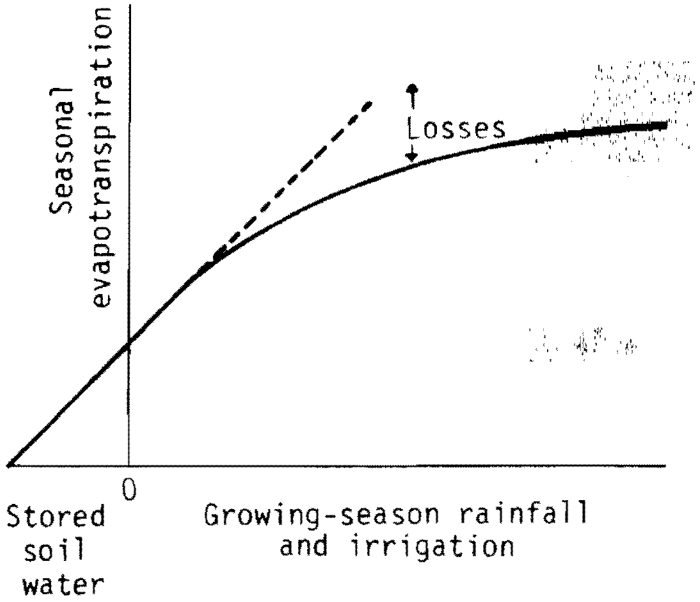

Figure 4. Schematic diagram of the effect of growing-season water inputs on seasonal evapotranspiration.

and preseason storage efficiency. When less than 20 mm of plant-available soil water remained at harvest, more than 40% of the precipitation received during the nongrowing season was present in the soil at seeding time of the next crop. When more than 40 mm remained at harvest time, less than 15% of the precipitation that occurred during the fallow season was stored as soil water.

The amounts of water lost by runoff or percolation depend on many factors and will vary greatly between locations. Runoff management deserves particular attention in supplemental irrigation systems when rainfall may occur at the same time as irrigation or soon after it. Under such conditions, runoff can be very high, resulting in low water-use efficiency and high losses of soil by erosion.

Relationship between Water-Use Efficiency and Yield

The term water-use efficiency (WUE) is used in many ways and can be grossly misunderstood unless the specific use is clearly stated. WUE is generally defined as Y/ET (yield/evapotranspiration), and the highest WUE will always be at the highest yield. This is necessarily so because the relationship of Y to ET (generalized in Figure 1) is linear, and the X intercept (evapotranspiration) is greater than zero. Therefore, the greater the yield, the greater the water-use efficiency. This is illustrated in Figure 5, which shows the data from Figure 2 plotted as a function of WUE against yield. WUE values were calculated as follows:

WUE (kg m^{-3}) = yield (t ha^{-1}) × 100/seasonal ET (mm).

The WUE value was about 0.7 kg m^{-3} at a yield level of 2 t ha^{-1} and about 1.1 kg m^{-3} at a yield level of 5 t ha^{-1}. The line drawn through the points was calculated from the regression line in Figure 2.

Since we have already shown that there is a linear relationship between evapotranspiration and yield (Fig. 4), yield can be substituted for evapotranspiration on the Y axis. In this case, water-use efficiency is defined as

WUE = yield/(water available during growing season).

Water-use efficiency will reach an optimum level and then generally decrease as yields increase further. This is particularly true when operators try to achieve maximum yields by irrigation. To achieve maximum yields, irrigation water applied must be sufficient to meet maximum crop-water demands. If this is done, then the probability of losses by deep percolation or runoff is greatly increased. In addition, considerable water will likely remain in the soil at harvest time. All of these situations will lower the efficient use of water resources.

Supplemental irrigation can be beneficial under rainfed conditions, when there is sufficient rainfall to sustain crop production but when water is still limited. If the irrigation source is consistent, water can be added in sufficient quantities, particularly at critical growth stages, to ensure amounts adequate for high yields. If water available for supplemental irrigation is limited, but the amount of dryland grain sorghum that must be irrigated is large, then it becomes more difficult to decide how to use the limited amount of water. Should a small amount of land be irrigated for high yields, or should the irrigation water be spread over more land? The concept presented in Figure 4 shows that a limited amount of water can be used more efficiently, in terms of evapotranspiration, by spreading it over more land. However, the economics and management alternatives will have to be considered for individual cases before a final decision can be made.

The Southern High Plains of the United States is a good example of limited irrigation water, because its primary source, the Ogallala aquifer, is being depleted at a far greater rate than it is being

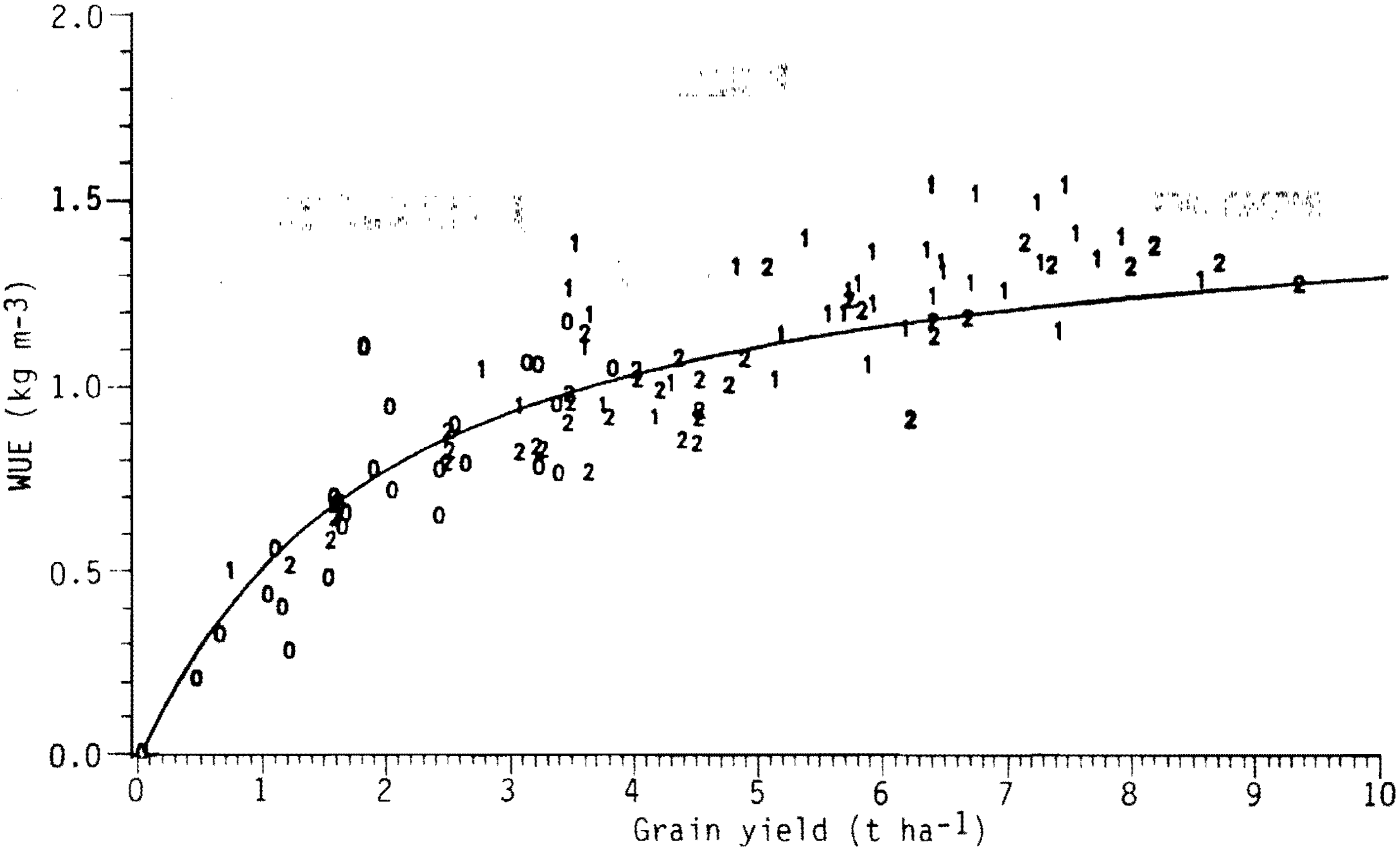

Figure 5. Effect of grain sorghum yield on water-use efficiency (WUE) at the USDA Conservation and Production Research Laboratory, Bushland, Texas. (0, 1, and 2 represent same data as in Figure 2.)

recharged (Gutentag et al. 1984). Because of the declining water level, wells become less productive with time. This decreased water supply can be temporarily alleviated by pumping longer or by drilling more wells, but at a greater cost. As water supply decreases, farm operators ultimately must choose between cutting back on the amount of land irrigated or on the amount of water applied to each unit of land irrigated. In some cases, the crop being grown dictates the decision. However, grain sorghum is a crop that does well under limited irrigation, and many operators are choosing to use only limited amounts of irrigation water on this crop in anticipation of rainfall.

Development of the Limited Irrigation/Dryland System

Stewart et al. (1983) developed a limited-irrigation/dryland (LID) farming system for the efficient use of limited supplies of irrigation water for grain sorghum production. While this is only one of several systems being used by farm operators, it serves as a good example of how water-use efficiency can be increased.

The objective of the LID concept is to maximize the combined use of growing-season rainfall, which varies for any given year, with a limited supply of irrigation water, which is fixed for a given year. The unique feature of the LID system is the flexible adjustment during the crop-growing season of the amount of land irrigated, allowing more land to be irrigated during above-average rainfall years than during dry years. Risk is low with the LID system, and response is good in favorable rainfall years.

The LID system concept, developed at the USDA Conservation and Production Research Laboratory, Bushland, Texas, is illustrated in Figure 6. A graded-furrow field, 600 m long on 0.3–0.4% slope, was divided into three water-management sections. The upper half of the field was managed as "fully irrigated." The next one-fourth was managed as a "tailwater-runoff" section that used furrow runoff from the fully irrigated section. Finally, the lower one-fourth was managed as a "dryland" section capable of receiving and utilizing any runoff resulting from either irrigation or rainfall on the wetter, fully

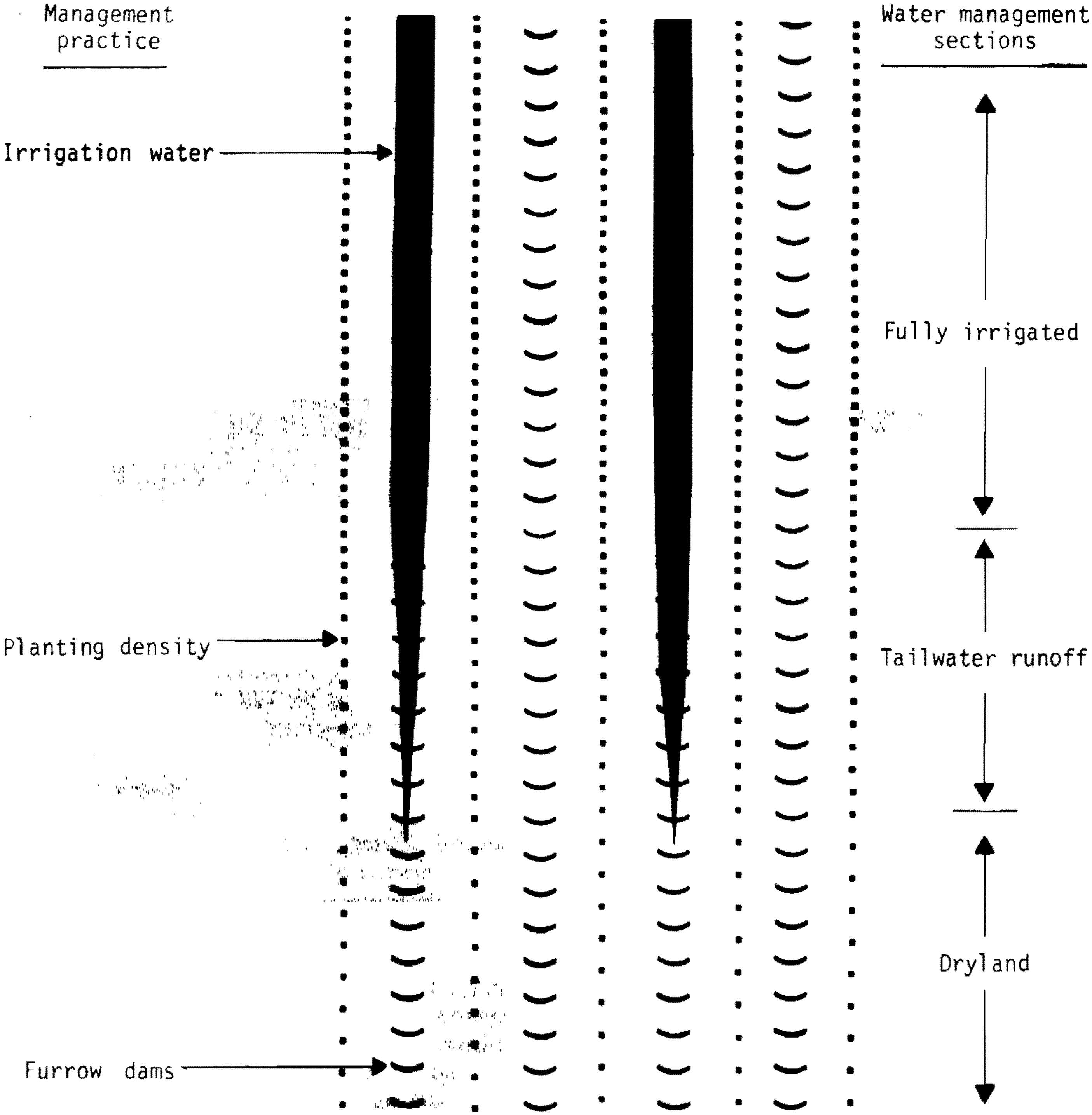

Figure 6. Schematic diagram of the limited-irrigation dryland (LID) system.

irrigated and tailwater-runoff sections. Plant densities were reduced down the field to alleviate stress, because irrigation water was decreased as the length of the field increased. Furrow dams (Clark and Hudspeth 1976) were placed about every 4 m throughout the length of the field. Alternate 76-cm furrows were irrigated, and the dams in the irrigated furrows were notched to ensure that irrigation water moved over the dams and down the furrow, rather than across the beds. The remaining furrow dams on the lower part of the field, and the dams in the nonirrigated furrows for the entire length of the field, prevented rainfall runoff. A predetermined amount of irrigation water was applied at regular time intervals. The extent to which the entire field was irrigated depended on the rainfall received–the wetter the year, the greater the advance of a fixed application down the field. The objective was to prevent or minimize any water from rainfall or irrigation from leaving the field. More recent studies with the LID system have used a medium seeding rate throughout the field and furrow dams only in the alternate furrows that are not used for irrigation. These changes make the system somewhat easier to manage, and the benefits are similar.

Results of the use of the LID over 3 years are shown in Figures 7 and 8. When grain yields were plotted as a function of seasonal ET, a linear relationship was found, which is in accord with the earlier discussion of Figures 1, 2, and 3. Therefore, the highest WUE (defined as yield of grain/seasonal ET) was obtained at the highest yield. The highest yields were obtained by full irrigation of every furrow to supply sufficient water to meet evapotranspiration demands. The lowest yields shown in Figure 7 were from dryland plots, and the remainder of the yields were from LID-system plots that received either 125, 185, or 250 mm irrigation water during the growing season. The amounts of irrigation water applied are the average for the entire field; but, as indicated in Figure 6, the upper end of the field received the greatest amount, and the lower end of the field received either none or very limited amounts. The values presented are the integrated yields for the entire length of the field.

Figure 8 shows the increase in ET of the various plots as a function of the amount of irrigation water applied. Evapotranspiration increased with increasing amounts of applied irrigation water, and as ET increased, grain yields were increased, as shown in Figure 7. However, WUE (defined as yield of grain per unit of irrigation water applied) decreased as amounts of irrigation water were increased. When only 100–200 mm of irrigation water was applied (see Fig. 8), there was almost an equivalent increase in evapotranspiration. This is because with small inputs of water under the LID system, there was no runoff and very little opportunity for leaching, and very little available water remained in the soil at harvest time. The highest grain yields occurred at the highest irrigation levels, but the data in Figure 8 illustrate the need to apply 500–600 mm of irrigation water to get an increase of about 350 mm in evapotranspiration. This is because of substantial losses of both rainfall and irrigation water as runoff and because large quantities of available soil water remain in the soil at physiological maturity.

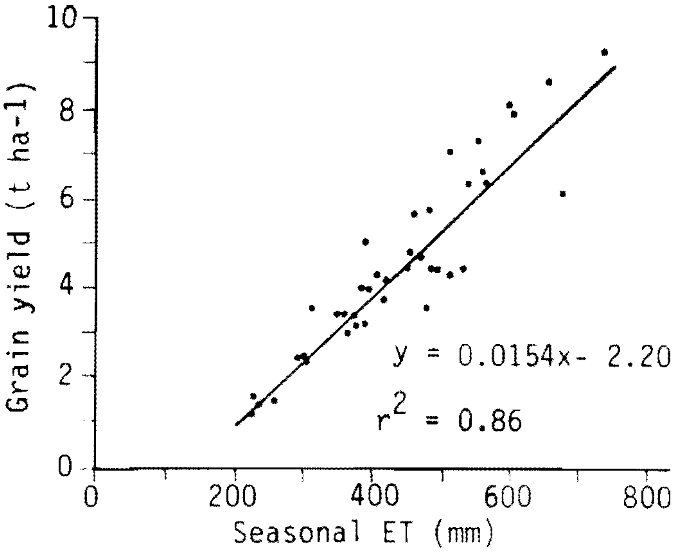

Figure 7. Effect of seasonal evapotranspiration (ET) on grain yield of sorghum, using the limited-irrigation dryland system (Stewart et al. 1983).

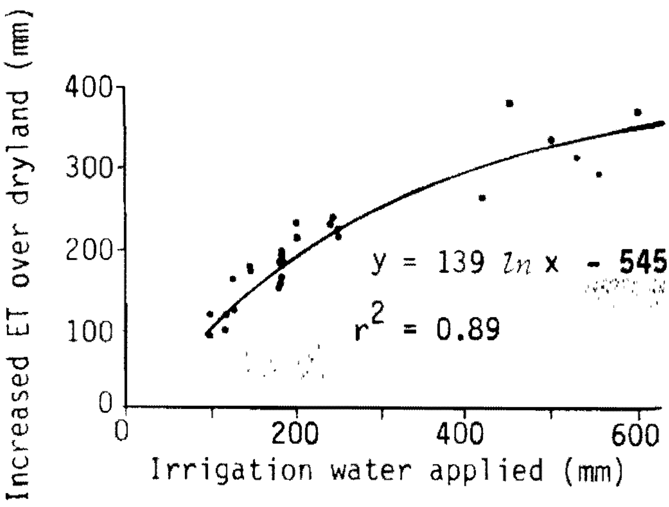

Figure 8. Increase in evapotranspiration (ET) over dryland as a function of the amount of irrigated water applied by the limited-irrigation dryland system (Stewart et al. 1983).

The data shown in Figure 8 for field conditions demonstrate the validity of the generalized relationship presented in Figure 4; they clearly show that limited amounts of irrigation water can be used more efficiently on grain sorghum by applying small amounts to more land than by fully irrigating less land. However, the extent of the benefits and the practicality and economics of the practice will depend on many factors. The value of the crop produced and the cost of irrigation are, of course, the dominant factors.

T. A. Howell (personal communication, USDA Agricultural Engineer, Bushland, Texas) has app-

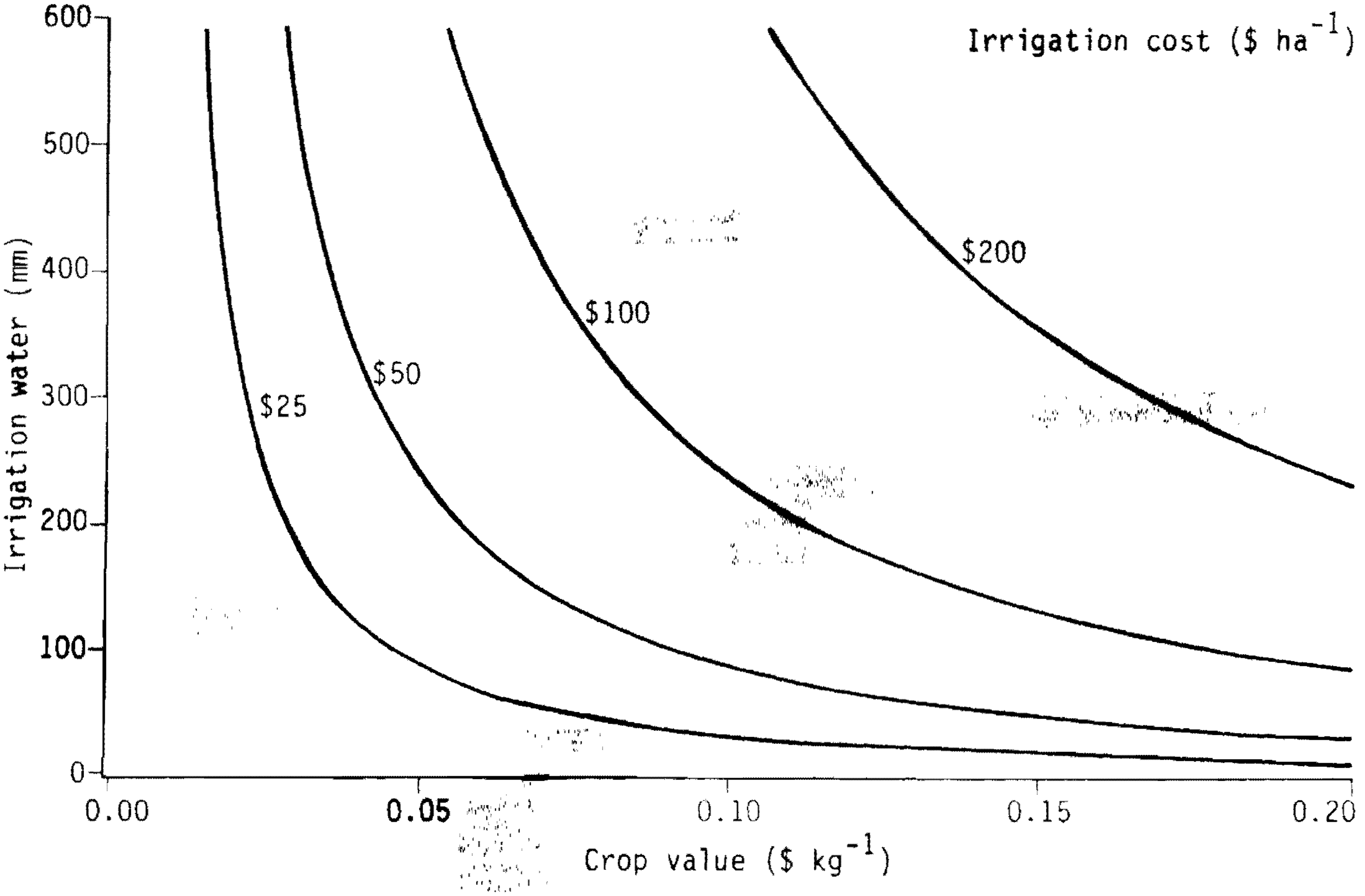

Figure 9. Effect of crop value and irrigation cost on the amount of irrigation water that should be applied when there is ample land suitable for irrigation but water supply is limited (based on personal communication from T.A. Howell, USDA-ARS, Bushland, Texas, 1985).

lied the concepts of Martin et al. (1984) to the response curve shown in Figure 8. The resulting relationships between cost of irrigation (quantified as fixed cost of the overall irrigation system), value of crop, and amount of irrigation water that should be applied for maximum net return are shown in Figure 9. The relationships shown are for the case where there is ample land suitable for irrigation but the water supply is limited. The curves in Figure 9 illustrate that when irrigation cost is low and the value of the crop is high, net return is enhanced by spreading the limited amount of water over a larger area. However, if irrigation costs are high and crop value is low, net return is greatest when less crop area is irrigated sufficiently to obtain near-maximum yields. When irrigation costs are very high, only high-value crops can be grown.

Conclusion

Decisionmakers need to have a good understanding of the relationships of transpiration and evapotranspiration to dry-matter and grain yields, and to water application rates. Unless these relationships are understood, it is very difficult to make correct decisions regarding the efficient use of irrigation water. Also, since WUE is used in many different ways, these relationships must be understood so the WUE values can be correctly interpreted. These relationships must be further interpreted with regard to risk management and economics, because these factors often dictate the final decisions.

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Discussion

Piara Singh: How do you optimize the use of fertilizers in a nonuniform system of application of water and seeding?

Stewart: Depending on the tillage and cropping system, fertilizer can sometimes be applied at right angles to the field and changing the rate down the field. Ideally, the fertilizer should be added with the water so that the fertilizer is truly optimized with the water because they are always added at the same ratio.

Virmani: A very interesting concept. It appears to have wide application on drylands. The concepts of intercropping, cropping for risk distribution, and changing crops in the irrigated and dryland part of the stripfurrow could be applied to the developing countries.

Stewart: Yes, but to put intercropping into systems with our harvesting techniques is difficult.

Willey: On the question of intercropping providing protection against drought stress, it is possible with some intercropping combinations. If the total population of both crops is not higher than that of the sole crops alone, then the partial population of each crop can behave like a low-population sole crop. There must obviously be some complementarity between the crops (e.g., different rooting depths) for this to happen.

Sagua: (1) Intermittent application of irrigation water on Vertisols poses a problem because once the cracks close up (due to swelling, after the initial flow of water) they cannot absorb more water. In Lake Chad Vertisols, we have to apply irrigation water very fast and over a short period. What is your comment on this? (2) Also in Lake Chad, we grow sorghum and rice in summer (May-September) under rainfall plus supplemental irrigation. The same land cannot be utilized for a subsequent crop (wheat) in winter (November-April) because the time interval between the harvest of the summer crop and the best sowing date of the winter crop is too short. What is to be done to maximize water efficiency under these conditions?

Stewart: Cracks pose problems during irrigation in Vertisols, but the use of little dams in the furrows help. Also, a high flow rate of irrigation water is advisable.

Dudal: How are the little dams within the furrows constructed?

Stewart: They are made by a mechanical device that simply has a paddle dragged from a tool bar. About halfway between the tool bar and the paddle is a wheel with a lug. When the wheel turns to the lug, the paddle is lifted, depositing the soil that forms the dam. The diameter of the wheel determines the space between the dams. In our area, we space the dams 2-3 m apart.

Taimeh: You have indicated that horizontal movement of water from a furrow might not be desired on cracking soils. I wonder whether the surge irrigation technique developed in Utah was incorporated into the system you presented?

Stewart: For 2 years we have used the surge system in some of our treatments. The surge technique uses an intermittent application of water; for example, cycles of 1 hour on and 1 hour off. In our experience, the surge system allowed us to apply water so that it was distributed further down the field.

Use of Vertisols for Rainfed Sorghum in the Central Clay Plain in Sudan

Ibrahim A. Babiker[1]

Abstract

About 33% of the cultivated land in the Sudan is planted with sorghum, the main staple food of the population. The principal sorghum-growing area is the low-rainfall savanna of the Central Clay Plain, where most sorghum is grown by mechanized farming. Sole cropping and the absence of fertilizer use has caused a declane in yields and degradation of the soils. The main problems at present are difficulties in land preparation and timely sowing, lack of fertilizer inputs and crop rotation, and inadequate control measures for pests and diseases. Improved crop varieties are also required. Socioeconomic factors must be taken into account. There is scope for considerable increase in production if integrated research and development programs consider both the interactions between the various yield-reducing factors and the socioeconomic environment.

Résumé

Utilisation des Vertisols pour le sorgho pluvial dans les Plaines centrales argileuses du Soudan : *Au Soudan, environ 33% des terres cultivées produisent du sorgho, aliment de base de la population. Les principaux terrains où poussent le sorgho se trouvent dans les savannes à faibles précipitations, dans les Plaines centrales argileuses, où la plus grande partie de la culture du sorgho est mécanisée. La monoculture et la non utilisation de fertilisants ont provoqué un déclin des rendements et la dégradation des sols. Actuellement, les principaux problèmes sont, d'abord les difficultés de préparation de sols et les semis en temps opportun, l'absence d'engrais et de rotations de culture ainsi que les mesures de lutte inadéquates contre les ravageurs et les maladies. Des variétés améliorées sont aussi nécessaires. Des facteurs socio-économiques doivent être pris en compte. Il y a des possibilités pour augmenter sensiblement la production si la recherche intégrée et les programmes de développement envisagent en même temps (1) les interactions entre les différents facteurs qui réduisent les rendements et (2) l'environnement socio-économique.*

Introduction

Sudan is a vast country that lies approximately between 4-22° N and 22-28° E; it has great agricultural potential. About 80 million ha of cultivable land is suitable for growing a variety of crops. At present, only 7 million ha under rainfed conditions and 3 million ha under irrigation are cultivated to grow agricultural and horticultural crops. Natural and cultivated forests cover vast areas, especially in

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the central and southern parts of the country.

Agriculture is the backbone of Sudan's economy: it provides livelihood for over 84% of the population (estimated at 22 million) and accounts for over 90% of the exports. It provides food for the people, raw material for industry, and commodities for export.

Ecological Zones

Sudan has a simple physiography; its climatic zones tend to be stratified in belts extending across the country from east to west, roughly parallel to the latitudinal lines. The major climatic zones include:

a. The arid zone—north of 17° N; annual rainfall is less than 75 mm per year.
b. The semi-arid zone—between 14-17° N; annual rainfall ranges from 75-300 mm.
c. The low-rainfall, grass-woodland savanna—between 10-14° N; annual rainfall is 400-1000 mm.
d. The high-rainfall, woodland savanna—south of 10° N; annual rainfall is 900-1500 mm.

Rainfall increases from north to south, as does the length of the rainy season. The peak of the rainy season is always in July and August. Throughout the year, average temperatures are high; relative humidity is low, except during the rainy season. Most of the land is level. The soils have a moderate level of chemical fertility.

The most important zone for agricultural production is the low-rainfall savanna, which occurs in the Central Clay Plain and supports both rainfed crops and major irrigated agriculture, such as that in the Gezira, Rahad, White Nile, Blue Nile, and Halfa Schemes.

The existing land use in the Central Clay Plain is quite diverse, including:

a. irrigated cultivation;
b. mechanized rainfed cultivation;
c. traditional cultivation;
d. animal raising, range management, and pastures;
e. horticultural crops;
f. forestry; and
g. wildlife reserves.

Of these, mechanized cultivation of rainfed crops is most important for food production. The principal crops grown include cotton, sorghum, millet, groundnut, sesame, and wheat. Irrigated cotton, grown in Gezira, is the most important export crop. But the main crop grown under rainfed conditions in these areas is sorghum, the staple food of the population.

Sorghum Production on Vertisols of the Central Clay Plain

In the Central Clay Plain, most crops are grown under rainfed conditions. Food production, especially of sorghum, has a very high national priority, and sorghum is grown as a summer crop both rainfed and under irrigation. By total area, sorghum cropping ranks first, comprising about 33% of the entire cropped land in the country.

About 2.5 million ha of sorghum are planted every season by mechanized farming. Seed is sown by machine at a rate of about 6 kg ha^{-1}. No fertilizer is used, and the crop is weeded by hand. Harvesting is also done by hand, and a stationary thresher is used. The straw is an important source of animal feed.

The current mechanized farming system used for sorghum is far from optimal. In a way, it can be considered a monocropping system: new land is sown with sorghum for the first few seasons with a minimum amount of tillage. Yields are initially satisfactory, but they soon decline to a very low level and, hence, land is abandoned. Cropping is shifted to a new land area, which had been under native grass fallow for some years. There is, of course, a limit to such a practice of "mechanized shifting cultivation." Because of its harmful effects on the soil and environment, and a continuous decline in yields, such a wasteful use of land can no longer be accepted. Production constraints are many and of different kinds, but there is scope for considerable improvement.

Following is a brief discussion of topics that need research and improvements in Vertisol technology.

Land Preparation

The usual practice for land preparation in mechanized farming is to cultivate the soil to a shallow depth once or twice, using the wide-level disk harrow, after the initial rains which occur in May or June. The second cultivation is done in July, when the crop is planted by machine. No further tillage operation is done. Improvements in cultivation techniques are possible through the use of heavier machines for deeper plowing and other machinery for finer seedbed preparation. Care needs to be taken, however, to prevent soil compaction in these heavy, cracking clays.

Crop Rotation

The framework for good crop rotation should consider the amount of rainfall and the nature of the soils. The officially recommended rotation is sorghum-sesame (or groundnut), but farmers do not adhere to it.

Rainfall and Sowing Date

Rainfall and sowing date are the most important factors that affect crop yields. A rainfall of 500–800 mm with reasonable distribution is optimal for sorghum. The most suitable time for sowing is July; later planting commonly causes yield reduction and may expose the crop to sorghum midge, which can also cause heavy losses.

The situation can be improved by developing varieties suitable for each agroclimatic zone. This work is in progress.

Use of Fertilizers and Herbicides

No fertilizer is applied for sorghum production under mechanized farming. The soils of the Sudan, however, are known to be deficient in nitrogen. Therefore, evaluation of the use of fertilizers is essential. Similarly, the use of herbicides must be seriously examined.

Use of Improved Varieties

Sorghum varieties released by the Agricultural Research Corporation are not grown in most of the mechanized farming schemes. These varieties are combinable (suitable for harvesting with modern combine-harvesters) and give high yields, but acceptance by farmers is poor. Local varieties now in use are not combinable, lack uniformity in growth and maturity, and have low yield potential.

The present efforts of the agricultural research service, the national seed administration, and the extension service in promoting the cultivation of improved combinable sorghum varieties of Dabar, Gadam El Hamam, D.W. Milo, and the hybrid Hageen Durra I will no doubt lead to increased production and thus help alleviate the present strain on food production in the country.

Pests and Diseases

Crop losses due to insects are estimated at 20%, due to storage pests at 5–15%, and due to diseases at 5%. *Striga*, birds, and rats can also cause appreciable crop losses at times. There is wide scope for development of good pest control methods.

Conclusions

Most of the factors discussed require further research, but such studies should not focus on one factor in isolation from the others. Some of the factors are interdependent; various combinations of factors need to be examined, to assess the relative importance of each and the extent of its dependence upon the others. An integrated approach will facilitate the eventual development of various packages of components, from which the farmer can choose the one most appropriate for his environment and needs.

Food production in the Sudan is approaching a critical stage, and a high priority has been given for rapid action. The order of activities has been established: first, research is required, then application to management systems, then an extension effort. Toward these goals, a series of applied research investigations is being planned; the approaches being used in the Canadian Project at Simsin on applied soil and crop management appear to be most appropriate for our needs. Additionally, a joint effort is required from all relevant institutions—the Agricultural Research Corporation, the Production Schemes Management, and other institutions. Demonstration farms will greatly assist in the transfer of improved systems to farmers of the surrounding areas.

A Vertisols network would be of great assistance in promoting a flow of ideas for all stages of development of improved systems. A high level of interest exists at present in the Agricultural Research Corporation and the Soil Survey Administration in favor of participation in a Vertisols network.

Discussion

Blokhuis: (1) Soil deterioration is often mentioned in the mechanized crop-production schemes. But what exactly is the nature of this soil deterioration? Is there loss of structure (related to loss of organic matter, perhaps), and is there soil erosion on the slightly sloping Clay Plains? (2) Do you know how (slight) the slope is on the least sloping lands that suffer from soil erosion?

Babiker: (1) Soil deterioration is occurring because heavy rainfall causes sealing of the soil surface, and the runoff water causes sheet erosion. But definitely, the loss of structure is the major cause of deterioration. (2) Yes, there is soil erosion even on very slight slopes: for example, a slope of 1% exhibiting some soil erosion with heavy rainfall.

Jutzi: What is the ratio of rainfed to irrigated agricultural use of Sudanese Vertisols?

Babiker: It is 70:30.

Hawando: (1) Do Vertisols in Sudan fix P? Is there any response to applied P? (2) Has the use of heavy machinery, particularly in the Gezira scheme in Sudan for 50 to 60 years, caused soil compaction and low water infiltration? (3) Does the burning of cotton stalks affect the structure of the surface soil?

Babiker: (1) Yes, there is a certain amount of fixation. There is a response to applied P in cotton and wheat. There is also a N × P interaction in faba beans and vegetables. (2) There is no evidence of soil compaction due to the use of machinery in the Gezira. Infiltration rate of water is slow, especially a day or two after irrigation water has been applied. (3) The burning of cotton stalks used to be a necessity to control blackarm in cotton, but I agree that it is a waste, and that a better method for controlling this pathogen could be developed.

Sagua: In the Gezira irrigated Vertisols, what herbicides are used and how are they applied?

Babiker: The preemergent herbicides, Rostat, Zorial, and Cotran, are used and are applied mainly by aerial spray by aircraft, but also by vicon spreaders, sometimes with the fertilizer.

Woldeab: (1) What are the major reasons for the large differences between national average yields and the research yields? (2) What soil fertility investigations have been carried out on the Vertisols of Sudan?

Babiker: (1) The main reasons for the yield gap are the problems of land preparation, sowing date, method of applying water, good husbandry practices, and some lack of attention on behalf of the farmer. Late sowing is one of the main causes of low yields. (2) We surveyed (using semidetailed maps) the Vertisols of Sudan; in a few other places, agricultural schemes are being set up and these are surveyed in detail. Broadly, the general profile characteristics are being worked out.

Virmani: (1) What is the scale of the use of animal-drawn equipment in Sudan? (2) Where can we get agrometeorological data for the Vertisol areas of Sudan?

Babiker: (1) The use of animal-drawn equipment in the Sudan is very limited. It is confined to small holdings of intensive agriculture around the Nile Banks, especially in the northern region. But the types of agricultural practice we are talking about are too big for those and, hence, we get the use of machinery. (2) Agrometeorological data can be obtained from the few stations scattered in the Vertisol area, but if a special type of agriculture is to be practiced, then agrometeorological instruments are installed on the site.

Technologies Available and Their Components

Cropping Systems for Vertisols in Different Rainfall Regimes in the Semi-Arid Tropics

R. W. Willey,[1] R. P. Singh,[2] and M. S. Reddy[3]

Abstract

This paper discusses the major advantages and disadvantages of different types of cropping systems appropriate for Vertisols in the semi-arid tropics. It draws examples from a wide range of on-station experiments and on-farm projects carried out by ICRISAT and Indian national programs. For the higher rainfall areas (> 750 mm annual average), there are several sequential, relay, ratoon, and intercropping systems that allow cropping during both the rainy season, which is traditionally fallowed, and the postrainy season, which is traditionally cropped. Emphasis is placed on a pigeonpea-based intercropping system that avoids the need to establish a second crop at the end of the rains. A promising pigeonpea ratoon system is also described. The drier Vertisol areas (< 750 mm average annual rain) need contingency systems, based on the traditional pattern of postrainy-season cropping, which also allow rainy-season cropping in good rainfall years. Data are presented for both wetter and drier locations to show how a simple water-balance model can help predict the suitability of different systems for a given rainfall regime.

Résumé

Systèmes de culture pour les Vertisols dans différents régimes de précipitations : *Cet article expose les principaux avantages et inconvénients des différents types de production agricole qui conviennent aux Vertisols dans les zones tropicales semi-arides. Il présente des exemples d'un large éventail d'expériences en milieux contrôlé et réel réalisées par l'ICRISAT et des programmes indiens nationaux. En ce qui concerne les zones de précipitations plus élevées (>750 mm de précipitations annuelles moyennes), il y a plusieurs systèmes de culture (séquentiel, de relai, de repousses et associé) qui permettent la culture pendant la saison des pluies, qui est traditionnellement en friche, et aussi pendant la saison post-pluviale traditionnellement cultivée. L'accent est porté sur un système de cultures associées à base de pois d'Angole qui évite le besoin d'établir une deuxième culture à la fin des pluies. Un système prometteur avec une culture de repousses du pois d'Angole est aussi décrit. Les régions de Vertisols plus sèches (<750 mm de précipitations annuelles moyennes) ont besoin de systèms d'éventualité fondés sur le modèle traditionnel de culture de saison post-pluviale, mais qui permet également de cultiver pendant la saison des pluies dans les années de bonnes précipitations. Les données sont présentées pour les emplacements aussi bien plus humides que plus secs, afin de montrer comment un simple modèle de bilan hydrique peut contribuer à prévoir l'aptitude des différents systèmes pour un régime déterminé de précipitations.*

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Introduction

A cropping system is usually defined as a combination of crops in time and space. Combinations in time occur when crops occupy different growing periods, and combinations in space occur when crops are interplanted. When annual crops are considered (as in this paper), a cropping system usually refers to the combination of crops within a given year.

The agronomic or physiological objective of a cropping system is to make efficient use of growth resources for as much of the year as possible, so that high and/or stable productivity can be achieved. At its simplest, this means that cropping should start immediately at the beginning of the potential cropping period; also, inefficient periods with little or no crop cover should be reduced to a minimum.

The main climatic feature that affects cropping systems in the semi-arid tropics, where 70% of the Vertisols occur, is the alternation of wet and dry seasons. Thus, appropriate cropping systems for rainfed areas are largely determined by the period of moisture availability, which, in turn, is primarily determined by the distribution and amount of rainfall. An important feature of the Vertisols themselves, of course, is their very high moisture-holding capacity. This not only provides a buffer against drought stress during periods of erratic rainfall but also considerably extends the potential growing period.

This paper illustrates the principles for determining appropriate cropping systems for Vertisols by reviewing work in the semi-arid areas of India. These areas typically have a short rainy season of about 3-4 months, during which 80-90% of the total annual rainfall is received. Mean annual rainfall ranges from 500 to 1250 mm. To consider the broad types of cropping systems possible in these areas, we can divide the potential cropping period into two seasons: rainy and postrainy. The total amount and reliability of the rainfall directly determines cropping during the rainy season, and, as discussed later in this paper, either insufficient or excessive rainfall may severely restrict crop growth. Postrainy-season cropping depends on how much moisture is stored in the soil profile at the end of the rains. The different situations where cropping occurs in one or both of these seasons are discussed in detail later in this report.

The types of cropping systems that may be applicable in the different Vertisol environments are briefly described below.

1. Single cropping. Only one crop is grown during the year. The crop may be a relatively long-season one, occupying both rainy and postrainy seasons, or it may occupy only a short part of the potential cropping period (e.g., the rainy season or the postrainy season).

2. Sequential cropping. Two crops are grown during the year, one after the other. In the past, this system commonly was termed "double cropping," but the term "sequential" is now preferred to distinguish it from the other two-crop systems (described later). The essential feature of sequential cropping is that the two crops do not overlap: the second crop is sown only after the harvest of the first. On Vertisols, the first crop is generally grown during the rainy season, and the second uses the residual soil moisture during the postrainy season.

3. Relay cropping. A second crop is sown shortly before the harvest of the first. The period of overlap is short, usually about 2-3 weeks: the second crop is established when the first crop is senescing and allows an increasing amount of light transmission to ground level. Although it is difficult to draw a rigid demarcation between relay cropping and intercropping (see no. 5), the major distinction is that there is no significant intercrop competition in the relay system because the period of overlap is too short, and it occurs when neither crop is making much demand on resources.

4. Ratoon cropping. The stubble of a harvested crop is allowed to regrow to produce a second crop. This is possible only with a limited number of annual crops because it depends on a crop's ability to perennate. The second, or ratoon, crop has a shorter growing period (by about 2-3 weeks, in the crops considered later) because of its rapid start from the established stubble.

5. Intercropping. Two or more crops are grown on the same area of land at the same time. The crops may be grown either in separate rows or in a more random mixture. The important feature of this system is the intercrop competition, which may result in several types of interactions between crops. On Vertisols, intercropping may take one of two forms: an early-maturing and a late-maturing crop can be sown together at the beginning of the rainy season, the early crop being harvested at the end of the rainy season, and the late crop at the end of the postrainy season; or, two relatively short-season crops can be grown during either the rainy season or the postrainy season.

Traditional Cropping Systems on the Indian Vertisols

In semi-arid India, the majority of Vertisols are left fallow during the rainy season. Sowing is done toward the end of the rains, or shortly afterward, and a single postrainy-season crop is raised using the stored soil moisture. In Central India, the main crops are sorghum, chickpea, and, to a lesser extent, safflower; they may be grown as sole crops or in intercropping combinations. In the North Central Plains, the main crop is wheat, most often as a sole crop but sometimes intercropped with chickpea.

Although the rainy-season fallow is prevalent throughout the Vertisols, the reasons for its occurrence vary. In the areas of low and erratic rainfall, rainy-season cropping is risky, despite the good moisture-holding capacity of the soil, because there is only sufficient moisture to support a limited period of cropping. Thus, by bare-fallowing during the rainy season and allowing rainfall to accumulate in the soil, the farmer is able to grow a relatively assured postrainy-season crop using the safely stored moisture. This is an astute traditional practice that is difficult to fault. On the other hand, in wetter areas that, in theory, could support a much longer period of cropping, farmers may fallow during the rainy season because the wet soil becomes too sticky and difficult to manage and crops may suffer from waterlogging. Growing only postrainy-season crops in these wetter areas is a very inefficient use of available moisture; in addition, the uncropped land is prone to severe erosion during the heavy rains.

In some Vertisols where moisture is adequate but not excessive, there is at least some traditional use of the rainy season. The most common systems are based on cotton, the crop associated with Vertisols in many parts of the world. But cotton tends to be sown well after the beginning of the rains, probably so that it will establish during the latter part of the rainy season and fully use the postrainy season for growth. This rather late establishment, coupled with cotton's slow, initial growth, results in incomplete use of early rainy-season resources. Cotton is commonly intercropped with occasional rows of pigeonpea, but because pigeonpea also establishes very slowly, this particular combination does not improve overall resource use. In some areas chillies or coriander are also planted late in the rains, and they play a role somewhat similar to cotton.

When considering this broad division into wetter and drier Vertisols, it is important to take into account the position in a toposequence (especially the effect on depth and texture of soil, to the extent that these vary within the strict definition of Vertisols), which also affects moisture conditions. For example, the cotton systems described can typically be found on the higher, better-drained parts of the toposequence, whereas, at the other extreme, rainfed rice might be found in flooded hollows. Rainfed rice, surprisingly, is not a common rainy-season crop on the wetter Vertisols. This is probably due to the relatively long growing period of traditional varieties, which precludes sowing a postrainy-season crop; in effect, therefore, rice simply replaces the traditional postrainy cereals of wheat or sorghum. Because of their underexploited cropping potential, research has focused primarily on the wetter Vertisol areas in the semi-arid tropics. Moreover, because of their potentially long cropping period, these wetter areas provide the greatest scope for a range and variety of cropping systems. For these reasons, the possible cropping systems for wetter Vertisol areas are given most attention in this paper.

Experimental Approaches

The initial approach of both the Indian Council of Agricultural Research (ICAR) and ICRISAT in experimental work on cropping systems was to examine a large number of crops and systems in relatively small plots. As more promising crops and systems have been identified, there has been a move to larger, operational-scale plots that incorporate the use of bullock-drawn equipment and economic levels of inputs such as fertilizers, chemical sprays, and weeding. These larger plots have provided more realistic estimates of field-scale yields and likely economic returns. Some systems have also been examined over several years in the even larger-scale watershed areas at ICRISAT Center.

In the National Dryland Agricultural Research Project, multilocational experimentation on cropping systems has been carried out on Vertisols over a range of different rainfall regimes. Also, a broad variety of systems has been examined in three ICA-

R/ICRISAT on-farm projects; one in a less-assured rainfall area at Farhatabad, Karnataka (700 mm mean annual rainfall); one in a rainfall regime similar to that of ICRISAT Center at Taddanpally, Andhra Pradesh (800 mm); and one in a wetter North Central Plains area at Begumgunj, Madhya Pradesh (1250 mm). At the third location, some experiments have also been conducted on a neighboring seed farm to examine a wider range of cropping systems options. In the following sections, examples are drawn from the whole range of on-station and on-farm activities.

The Wetter Vertisol Areas

Krantz et al. (1978) described a graded bed-and-furrow system of land and water management, designed to improve drainage and workability of Vertisols and to allow rainy-season cropping in the wetter areas. In this technology, the beds are relatively broad (150 cm furrow-to-furrow), which allows considerable flexibility of row arrangement for both sole and intercropping systems. In addition, the rainy-season crop is sown in a dry seedbed before the onset of the rains. Not only does this dry-sowing technique ensure an early start to the growing period, but also it avoids cultivating and sowing after the rains have begun, when it may be difficult to get onto the land because of the wet conditions. However, the technique relies on a relatively assured onset of the rainy season. Virmani et al. (1980) estimated that the low-risk areas for dry seeding were approximately those that also had a sufficient amount and dependability of rainfall to sustain cropping throughout both the rainy and postrainy seasons. These are approximately the areas receiving 750 mm or more annual rainfall. It is these assured-rainfall areas that are being considered in the discussion here of possible cropping systems.

Sequential Cropping

The initial objective of ICRISAT cropping systems experiments was to determine the feasibility of replacing the fallow with a rainy-season crop and to examine whether this jeopardized yields of sequentially sown, traditional, postrainy-season crops. By comparing rainy-season cropping with fallowing over a 3-year period, it was found that a good rainy-season crop of maize could be grown with little or no yield reduction in postrainy crops of sorghum or chickpea (Table 1). A similar pattern was found with a postrainy-season crop of pigeonpea, although earlier sowing after fallow produced 29% more pigeonpea yield than sequential sowing after maize. This pigeonpea system emphasizes the one possible problem with adding a rainy season crop to the system: delayed sowing reduced yield of some postrainy-season crops. Although no yield reductions occurred with postrainy-season crops of sorghum and chickpea in these early experiments, current recommendations from ICAR are that postrainy-season sorghum should be sown by mid-September to avoid shoot fly attack, but this is still earlier than can normally be achieved after a full rainy-season crop. Later experiments have not included comparisons with fallowing, but operational-scale experiments both at ICRISAT Center (Fig. 1) and in Madhya Pradesh (Fig. 2) have confirmed that rainy-season maize can still be followed by good crops of chickpea and safflower.

Rainy-season sorghum was also examined in these early ICRISAT experiments, and in the first year (see Table 1) there was a drastic yield reduction in the postrainy-season crops of chickpea, pigeonpea, and sorghum. This was thought to be a phytotoxic effect of the kind quite widely reported after sorghum (Nambiar 1942, Singh and Singh 1966, Guenzi et al. 1967). The literature suggests that this effect is little understood and very erratic, and it seems clear that the reductions reported here were of unusual severity. In the two subsequent years of small-plot experiments, there were no visual signs of phytotoxicity, but yields of postrainy-season crops after sorghum were less than after maize: sorghum by 14%, chickpea by 19%, and pigeonpea by 12%.

After a maize crop, the second crop in a sequential system can sometimes be sown directly into the stubble without cultivating; after a sorghum crop, however, the stubble usually has to be cultivated to prevent regrowth. This is one practical factor that affects the choice of maize or sorghum as a first-season crop. Other factors include the respective yields of the two crops, the need for good forage, and the risk of specific diseases or bird damage, but these factors are independent of the system in which the crops occur.

The All India Coordinated Research Project for Dryland Agriculture (AICRPDA) has examined the possibility of early-maturing (100-105 days) rainy-season rice in sequential systems. At Rewa, in Madhya Pradesh, yields of about 2.5 t ha^{-1} of rice have

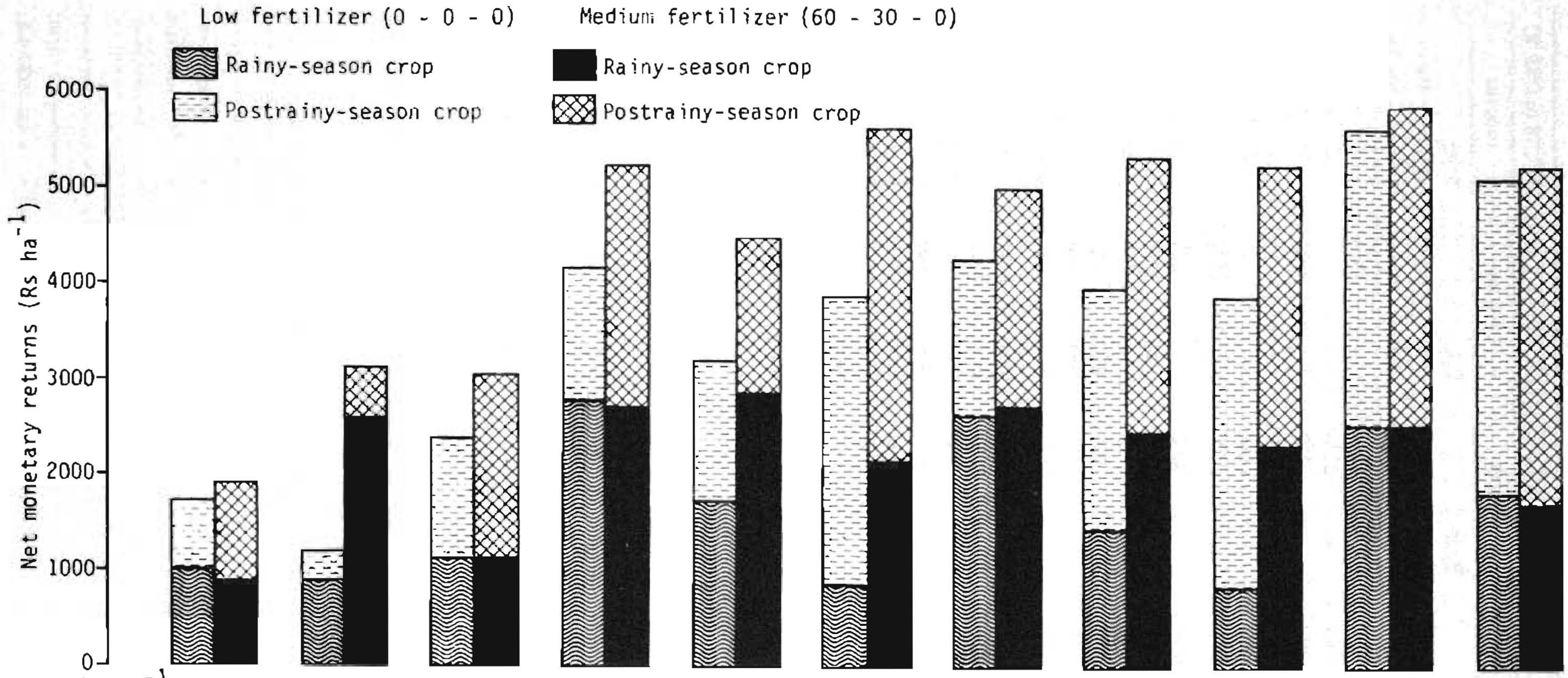
Table 1. Grain yields (kg ha^{-1}) from small-plot experiments grown on Vertisols at ICRISAT Center, 1977/78 to 1980/81.

Treatments[1]	1977/78 Post-rainy season[1]	1977/78 Rainy season	1978/79 Post-rainy season[2]	1978/79 Rainy season	1979/80 Post-rainy season	1979/80 Rainy season	1980/81 Post-rainy season	1980/81 Rainy season
Fallow + rel. sorghum	-	2890	-	2750	-	2710	-	
Fallow + seq. sorghum	-	2860	-	2570	-	-	-	
Fallow + rel. pigeonpea	-	890	-	810	-	1100	-	
Fallow + seq. pigeonpea	-	680	-	740	-	-	-	
Fallow + rel. chickpea	-	1010	-	1140	-	-	-	
Fallow + seq. chickpea	-	1460	-	1360	-	1500	-	
Maize + rel. sorghum	4020	3070	3310	2690	3190	2600	-	
Maize + seq. sorghum		3040		2650	3160	2410	-	
Maize + rel. pigeonpea		910		720	3160	840	3270	610
Maize + seq. pigeonpea		730		660	3030	620	-	
Maize + rel. chickpea		970		1100	3050	980	-	
Maize + seq. chickpea		1280		1380	3020	1450	3340	F[3]
Sorghum + rel. sorghum	3120	1000	2530	2340	3840	2440	-	
Sorghum + seq. sorghum		650		2120	3750	2210	-	
Sorghum + rel. p'pea		530		660	3600	820	3830	550
Sorghum + seq. p'pea		380		600	3900	540	-	
Sorghum + rel. chickpea		190		930	3750	810	-	
Sorghum + seq. chickpea		170		1140	3530	1430	3720	F
Sorghum + rat. sorghum		-		-	3630	1860	3780	F
Mung bean + seq. sorghum	-	-	-	-	620	2580	-	
Sorghum/pigeonpea intercrop	-	-	-	-	3600	1060	3620	1280
Sorghum/pigeonpea intercrop-rat. sorghum	-	-	-	-	3650	990/260	-	-
Sorghum/pigeonpea intercrop-seq. chickpea	-	-	-	-	-	-	3660	1200/F
Maize/pigeonpea intercrop	-	-	-	-	2990	1100	3220	1150
Maize/pigeonpea intercrop-seq. chickpea	- -	- -	- -	- -	2990 -	1060/530	3180	1300/F

1. "Relay" and "sequential" after fallow are used to indicate the sowing, not the cropping system.
2. Rainy-season yields in 1977/78 and 1978/79 were measured as main plot means.
3. F = crop failed.

been reported, followed by almost 2 t ha^{-1} of the crucial postrainy-season wheat; postrainy-season crops of chickpea, safflower, linseed, lentil, and pigeonpea have also been good (Singh 1985).

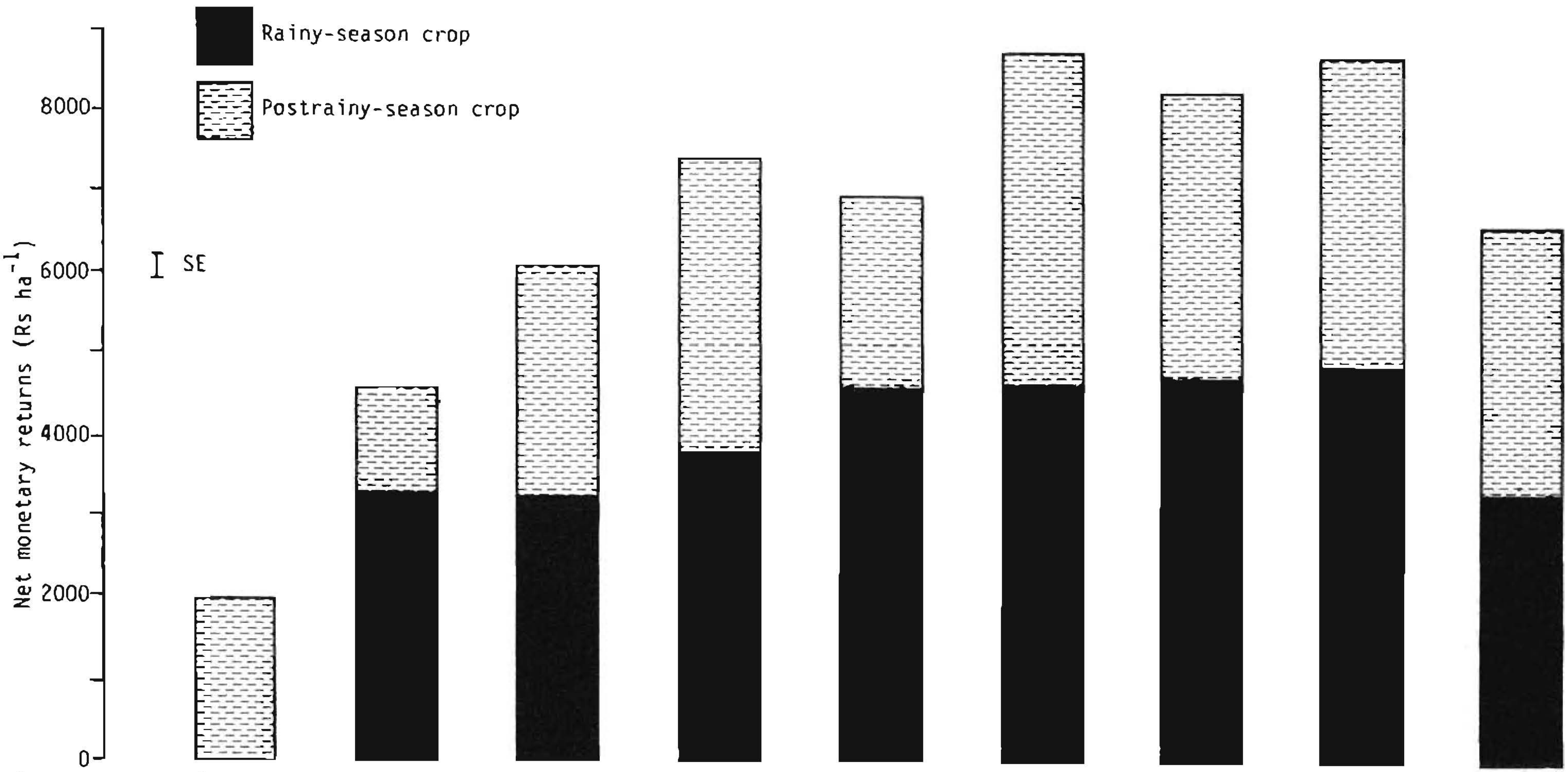
Whether based on sorghum, maize, or rice, these sequential systems suggest that in the wetter areas virtually two full crops, each of about 100 days maturity, may be produced. It is evident even under experimental conditions, however, that such systems can be difficult to manage, and they incur considerable risk. Harvest of a 100-day rainy-season crop occurs roughly at the cessation of the rains, and good establishment of a postrainy-season crop depends on end-of-season showers. The risks involved were clearly illustrated by the complete failure to establish a postrainy-season chickpea crop when the rains ended early in 1980/81 (see Table 1). In farming practice, these risks are likely to be even greater because of the problems of achieving a rapid turnaround between crops; unlike experimental



Yield (kg ha^{-1})	Mung-	Maize-	Mung-	SB-	Sorg -	Maize-	P.pea	Sorg./	Maize/	SB/	Sesamum/
Fert Low	483	1104	550	1260	1911	1037	887	1598	897	1099	372
Fert Med	567	2796	653	1280	3337	2440	1019	2876	2290	1151	407
Yield (kg ha^{-1})	Seq. Chilies	Relay Chilies	Seq. Sorg.	Seq. Sorg.	Seq. Saff.	Seq C.pea	Ratoon P.pea	IC P.pea	IC P.pea	IC P.pea	IC P.pea
Fert Low	302	230	1297	1037	593	1091	532	845	993	944	1007
Fert Med	452	329	2070	1831	785	1305	704	936	989	1039	1115

(Seq. = Sequential; IC = Intercrop)
(SB = Soybean; Sorg. = Sorghum; P.pea = Pigeonpea; Saff. = Safflower; C.pea = Chickpea)

Figure 1. Net monetary returns and grain yields from various cropping systems grown on deep Vertisols on an operational scale at ICRISAT Center, 1981-1984.



System	F-W	SB-W	SB-SF	SB-CP	M-W	M-CP	SB/M-CP	M/PP	SB/PP
Yield (kg ha^{-1})									
RS	-	1650	1610	1870	4550	4600	330/4410	4590	1540
PRS	1690	1380	1300	1900	1800	2090	1840	1390	1250

(F = fallow; W = wheat; SB = soybean; SF = safflower; CP = chickpea; M = maize; PP = pigeonpea); - = sequential cropping; / = intercropping; RS = rainy season; PRS = postrainy season.

Figure 2. Net monetary returns and grain yields from various cropping systems grown on deep Vertisols at the Begumganj Seed Farm in Madhya Pradesh, India, during the 1982 and 1983 rainy and postrainy seasons.

situations, the farmer may have to spend considerable time harvesting, threshing, storing, and even marketing his first crop before he is able to give much attention to sowing a second one. Not surprisingly, therefore, experience in on-farm projects indicates that the farmer views sequential systems of two full crops as very demanding and highly risk-prone.

A more easily managed sequential system has been shown to be a mung bean (green gram) rainy-season crop followed by sorghum; the major advantage of this system is that the very early-maturing mung (65-75 days) allows an early, assured establishment of the sorghum. This is a system already practiced by farmers in areas where rainfall, and, consequently, the risk of foliar diseases and waterlogging, is not too high. A disadvantage of the system is the relatively low yield of mung bean, and, thus, the low overall system yield; nevertheless, farmers in the Taddanpally on-farm project have clearly preferred this system to the potentially higher yielding but riskier rainy-season cereal systems. Mung bean has also been tried before a transplanted chili crop, which, as described earlier, is normally planted quite late in the rains. This is another demanding system, requiring a rapid turnaround between the two crops, but it has been successfully grown both in operational-scale, on-station experiments and in the on-farm project at Taddanpally.

The sequential system of mung bean and sorghum also highlights the advantages of having a noncereal rainy-season crop, which allows the retention of the traditional postrainy cereals that are so common on the Indian Vertisols. ICAR experiments have placed particular emphasis on pulses and oilseeds, in the cropping-systems experiments because of the general shortage of these commodities. Unfortunately, choice of noncereal rainy-season crops is limited. Black gram and cowpea are possibilities, but they yield little more than mung bean and, in many areas, cowpea is unpopular. Similarly, sesame is a possibility, but even its very high unit value does not sufficiently overcome its low yield potential. On a much more favorable note, for the North Central Plains, where oil-extraction factories are now established, soybean has an enormous potential because of its high yield and its tolerance to waterlogging. However, although the sowing time of wheat in this area is well after harvest of the soybean, a sequential system of soybean-wheat can still be a problem because the farmer may not be able to use end-of-season showers for the good seedbed preparation that seems so necessary for high wheat yield.

A recent possibility for a noncereal rainy-season crop is the extra-early type of pigeonpea (90-110 days maturity). Breeders have found it difficult to produce a genotype that is sufficiently early to allow postrainy-season cropping, but in the 1984/85 operational-scale trials at ICRISAT Center, genotype ICPL 4 was successfully followed by sorghum. Pigeonpea yields were only moderate (up to 883 kg ha^{-1}), but this same genotype has yielded over 1 tonne in another ICRISAT experiment, and the future for this crop looks promising.

Relay Cropping

Compared with sequential systems, the earlier sowing of second crops in relay systems has several potential advantages. One fairly obvious advantage is that the total cropping period is shortened, so second crops are less likely to run out of moisture at the end of the season. Under the rainfall regimes typical of the Indian Vertisol areas, however, probably the major agronomic advantage is that establishment of the second crop is more assured. This is primarily due to the greater likelihood of catching end-of-season showers, but there is also some benefit from the first crop, which affords some protection against drying out of the soil surface. This greater assurance of establishment was clearly evident in the ICRISAT 1980/81 experiment. Because the rains ended early that year, relay crops of pigeonpea were established after maize and sorghum, but sequential crops of chickpea did not establish (Table 1).

In defining relay cropping, we emphasized that there is no significant competition between crops. Thus, in theory, the system should produce yields equivalent to the full potential of a sequential system. However, early ICRISAT experiments showed that, at least for the second crop, there can be considerable variation in this pattern (see Table 1). Whereas a relay crop of sorghum produced yields similar to a sequentially sown crop, relay pigeonpea produced higher yields and relay chickpea lower. These different effects were not due to the relay system per se, because similar differences occurred if the crops were sown at the relay and sequential times after fallow. Clearly they were simple time-of-sowing effects: the earlier relay sowing benefitted the potentially long-season pigeonpea, but it was too early for the chickpea, which has a fairly critical optimum sowing time because of its adaptation to the postrainy-season cool-temperature pattern.

The practical advantage of relay systems is that the second crop can be sown before the first is harvested, eliminating the problem of rapid turnaround of sowing and harvesting necessary in sequential systems. But relay systems also have a practical disadvantage: the second crop must be sown in a standing first crop, and the first crop must be harvested without damaging the second crop seedlings.

To try to avoid the problems associated with mechanical sowing of the second crop into the first crop, we examined a cropping system of maize and transplanted chilies. The rationale here was that since, in any case, transplanting of chilies must be done by hand, it can easily be done in a standing maize crop. The system was found feasible in operational-scale experiments, and it added a substantial maize yield to the traditional system of fallow followed by chilies; with higher fertilizer inputs, the system also gave greater monetary returns than the sequential system of mung bean and chilies. But this system of maize and transplanted chilies still has not been favored by farmers at Taddanpally, where chili is an important crop.

Ratoon Cropping

Because of the shorter growing period, ratoon cropping, like relay cropping, reduces the total cropping period; thus there is less likelihood of yield loss due to end-of-season drought stress. In addition, ratoon cropping avoids most of the risks, and costs, of establishing a second crop. However, for annual cropping systems, there are few crops that will produce a ratoon growth; of the cereals, only millet and sorghum will ratoon, and, of these, only sorghum is suited to the wetter Vertisols.

Many local genotypes of sorghum are known to ratoon well; a study at ICRISAT examined a large number of improved genotypes in small plots over a 3-year period. It was found that, with only very moderate nitrogen dressings, some of the currently recommended hybrids from the All India Coordinated Sorghum Improvement Project could produce ratoon yields of over 3 t ha^{-1}, equivalent to about two-thirds of the first crops. As an assured crop that runs little risk of establishment failure, these yields appear very attractive. However, experience in larger operational-scale plots has been very different, and ratoon yields of the high-yielding CSH 6 hybrid have only averaged about 20% of the first crop. This kind of yield level might be acceptable for a low-cost additional crop when there is insufficient moisture for a full second crop, but, in general, it would be unacceptable on Vertisols in wetter areas.

A new possibility for ratoon cropping has arisen with the development of early-maturing pigeonpea varieties. Initial experiments at ICRISAT examined yield potential under very high input situations—i.e., with fertilizer, intensive irrigation, and pest control. One variety (ICPL 87) produced a first crop of 2380 kg ha^{-1} with two ratoon crops of 2120 and 1000 kg ha^{-1}, giving the extremely high total of 5500 kg ha^{-1} over a 213-day cropping period. Although different ratoon systems were tried, these particular yields were produced by picking the pods without any cutting of stems. Yields have been poorer in operational-scale experiments, but the system still looks very promising (Fig. 1).

Intercropping

One of the most successful intercropping systems on the wetter Vertisols has been the cereal/pigeonpea combination. This has usually been grown in a 2:1 cereal/pigeonpea row arrangement, with the populations of each crop the same as the recommended sole crop population. Both crops are dry-sown just before the beginning of the rains, the cereal being harvested after about 100 days and the pigeonpea going on for about a further 100 days until the end of the postrainy season. On the average, intercropped cereal yields have been about 90-95% of the sole crop cereal yields, and pigeonpea yields have been only a little less or even roughly similar to those of a sequential chickpea. In general, therefore, overall productivity has been little different between these intercropping systems and sequential systems. For example, a 4-year average for large-scale watershed areas gave 2791 kg ha^{-1} maize and 1060 kg ha^{-1} pigeonpea in the intercropping system, and 3197 kg ha^{-1} maize and 976 kg ha^{-1} chickpea in a sequential system.

One of the great advantages of the pigeonpea intercropping systems is that they avoid both the costs and the problems associated with sowing the second crop in sequential and relay systems. Not surprisingly, of all the high-productivity systems tried in the on-farm studies, farmers like these pigeonpea intercropping systems best. Further, risk is reduced by not having to establish a second crop. This effect was very evident in the small-plot trials in

1980/81; it was impossible to establish the postrainy chickpea in sequential systems, but pigeonpea in the intercropping system gave excellent yields. Even when postrainy-season crops do not fail outright, the intercropping system may still provide greater stability; in the 4-year watershed study quoted above, Ryan and Sarin (1981) found a coefficient of variation of only 24% for the intercropping system, compared with 54% for the sequential one.

Pigeonpea can also be intercropped with most of the other rainy-season crops, although their low yields with crops such as mung bean or cowpea again reduce the overall productivity of the system. One very promising system in Madhya Pradesh is soybean/pigeonpea, which has given very good yields of both crops, producing a total of 2.5 3 t ha^{-1} of high-value seeds.

As outlined earlier, intercropping need not involve a long-season crop such as pigeonpea, and it can be either a rainy-season or postrainy-season combination. For example, a review of rainy-season sorghum systems cited many experiments where intercropping with various legumes gave yield advantages of up to 20 25% (Willey et al. 1982). A maize/soybean system tried in the ICAR/ICRISAT cropping-system project in Madhya Pradesh proved disappointing, though this system has been promising in other national projects in India. Chowdhury (1981) has shown similar advantages for several postrainy systems. Thus, there could be opportunity to increase the productivity of sequential systems by intercropping within either or both of the seasons, although the increase in the number of crops that the farmer has to handle could make some of the already intensive sequential systems very demanding in practice.

In the early small-plot trials at ICRISAT, a three-crop system was tried, where a chickpea intercrop was sown after the harvest of the maize intercrop in a maize/pigeonpea system. In 1979/80 when late rains were good, this system gave an additional 528 kg ha^{-1} of chickpea, without causing any reduction in yield of pigeonpea. In the next year, when late rains were poor, the chickpea could not be established, but, as seen earlier, this was also the case for the full sequential crop of chickpea after sole crops of cereals. These results suggest that this three-crop system is practical and flexible, the chickpea being sown only in years of good late rainfall. This system provides the reliability of intercropping in the poor years, and also allows the farmer to cash in on some additional chickpea yield in the good years. A similar three-crop system has been developed by AICRPDA at its Indore Center (990 mm average annual rainfall). In the rainy season, a very early maize (cv. Satha, 65 70 days) is intercropped with soybean. Before harvest of the maize, safflower is "relay" sown along the sides of the maize rows. The maize is harvested at physiological maturity, and the safflower, sown as an intercrop between the soybean rows, continues as a sole crop after the soybean harvest.

Drier Vertisol Areas

Earlier we stated that, in those Vertisol areas with lower and less-assured rainfall (< 750 mm annual average), there is usually not enough moisture to support cropping during both the rainy and postrainy seasons. It was also emphasized that if crops are grown in only one season, then the postrainy-season crops involve much less risk since they depend on moisture already safely stored in the profile and are not subject to the problems of erratic rainfall. However, while this means that the traditional system of rainy-season fallow is fundamentally sound when there is genuinely only sufficient moisture for one crop, it leaves little scope for increasing productivity by improving the system per se. Productivity increases will mainly have to be brought about by improvements in the individual crops. In fact, the only major option open to farmers for postrainy-season cropping is whether to grow sole crops or intercrops. In India it has frequently been argued that intercropping must be less worthwhile in the postrainy season than in the rainy season, because it is less commonly practiced in the postrainy season. While this argument is probably sound, the main reason for intercropping in the rainy season is probably that it can help improve yield stability in a period of greater risk. A review of postrainy-season intercropping (Chowdhury 1981) has shown that there can still be worthwhile yield advantages (e.g., 15-20%) in any given season. While these advantages are not spectacular, it must be remembered that they are easily and cheaply obtained, and in a situation where the options for yield improvement are limited.

But the most difficult of all the Vertisol situations are those less-assured areas where rainfall is just below sufficient for both rainy- and postrainy-season cropping. In practice, these areas can support cropping during both seasons in years of good rainfall, but not so in years of poor rainfall. Thus, for these areas, some kind of contingency system is needed so the farmer can cash in on the good years but still be safe in the poor years. To some extent, contingency systems are already operated in farming practice, and farmers may sow very early-maturing rainy-season crops, such as mung bean or pearl millet, if the rains are good and they arrive early. In theory, it is also possible to thin out crops midway through the season if drought stress becomes severe. Experiments by AICRPDA have shown that thinning can substantially improve yields in years of subnormal rainfall (Table 2). However, even though the thinned material can be used as a much-needed fodder, farmers show considerable reluctance toward thinning.

The resilience of pigeonpea-based intercropping systems is particularly suited to these marginal, less-assured areas, and the farmer's preference for these systems has been evident in the on-farm project in Karnataka. A contingency approach can still be adapted for the rainy-season intercrops, and, in the 1984 season, when rains were late, farmers in the Karnataka project opted only for very short-season intercrops of mung bean and pearl millet. A different pigeonpea system that could be useful for these areas is a variation on the ratoon system described earlier. Studies at ICRISAT have shown that if pigeonpea is established as a postrainy-season crop, it can be left to produce an early ratoon yield during the following rainy season, which, in turn, can be followed by a further postrainy-season ratoon, or perhaps a different crop. Potential problems with the systems are disease buildup, now largely controllable with resistant and tolerant varieties, and plant mortality during the dry season. But the advantage of the system for the less-assured rainfall areas could be that it provides a crop which is well-established at the beginning of the rains, making the crop much less susceptible to periods of drought stress.

Probability of Success of Different Cropping Systems

The previous sections have described the merits and suitabilities of various types of cropping systems, based on the practical results of on-station and on-farm experiments. Clearly, because of the paramount importance of moisture in these Vertisols, it is useful to predict the suitability of given systems according to moisture patterns. A cooperative study between cropping systems scientists and agroclimatologists at ICRISAT has attempted to do this by fitting a water-balance model to long-term rainfall data. The model estimates the possibility of having sufficient water for growth and, in the sequential and relay systems, sufficient rainfall to establish the second crop.

Table 3 gives an example of a wetter Vertisol area—Indore, with 990 mm average annual rainfall. After a 91-day rainy-season sorghum crop, there is still quite a high probability (73%) of having sufficient stored moisture for a postrainy crop. After allowing for those years in which rain is insufficient at sowing time to establish the postrainy-season crop, this probability reduces to 60%. If the rainy-season crop has a 105-day growing period, the probability for a second crop is only 27%. These may seem to be surprisingly low for a 990-mm rainfall regime, but they highlight the risks of sequential systems emphasized earlier and the greater problems caused by longer growing periods of the first crop. Table 3 also shows that if a relay system with a 14-day overlap could be adopted, then the 105-day first crop could still be grown, and the overall probability would be the same as for a sequential crop based on a 91-day first crop. The advantage of a sorghum/pigeonpea system is very striking in this situation: there is an extremely high probability of success (97%), and a full-season, 105-day rainy-

Table 2. Effect of thinning on yield of sorghum. (Source: All-India Coordinated Research Project for Dryland Agriculture, Report for 1977/78, Bellary Center.)

	Grain yield (kg ha⁻¹)			
	1974/75 (Subnormal rainfall)	1975/76 (Above normal rainfall)	1976/77 (Subnormal rainfall)	1977/78 (Above normal rainfall)
Original population	1550	2420	540	2490
Third row removed	2110	2020	920	2330

Table 3. Probability of success of different cropping systems, predicted from a water-balance model and long-term rainfall data.

	First crop		Second crop (or pigeonpea intercrop)		
Cropping system	Sufficient moisture for growth (%)	Wet week at harvest (>50 mm) (%)	Sufficient moisture for growth (>200 mm) (%)	Insufficient rain for establishment (<20 mm), though sufficient for growth (%)	Total probability of success (%)
Indore[1]					
Sequential system (First crop, 91-day sorghum)	100	30	73	13	60
Sequential system (First crop, 105-day sorghum)	100	24	51	24	27
Relay system (First crop 105-day sorghum; overlap, 14 days)	100	24	73	13	60
Sorghum/pigeonpea intercrop (Sorghum 105 days, pigeonpea 180 days)	100	24	97	-	97
Sholapur[2]					
70-day first crop	75	17	81	0	81
91-day first crop	58	25	81	0	81
105-day first crop	58	11	72	5	67
Fallow	-	-	81	0	81

1. Average annual rainfall, 990 mm; 37 years' data.
2. Average annual rainfall, 700 mm; 36 years' data.

season intercrop can be grown just as satisfactorily as a 91-day crop.

Table 3 also gives a similar analysis for a drier Vertisol area (Sholapur, with 700 mm average annual rainfall). It can be seen that even for a very early-maturing rainy-season crop of only 70 days, there is only a 75% probability of success. For longer season crops, this reduces to 58%. However, because the most-assured rains occur at this location toward the end of the rainy season, a rainy-season crop has little effect on postrainy-season cropping, which, after fallow, has an 81% probability of success.

These results from both drier and wetter Vertisol areas suggest that this modeling approach may be a useful adjunct to field experimentation, by providing further information on the likely long-term suitability of different systems.

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Discussion

Ahmed: To what extent can you mechanize and how would you mechanize in the inter- and relay-cropping systems developed at ICRISAT?

Willey: Certain aspects of mechanization are probably more easily managed in intercropping than often imagined. The key to this management is to confine the different crops to separate rows, the system commonly practiced in India. Seeding can easily be done in separate rows, as can topdressing with nitrogen on those rows that need it. Even herbicides could be directed to specific rows if really needed. The major difficulty, however, will continue to be mechanized harvesting. Crops that are established by transplanting seedlings, such as chillies, can be relay planted with fewer problems; but, in the case of others, there can be some operational difficulty.

Cooper: Are the long-term effects of the different cropping systems being evaluated with regard to whether they might modify fertilizer requirements and recommendations?

Willey: This type of work has only recently been started, and there is a great need to get more information on this topic than is currently available. The role of the legume (or N fertilizer) and the effect of continuous P application on P status are important. This work is being done on both Vertisols and Alfisols at ICRISAT.

Land and Water Management Practices for Vertisols

Earl Burnett[1]

Abstract

Land- and water-management practices for Vertisols to maximize crop production or to reduce soil *erosion are constrained by climate, including rainfall and temperature, and by soil physical and chemical characteristics. Most Vertisols in the United States occur in the south, primarily in Texas, Mississippi, and Alabama. The climate of the region varies from semi-arid on the west to humid on the east and is characterized by long, hot summers and mild winters. Water deficits in the soil occur almost every year in the western part of the region and infrequently in the east. Crop yields are affected adversely by the soil's water deficit.*

Soil erosion has been a major problem on Vertisols in the United States since they were first cultivated. Management practices to reduce erosion while maintaining crop yields have been developed for these soils and climatic conditions; such practices include terracing, crop rotations, fertility management, graded furrows, narrow rows, wide-bed systems, conservation tillage, and runoff-water management. This paper reviews the management problems of Vertisols and discusses research approaches to Vertisol management for the southern United States.

Résumé

Pratiques de gestion des sols et de l'eau chez les Vertisols : *Les pratiques de gestion des sols et de l'eau pour les Vertisols, afin d'augmenter la production agricole ou de réduire l'érosion du sol, sont affectées par le climat, y compris les précipitations et la température, et par les caractéristiques physiques et chimiques du sol. La plupart des Vertisols aux Etats-Unis se trouvent dans le sud, particulièrement au Texas, au Mississippi et en Alabama. Le climat de la région varie de semi-aride à l'ouest à humide à l'est, et se caractérise par des étés chauds et longs, et des hivers doux. Les déficits d'eau dans le sol se produisent presque tous les ans dans la partie ouest de la région et de temps en temps à l'est. Les rendements de culture sont touchés défavorablement par le déficit d'eau du sol.*

Aux Etats-Unis, l'érosion du sol représente le problème le plus grave sur les Vertisols lorsqu'ils sont mis en culture. Les pratiques d'aménagement pour réduire l'érosion, tout en maintenant les rendements des cultures, ont été développées pour ces sols et ces conditions climatiques; de telles pratiques englobent l'aménagement de terrasses, les rotations de culture, la gestion de la fertilité des sols, des sillons en pente douce, des rangées serrées, des planches larges, le labour de conservation et la gestion de l'eau du ruissellement. Cet article passe en revue les problèmes de gestion des Vertisols et examine les démarches de recherche relative à la gestion des Vertisols dans le sud des Etats-Unis.

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Introduction

Management of Vertisols throughout the world has historically been difficult. These soils are intractable when dry, poorly aerated and sticky when saturated, and frequently highly erodible when they occur on sloping terrain; they have low infiltration rates when wet. In the subhumid and semi-arid areas where they commonly occur, Vertisols tend to be droughty, even though they have a high water-holding capacity. This high water-holding capacity, however, enables the maturation of a marginal crop under adverse moisture regimes, so that subsistence agriculture exists on Vertisols in regions of erratic rainfall. In addition, Vertisols can be very productive under well-watered conditions, including irrigation. Good land and water management is the key to maintaining crop yields under both limited and adequate rainfall conditions.

This paper reviews some of the land- and water-management problems of Vertisols, discusses current Vertisol management, and presents recent research approaches to Vertisol management in the United States.

Location of Vertisols in the United States

Vertisols occur mainly in semi-arid parts of southwestern Texas, in subhumid parts of central Texas and southern Oklahoma, and in humid areas of southeastern Texas near the Gulf of Mexico and in Mississippi and Alabama (Buol 1973). Smaller areas of Vertisols also occur in Arkansas, Puerto Rico, the Virgin Islands, and in several western states. The location of Vertisols in the south is shown in Figure 1. (Not shown are clayey soils with vertic properties in other soil orders that have similar management problems to Vertisols.) The total land area occupied by Vertisols in the southern United States approximates 7.2 million ha (Buol 1973).

The climate in these areas of Vertisols is extremely varied, although most of the region has frost-free periods in excess of 6 months each year and abundant radiant energy for plant growth. Mean annual air temperatures range from 15 to 21° C (Fig. 2). Soil temperatures parallel air temperatures closely, with most of the Vertisols in the thermic or hyperthermic class.

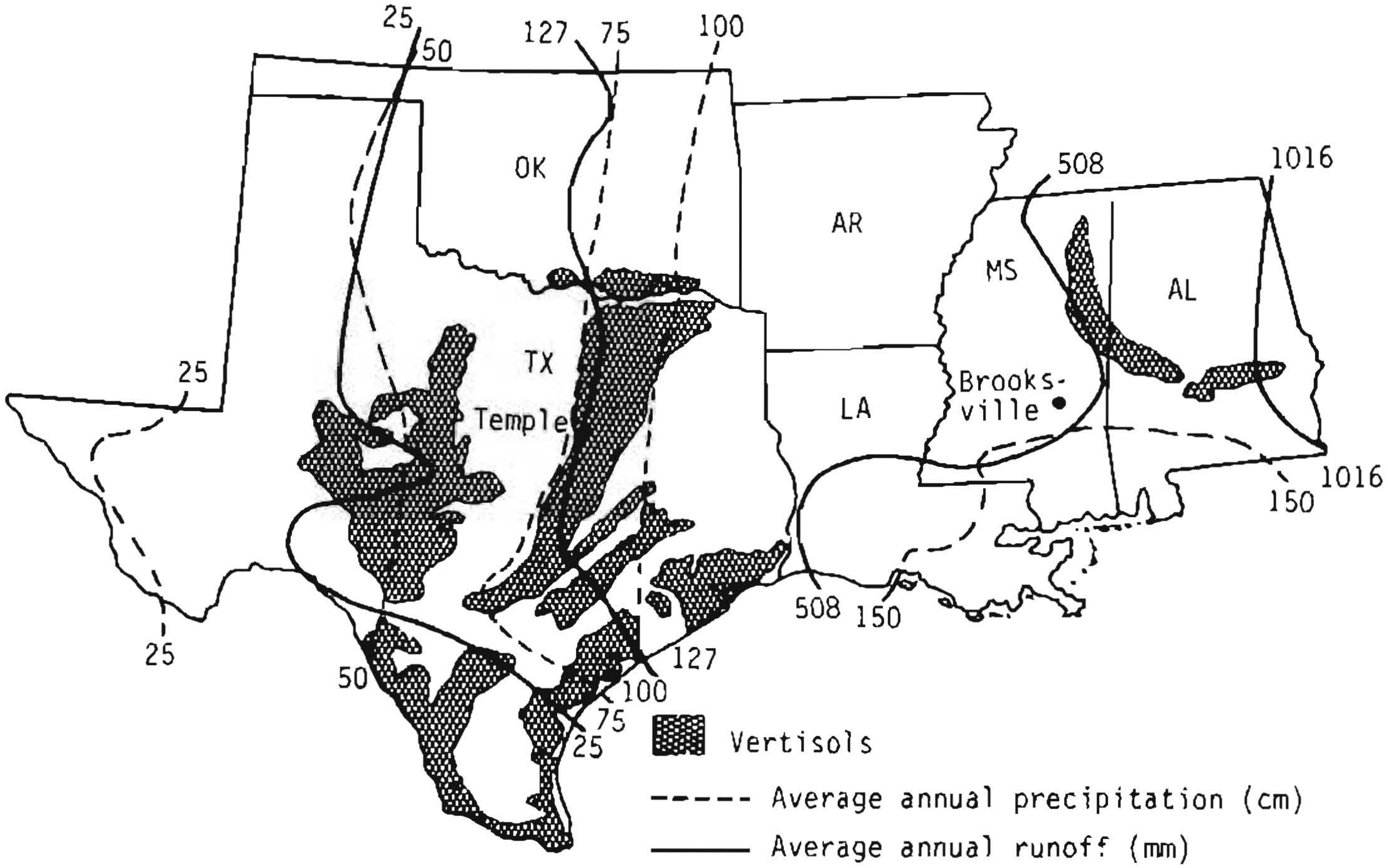

Figure 1. Location of Vertisols in the southern United States, with average annual precipitation isohyets (after Buol 1973) and average annual runoff (after U.S. Water Resources Council 1978).

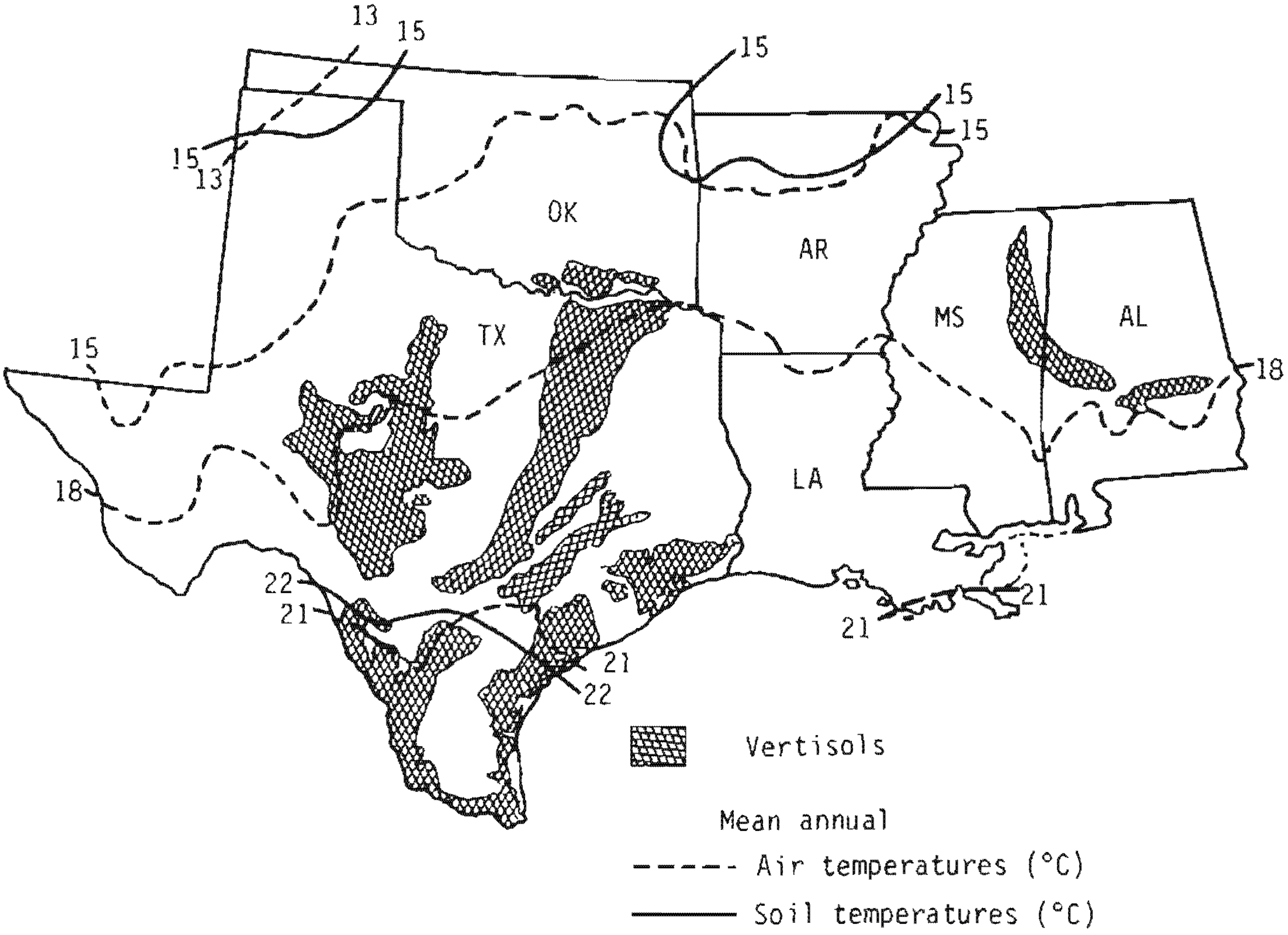

Figure 2. Mean annual air and soil temperatures in the southern United States in relation to location of Vertisols (after Buol 1973).

The major portion of Vertisols occurs between the 50-cm and 100-cm rainfall isohyets (see Fig. 1). This semi-arid to subhumid region is characterized by mild, moist winters and hot, dry summers. Average monthly precipitation at Temple, Texas, is typical of the region (Fig. 3); a bimodal distribution occurs with a rainfall peak in spring, a depression in summer, and a secondary peak in early autumn. The average precipitation is misleading, however, because there have been several extremely large precipitation events; in addition, precipitation in this region is highly erratic (see Fig. 3). Figure 4 illustrates that all months have a probability of 60% or more of receiving at least 25.4 mm precipitation, but only 2 months (April and May) experience a probability greater than 50% of receiving 76.2 mm or more. This suggests that crops may frequently experience water deficits if grown during the summer.

Smaller areas of Vertisols occur in the humid portion of the southern United States, primarily in Mississippi and Alabama. Precipitation in this region is higher and less erratic than in the western Vertisol region (see Figs. 1 and 3). Although crops are subject to occasional water deficits because of the soil's low water release rate coupled with high evaporative demand, in this region excess water is a more pervasive problem than water deficit, especially in spring.

Management Problems

Runoff and Erosion

Low infiltration rates when the surface soil is wet and high rainfall intensities during thunderstorms result in large amounts of storm-water runoff in much of the Vertisol region. From 25 to 127 mm

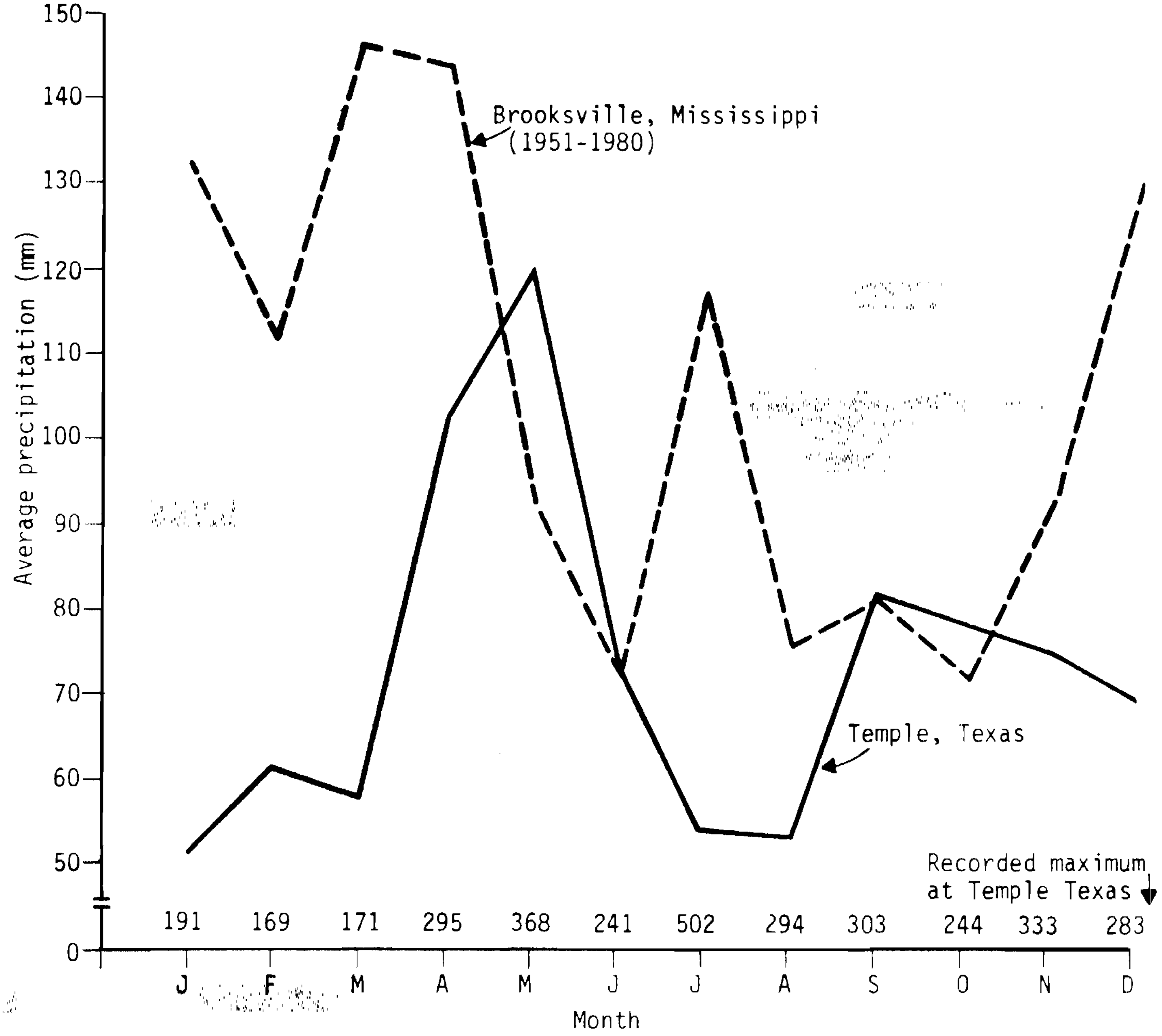

Figure 3. Mean monthly precipitation in semi-arid and subhumid Vertisols (represented by Temple, Texas; after Dugas 1983) and in humid Vertisols (represented by Brooksville, Miss.; after Hairston et al. 1984b).

$a^{-1}$of storm runoff occurs in the Texas Vertisol region, whereas 508-1016 mm a^{-1} occurs in the Mississippi-Alabama Vertisol region. Runoff is most prevalent with clean-tilled, row-crop cultivation.

The Vertisols of the United States are highly erodible, and erosion rates have been excessive on sloping terrain. Predominant use of these soils during the first 50-60 years of cultivation was production of cotton and feed grains. Most of the land was farmed in straight rows without regard to slope (Hill et al. 1944). This practice resulted in severe sheet erosion, with consequent adverse effect on soil productivity. With time, much of the steeper land was taken out of cultivation and returned to trees in the humid areas and to grassland in the less-humid areas. Currently, the land slope of cultivated areas is usually less than 5% in the eastern humid area, and less than 3% in the west. In addition to taking the steeper land out of crop production, such conservation practices as terracing, contour farming, and crop rotation were developed to reduce soil erosion. Even so, soil erosion continues to be a major problem on these Vertisols.

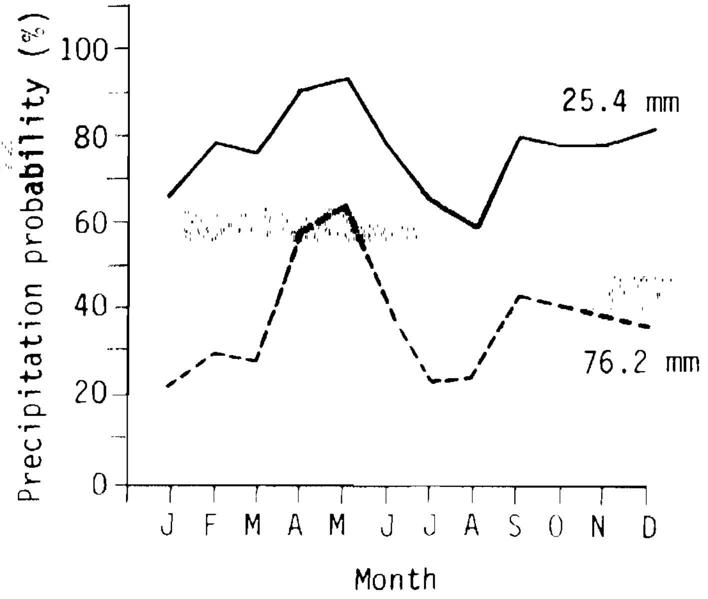

Figure 4. Probability of occurrence of at least 25.4 mm or 76.2 mm of monthly precipitation at Temple, Texas (after Dugas 1983).

Water Intake and Internal Drainage

Infiltration rates of Vertisols vary from almost infinity to extremely low, due in part to the high coefficient of expansion and contraction. Large soil-volume changes accompany changes in soil-water content: shrinkage curves of the Houston Black clay surface soil indicate volume changes of up to 40% by drying from field capacity to -15 bar water potential (Johnston and Hill 1945). As drying proceeds, shrinkage cracks develop. These cracks may be 5-7 cm wide and 60 90 cm deep at the end of a dry growing season with row crops. While the cracks are open, the water intake rate is very high. Expansion of the swelling clay soil begins immediately upon wetting, with an attendant decline in infiltration rate. As the soil approaches saturation, the infiltration rate drops to 2 3.5 cm day^{-1} (Ritchie et al. 1972). Therefore, precipitation rates in excess of about 2.5 cm day^{-1} will result in runoff after the swelling clay soils are near saturation.

If the soil remains saturated with the infiltration rate of about 2.5 cm day^{-1}, poor internal drainage contributes to soil-aeration problems, with a consequent detrimental effect on plant growth. This situation occurs most frequently in the early spring growing season and particularly in the humid Vertisol region.

Soil Tilth

The alternating expansion and contraction of Vertisols on wetting and drying also contributes to the so-called "self-mulching" characteristic of many Vertisols. In swelling clay soils, a vigorous disruptive action is associated with swelling. As water is absorbed, the volume increases, cohesion is diminished, and any unconfined mass of the soil exhibits warping, cracking, exfoliation, and various degrees of disruption (Smith 1959). As a result of this process, these surface soils may be well-aggregated and porous after cyclic wetting and drying. Under dry conditions, it is difficult to achieve adequate seed-soil contact, and crop stand establishment may be impaired. If high-intensity precipitation occurs after seeding, the aggregates slake down, and a crust forms as the soil dries. This crust can reduce emergence of planted crops.

Soil Fertility

The Vertisols of the United States were considered to be very fertile when first put into cultivation. While organic-matter levels of these soils were not extremely high, compared with the Prairie soils of the Corn Belt, organic-matter content was distributed fairly uniformly to considerable soil depths. Organic-matter levels in Houston Black clay at Temple, Texas, both cropped and uncropped, are shown in Table 1. It is of interest to note that the distribution of organic matter is relatively uniform at depths below 30 cm. These levels of organic matter were

Table 1. Organic-matter levels of Houston Black clay in land covered by native grass or cultivated, Temple, Texas (from Smith et al. 1954b).

	Organic-matter level (%) in	
Soil depth (cm)	Native grassland	Cultivated land[1]
0-15	5.09	1.98
15-30	3.17	1.84
30-45	1.97	2.03
45-60	1.69	2.24
60-75	1.72	1.55
75-90	1.72	1.63

[1] Cultivated for 60-70 years prior to collection of samples for analysis.

adequate to provide sufficient nitrogen for low to moderate crop yields during the first half-century of cropping; today, however, increased crop-yield responses to nitrogen fertilizer are obtained using intensive-management systems. Part of the decline in fertility is a result of past accelerated erosion when few conservation practices were used. The Vertisols of the United States are generally low in phosphorus and sufficient in potassium in the western Vertisol region, but may be deficient in both phosphorus and potassium in the humid region.

Management Practices for Soil and Water Conservation

Early Practices

Conservation practices to control water runoff and soil erosion on United States Vertisols have ranged from structural measures, such as contouring and terracing, to vegetative practices, including crop rotations. Terraces, contour farming, grassed waterways, crop rotations, and other conservation practices were studied at the Blacklands Experimental Watershed near Waco, Texas, beginning in 1938 (Baird and Potter 1950, Baird 1964, Baird et al. 1970), to observe their effect on water runoff and soil erosion. Conservation practices were found to reduce erosion and peak rates of runoff, but the effects of terraces on amounts of runoff were not consistent. If runoff-producing storms occurred when the soils were moderately dry, terraces sometimes reduced amounts of runoff; if large amounts of rainfall occurred when the soils were wet, however, terraces increased runoff. The inconsistencies may be explained by the following: (1) terraces reduce the velocity and increase the travel distance of runoff water, thus allowing more time for water to infiltrate; (2) terrace channels are frequently wetter than interterrace areas, thus contributing to increased runoff volumes; and (3) terrace construction increases the average field slope, with the steepest area being near the terrace channel, thus increasing runoff volume.

Land-use practices may also affect volume and rates of runoff, and, in addition, tillage operations affect runoff amounts by changing water-retention characteristics. The combined effect of terraces, land use, and tillage on runoff becomes very complex. In most cases, some reduction in amounts of runoff can be expected with a complete conservation system, including terraces and crop rotations. For instance, Baird (1964) found that using terraces and other conservation practices reduced sediment yield (from a total of 523 to 62 t ha^{-1}), but only slightly affected water runoff (from a total of 369 to 335 cm). Some of the soil that was eroded was deposited in terrace channels and grassed waterways; therefore, the terraces and grassed waterways probably had a greater effect on reduction of sediment yield than did other conservation practices.

Other studies in the Texas Blackland Conservation Experiment Station assessed the effect of crops on runoff and erosion (Hill et al. 1944, Smith et al. 1954a, Smith and Henderson 1967). In one study (Table 2), little difference in runoff or erosion was evident when the land was cropped to either maize or cotton. Thus, it cannot be expected that cotton or maize will give much protection to the soil surface during the critical months of March, April, May, and September. In contrast, small grain crops or sweetclover, or a combination of the two, can provide good protection against soil losses during the spring months. Two-year crop rotations of row crops, followed by a small grain crop with sweetclover, reduced soil losses to about half that from a continuous row crop, either maize or cotton (Smith et al. 1954a).

Crop rotations on Vertisols can have residual effects on water intake and soil loss, which last for several years. Adams (1974) studied the residual effects of three rotations that had been applied for 12 years. At the end of the rotation study, for the next 3 years, all plots were cropped to forage sorghum as hay crop. Water intake and soil loss were measured annually for 3 years, using a falling-drop infiltrometer on undisturbed soil cores. The results (Table 3) indicate that in the first 2 years, water intake was lowest and soil loss highest from continuous crop-

Table 2. Effect of crop on water runoff and soil erosion on Houston Black clay, Temple, Texas, 1942-1951[1] (from Smith et al. 1954a).

Crop	Runoff (cm)	Soil loss (t ha^{-1})
Cotton	4.6	8.7
Maize	5.6	7.8
Oats	3.3	1.1
Sweetclover	5.3	3.8

[1] Average annual rainfall = 81.8 cm.

Table 3. Water intake and soil loss (suspended sediment in runoff) from Houston Black clay following termination of rotations in 1964[1], Temple, Texas (from Adams 1974).

		Water intake[2] (cm core^{-1})			Soil loss[2] (g core^{-1})		
Cropping sequence	1964 crop	1965	1966	1967	1965	1966	1967
Continuous grain sorghum	Grain sorghum	1.40 b	1.58 b	2.17 a	1.89 a	1.18 a	0.65 a
Oats-grain sorghum	Oats	2.60 a	2.26 b	2.23 a	0.78 b	1.07 ab	0.69 a
	Grain sorghum	2.49 ab	–	2.00 a	1.77 a	–	0.95 a
Mean		2.54	2.12	1.28	0.82		
Fescuegrass-fescuegrass-grain sorghum	Fescuegrass (1st yr)	2.45 ab	3.51 a	2.80 a	0.66 b	0.57 c	0.54 a
	Fescuegrass (2nd yr)	3.20 a	3.31 a	1.86 a	0.78 b	0.58 c	1.05 a
	Grain sorghum	2.33 ab	2.47 b	2.55 a	0.66 b	0.72 bc	0.78 a
Mean		2.66	3.21	2.40	0.70	0.62	0.79

1. Crop rotations started in 1952, and were discontinued after the 1964 crop.
2. Means for each year followed by the same letter are not significantly different at $P = 0.05$.

ping with grain sorghum. Beneficial effects were noted from the fescuegrass rotations up to 2 years after the rotations were discontinued.

Recent Developments in Management Practices

The conservation-management practices developed for these Vertisols have been reasonably effective in reducing crop losses from soil erosion. After World War II, however, low prices for nitrogen fertilizer led to farmers abandoning soil-building legumes in their crop rotations. In addition, the development of large multirow equipment made the farming of terraced land with numerous point rows more difficult, so that many farmers either destroyed their terrace systems or performed tillage operations across the terraces. In many cases, the cropping pattern evolved into a continuous row-crop sequence. A few growers now include small grains (either wheat or oats) every second or third year. As a result, soil erosion is still a major problem throughout the Vertisol region. To meet the new demands for maximal crop production and to reduce soil erosion, other land- and water-management practices have been developed; these include parallel terracing, graded furrows, narrow crop rows, wide-bed systems, conservation tillage, double cropping, improved fertility management, and supplemental irrigation. Brief descriptions of these practices follow.

Parallel terraces. Parallel terracing is a water-management practice that has become very prominent in the semi-arid region and, to a lesser extent, in the subhumid and humid Vertisol regions. There must be some mechanism to provide surface drainage for storm runoff during periods when the rate of precipitation exceeds that of water intake. In a terrace system, conventional or parallel, this is accomplished with graded channels. In a parallel system, rows are laid off parallel to the terrace, and, when the land is ridged, each row functions as a miniature terrace, conducting water to the outlets without allowing it to concentrate in the terrace channels. Frequently, some land planing or smoothing is necessary to eliminate low spots to maintain the channel grade. Point rows can be reduced or eliminated in a parallel terrace system. Maintenance of terrace height is critical to avoid downslope gullying by overtopping runoff water.

Graded-furrow system. Another alternative water-management practice to conventional terraces is the graded-furrow system, designed to convey all runoff originating in the furrow to a waterway. Because this system eliminates or reduces the number of terraces, it is compatible with large, multirow farm equipment. Such systems have been investigated at a number of places throughout the southern United States (Carter and Carreker 1969, Richardson et al. 1969, Harris and Watson 1971, Richardson 1973). Harris and Watson (1971) found graded rows to be stable erosion-control structures that, when properly constructed and maintained, could reduce rill erosion and failed only when reverse row grades occurred. In Mississippi, graded rows with 0.3% furrow slopes and 2.5 to 10% cross slopes reduced erosion about 44% over up-and-down hill rows (Carter and Carreker 1969). On Vertisols in Texas, with a uniform slope of 1%, runoff increased by 50% and soil loss by 75% when furrow length increased from 104 to 284 in graded-furrow systems (Table 4).

Later studies compared the effects of graded furrows and terraced watersheds on runoff, erosion, and tillage efficiency (Richardson 1973). The graded-furrow system controlled erosion, reduced tillage times, and reduced runoff. Less runoff on the graded-furrow watershed was due to more uniform distribution of excess water. On the terraced watershed, excess water concentrated in the terrace channels. Erosion on both watersheds was within acceptable erosion tolerances for Houston Black clay soil. Tillage rates were 21% faster on the graded-furrow areas.

The graded-furrow system requires that furrow ridges be maintained at all times to convey runoff water. Operating farm equipment on these ridges is not appreciably more difficult than on conventionally tilled areas, provided the row width is not less than 1 m.

Narrow rows. Historically, row spacing in the United States was around 100 cm. This spacing for row crops was originally based on the space needs for equipment pulled by draft animals. As farming became more mechanized, such wide rows were no longer necessary and attention was given to reducing row spacing to maximize crop production (Mitchell 1970, Adams et al. 1976). Other advantages from cropping on narrow-row spacing include earlier attainment of complete ground cover for weed control and protection of the soil surface from the impact of raindrops, thereby reducing erosion. In addition, evaporation from the soil surface is reduced.

The effect of narrow-row spacing with grain sorghum grown on Houston Black clay on ground cover, grain yields, runoff, and erosion was reported by Adams et al. (1976, 1978). They found that sorghum planted in narrow, 50-cm rows establishes a more complete canopy earlier than when conventional row spacing (100 cm) is used: at 35 days after emergence, ground covered by canopy was 19% with 50-cm row spacing but only 8% with 100-cm spacing; at 63 days it was 81 to 46% (Adams et al. 1978). The improved plant canopy intercepted 12% more radiant energy and resulted in grain yield increases of 18 to 25% (Adams et al. 1976). The earlier attainment of more complete ground cover also reduced runoff and erosion (Table 5); however, under semi-arid conditions, wide-row spacings permit the plant roots to obtain water from a larger volume of soil, thus contributing to increased yield.

Table 4. Effect of row length on average runoff volumes and soil loss[1] in graded-furrow plots, Temple, Texas (from Richardson et al. 1969).

Row length (m)	Runoff (cm)	Soil loss (t ha⁻¹)
104	2.7	2.6
158	3.2	3.1
284	4.1	4.6

1. Average of 3 years, 1965-1967.

Wide-bed, narrow-row systems. A potential problem of narrow-row production systems is the difficulty of cultivation and consequent weed-control problems. This is particularly true for ridge planting in graded-furrow systems and where effective herbicides for weed control are not available. As a consequence, wide-bed, narrow-row systems have been developed to capitalize on the potential for crop yield increases and still provide the needed surface drainage for storm runoff as in the graded-furrow system (Arkin et al. 1978, Morrison and Gerik 1983) (Fig. 5).

The wide beds consist of slightly raised cropping strips between widely spaced furrows. The width of the beds is determined by the farm equipment available to the operator and the required water-carrying capacity of the furrows so that effective drainage is provided but the beds are not overtopped. The beds can be either flat-topped or slightly crowned. They are formed across the general slope and are compatible with a parallel terrace system. The furrows between the beds allow for controlled surface drainage of storm runoff to grassed waterways. In addition, wheel traffic is confined to the furrows, resulting in compacted traffic lanes, while the cropped areas are not subject to compactive forces. This system saves energy by (1) reducing tractor

Table 5. Effect of row spacing of grain sorghum on water runoff and soil loss from Houston Black clay soil in 1973 (from Adams et al. 1978).

Date	Days after emergence	Rainfall (cm)	Runoff (cm)		Soil loss (t ha^{-1})	
			50-cm row spacing	100-cm row spacing	50-cm row spacing	100-cm row spacing
		Before full development of plant canopy (ground cover)				
10 Mar	- 9	2.5	0.1	0.1	0.1	T[1]
24 Mar	5	4.2	0.5	0.4	0.6	0.4
2 Apr	14	1.5	0.3	0.3	0.3	0.4
15 Apr	27	1.4	T[2]	T[2]	T[1]	T[1]
5-6 May	47-48	6.5	0.9	0.7	1.4[2]	0.8
Subtotal		16.1	1.8	1.5	2.4	1.6
		After development of plant canopy (ground cover)				
1-3 Jun	74-76	7.2	0.6	2.8[2]	1.8	5.0[2]
5 Jun	78	2.9	0.9	1.4[2]	1.0	1.8
15 Jul	118	3.0	0.1	0.5	T[1]	T[1]
Subtotal		13.1	1.6	4.7	2.8	6.8
Annual total		29.2	3.4	6.2	5.2	8.4

1. T = trace; 0.05 ha^{-1} soil loss, 0.01 cm runoff.
2. Difference between means for these dates significant at the 5% level, according to t-test of paired means.

rolling resistance in compacted furrows; (2) requiring less pulling force for tillage in the uncompacted cropping strips; and (3) reducing the tillage area about 20% by the presence of untilled furrows. The beds may need to be rebuilt periodically, depending upon soil type and tillage needs. Wide beds improve erosion control on sloping land, and surface drainage on nearly flat land.

With wide beds on 2-m centers, row spacing varies from two rows per bed with 1-m spacing between the rows, to 8 rows per bed with 20-cm spacing between rows, depending upon the crop to be grown (see Fig. 5). Crop yields increased as interrow spacing decreased (Table 6), which is comparable to findings under flat cultivation (Adams et al. 1976). Other investigators have shown similar crop yield increases in a wide-bed, narrow-row system (Parish and Mermoud 1974, Kampen and Krishna 1978).

Conservation tillage. The practice of terracing and contouring with clean tillage does not provide adequate erosion control on some soils with moderate to steep slopes. In addition, many farmers plow across their terraces and leave the land flat, rather than use furrows and ridges on contour. Consequently, conservation tillage is being advocated as an erosion-control practice, with or without terracing. The term "conservation tillage" has been defined in various ways, but it is generally accepted to mean any tillage system that maintains crop residues on the soil surface to reduce wind and water erosion and to conserve moisture. It includes chisel-plow, ridge planting, stubble-mulch, and no-till practices. Some people use reduced tillage or minimum tillage as synonyms for conservation tillage, but the terms should not be so used because the quantity of residue retained may not be adequate to provide acceptable erosion control.

While conservation tillage systems have good potential for erosion control, crop yields may be reduced on poorly drained soils, such as Vertisols. This may be due to cooler soil temperatures, which reduce crop germination, emergence, and early growth. Research has shown that the problem is reduced using no-till on raised wide beds (Morrison and Gerik 1983). The raised beds permit drainage

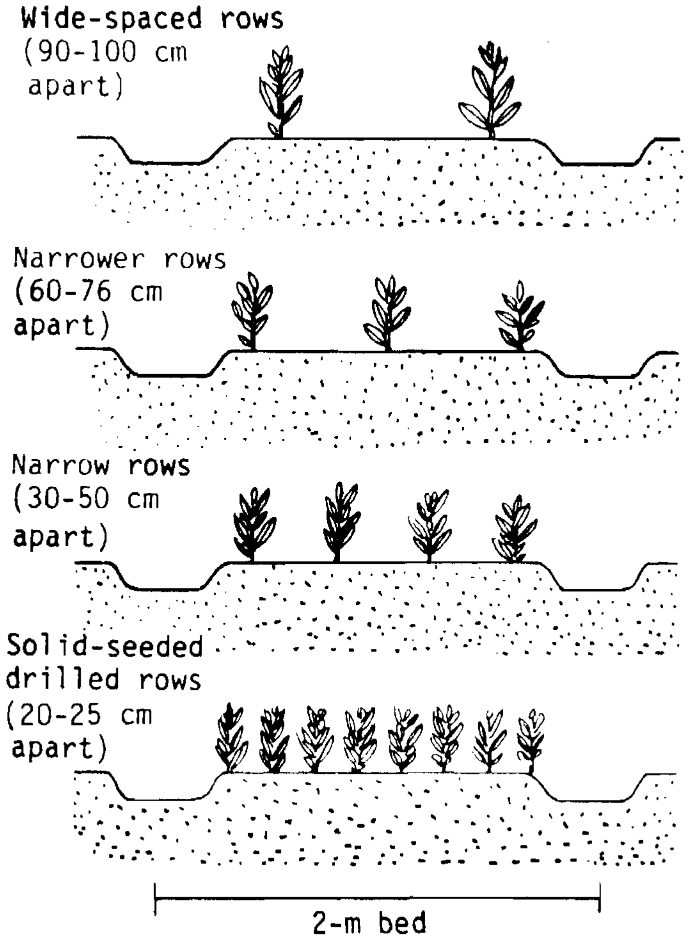

Figure 5. Wide-bed, narrow-row spacing configurations (from Morrison and Gerik 1983).

and earlier surface drying during the critical planting season. Weed control in wide-bed, no-till systems is a critical problem, and additional research is needed before the practice will gain widespread acceptance.

Double cropping. The practice of double cropping, to maximize crop yields with available rainfall, is confined to the humid Vertisol region or to areas with irrigation potential (Sanford 1982, Hairston et al. 1984a and 1984b). Double cropping soybeans and wheat has become an accepted practice in the southern United States, and it is used on Vertisols in Mississippi and Alabama. Sanford (1982) indicates that the advantages of this more intensive farming practice are (1) increased profits resulting from more complete use of land and other resources, (2) reduced soil and water losses from having the soil covered with a plant canopy during most of the year, and (3) increased use of soil-, water-, and energy-conserving tillage methods. With soybean-wheat double cropping, soybeans are planted after wheat on seedbeds prepared by chiseling or disking and harrowing, or are planted directly into the wheat stubble. In either case, wheat straw may or may not be burned before seeding the soybeans. Other crops that are used in double cropping are maize, grain sorghum, and, to a lesser extent, sunflowers.

Sanford et al. (1973), Sanford (1982), and Hairston et al. (1984a and 1984b) compared the effects of monocrop and double-crop production systems on water runoff and soil erosion, plant growth, crop yield, soil characteristics, and net returns. In one study, soybean yields were lower than normal because of low rainfall during the period; soybean yields were not affected by chiseling the previous fall season. Yields on monocrop minimum till (MIN) and no-till (ZERO) were consistently below monocrop conventional tillage (CON+ or CON) treatments. Double-crop (DUO) soybean yields were significantly less than all monocrop yields (Table 7).

Table 6. Effect of row spacing in a wide-bed, narrow-row system on grain sorghum yields at Temple, Texas (from Arkin et al. 1978).

Spacing treatment	Interrow spacing (cm)	Grain yields (kg ha^{-1})			
		1975	1976	1977	Mean[1]
Conventional flat cultivation	100	5490	4480	5890	5285
Wide-bed system (2 m)					
2 rows on 2-m bed	90-100	–[2]	5080	4890	4990 a
3 rows on 2-m bed	60-76	6380	5895	5980	6085 b
4 rows on 2-m bed	30-50	6720	6690	6045	6485 b

1. Means followed by the same letter are not significantly different from conventional at $P = 0.05$.
2. Not planted.

Table 7. Water runoff, soil loss, soybean yields, and net returns above total direct and fixed costs for five tillage systems in the Mississippi Blackland Prairie (after Hairston et al. 1984b).

Tillage system	Soybean yield[1,2] (kg ha^{-1})	Annual runoff (cm)	Annual soil loss (t ha^{-1})	Net returns[1] (\$ ha^{-1})
Monocrop				
Fall chisel + spring chisel, prepare seedbed, plant,cultivate (CON+)	1814 a	21.0	12.3	105.18
Spring chisel only, prepare seedbed, plant, cultivate (CON)	1778 a	19.4	7.8	131.75
Stubble-plant with no seedbed prepared, cultivate (MIN)	1338 b	14.6	6.7	51.28
Stubble-plant with no seedbed prepared, no cultivation (ZERO)	1253 b	21.1	6.5	59.48
Double crop				
Overseed or stubble-plant wheat, burn straw, no-till plant soybeans, cultivate (DUO)	1045 c (2976)[3]	11.5	2.5	315.02

1. 2-year average.
2. Means in a column followed by the same letter are not significantly different at $P = 0.05$, by Duncan's New Multiple Range Test.
3. Value in parenthesis is the wheat yield (at 13.5% moisture) in the double-crop system.

Even though double-crop soybean yields were lower, net returns from double cropping (DUO) were much higher than any of the monocrop systems, because of the added income from the wheat in the double crop system. Net returns from monocrop soybeans with minimum (MIN) or no-tillage (ZERO) were much lower than with the monocrop conventional tillage (CON or CON+) systems.

The double-crop (DUO) treatment was the most efficient in reducing runoff, with only 10% of the rainfall being lost as runoff. Similarly soil losses were much less from this treatment than from any of the monocrop treatments. The additional fall chiseling operation in the conventional (CON+) treatment increased erosion dramatically.

The reduced monocrop soybean yields will adversely influence farmer acceptance of no-till and minimum tillage practices. The wheat-soybean double-crop system is not only more profitable but is also more soil-conserving, and it provides a viable alternative to the continued use of conventional tillage practices, especially fall chisel plowing, that are contributing to excess erosion.

Fertility management. Crop yield response to commercial fertilizers, using conventional tillage practices, on Vertisols across the southern United States is quite predictable, and fertility management systems function adequately. Almost all crops respond to nitrogen and phosphorus on all Vertisols. Response to added potassium usually occurs in the humid Vertisol region but only infrequently in the subhumid and semi-arid Vertisols. Analysis of soil test results in Texas show that 70% of the samples were low or very low in P, while over 80% were medium to very high in K. Due to introduction of new crops and varieties, new production and management practices, including conservation tillage and no-till, and constantly changing economic conditions, recommended fertility management is constantly evolving in the United States.

Supplemental irrigation. There is little groundwater available for supplemental irrigation in the semi-arid and subhumid portions of the U.S. Vertisol region. Some surface-impounded water is used to irrigate rice in the Gulf Coast area. There is limited supplemental irrigation in other parts of the humid region. Since crops are subject to moisture deficits in almost every growing season even in the humid areas, the potential of small-scale impoundments for farm-size supplemental irrigation has been investigated. In addition to the hydrologic research at ICRISAT, Krishna (1982) and Krishna and Arkin (1984) have analyzed the hydrologic data from experimental watersheds in central Texas to evaluate the potential for improved water conservation, using furrow dikes or small surface impoundments. They concluded that more than 5 cm of runoff can be expected in the area between March and June. This runoff could be captured with furrow dikes or in a surface impoundment. Since the soil is usually near saturation in this area through late May, the benefit of water captured by furrow dikes may be questionable. The additional water could move below the root zone and become unavailable for plant growth. Only the runoff occurring in June or later is likely to benefit crop growth. The probability of significant runoff events after mid-June is quite low. In some cases, the water captured in small impoundments could be used to alleviate crop moisture deficits during critical growth stages. In situations where the surface topography is such that an impoundment can be economically constructed, supplemental irrigation could be successfully accomplished. In most of the subhumid Vertisols in Texas, such sites are infrequent. In most cases, potential sites would hold only 15 000–60 000 m^3, which is not adequate for extensive irrigation. Site-specific information regarding runoff probability, slope, and other factors must be taken into account in determining whether supplemental irrigation with small impoundments is feasible.

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Discussion

Dudal: Is the shrinking and swelling in Vertisols a hindrance to the construction and maintenance of terraces?

Burnett: Terraces in U.S. Vertisol regions are the broad-base type; hence, cracking has not been a major factor in terrace failures.

Sampath: Was the fertilizer applied per hectare the same in the 4 rows on the 200-cm bed system as well as in the 2 rows on the 200-cm bed system? Or were the differences in yields related to different quantities of fertilizer applied?

Burnett: Whether it was a 4-row or 2-row system, the per hectare plant population was not altered, and the fertilizer was applied at the same rate per hectare, for each treatment. Hence, the question of varied fertilizer application does not arise.

Nutrient Management in Vertisols in the Indian Semi-Arid Tropics

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Abstract

Nutrient inputs are one of the important components of improved farming systems for deep Vertisols within the assured rainfall area (>800 mm a^{-1}*) of the Indian semi-arid tropics (SAT). In this area, deficiencies of nitrogen, phosphorus, and zinc are the most common in the staple cereal crops. Fertilizer use remains low, apparently due to uncertainty over the reliability of responses to nutrient inputs. Another reason for the low fertilizer use has been the need to use several component inputs in combination (especially improved cultivars, fertilizers, and agronomic management) to ensure optimum benefits from each input. Our recent research has attempted to delineate the most responsive environmental situations, so that the farmer's risk can be minimized.*

At ICRISAT Center, yields of rainy-season sorghum were reliable. Grain yields of 5000 kg ha^{-1} *were consistently attained in six successive seasons, when nutrients were supplied; but, in the absence of fertilizer, grain yields were as low as 1500 kg* ha^{-1}*. Nutrient inputs were a much more important determinant of sorghum yield than variations in seasonal rainfall. Use of* ^{15}N*-labeled fertilizer has shown that rainy-season sorghum was quite efficient in the use of added fertilizer-N, except in the much wetter (1200 mm* a^{-1} *rainfall) than normal (800 mm* a^{-1}*) year where fertilizer-N was applied using traditional (local) means. Compared with improved application methods, uptake of N by the crop in this year was reduced from 45% to 30%, and losses (presumably as gases) increased from 7% to 25%. Because ICRISAT Center is located on the edge of the assured rainfall area, these results on the reliability of responses and losses of fertilizer have much relevance to the whole area, where annual rainfall rises to as high as 1300 mm* a^{-1}*.*

Preliminary research on phosphorus has confirmed earlier agronomic experiments indicating a lower requirement for fertilizer-P on Vertisols. Of particular interest are indications of the need to reevaluate soil-test procedures, and the modest rate of phosphorus fixation by Vertisols.

Past research has given major emphasis to determining the nutrient requirements of single crops. Needed in the future are two types of general approaches: research into variability in responses from year to year, especially as affected by water × soil × crop interactions, and long-term studies to assess strategies for maintenance of fertility. Specific subject areas of high priority are studies on N—both on the efficiency of fertilizer-N and on the potential benefits of legumes—and the need for phosphorus, especially in relation to long-term cropping systems (rather than for single crops). Both are suitable for network activities, within and outside India, because of the occurrence of similar and dissimilar environments across the SAT.

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Résumé

Gestion des éléments nutritifs dans les Vertisols des zones tropicales semi-arides de l'Inde : *Les apports des éléments nutritifs font partie des composantes des technologies améliorées pour les Vertisols profonds dans les régions tropicales semi-arides de l'Inde à pluviométrie assurée (>800 mm par an). Dans cette zone, des carences en azote, en phosphore et en zinc sont très courantes parmi les cultures de base. Pourtant, l'emploi d'engrais reste faible. L'incertitude de la fiabilité des réponses aux apports des éléments nutritifs est une des causes; une autre est le besoin d'utiliser des apports à composantes multiples, surtout la combinaison de variétés améliorées, d'engrais et de gestion, afin d'assurer des bénéfices optimums de chaque apport. Notre récente recherche a essayé de dégager les situations les plus bénéfiques afin de réduire les risques encourus par les paysans.*

Au Centre ICRISAT, les rendements en grain du sorgho ont régulièrement atteint 5000 kg de grains par hectare pendant six saisons successives, lorsque les éléments nutritifs étaient fournis. Mais, les rendements ont baissé à 1500 kg ha^{-1} *sans application d'engrais. Des variations dans les précipitations saisonnières étaient un facteur nettement moins important du rendement du sorgho que les apports des éléments nutritifs. L'utilisation de l'engrais* ^{15}N *a montré que le sorgho de la saison des pluies répond bien à l'apport supplémentaire de l'engrais azoté, sauf dans l'année plus humide (1200 mm par an) que la normale (800 mm) avec des moyen traditionnels d'application d'engrais azotés. En comparaison avec les méthodes d'application améliorées, l'assimilation de N par la récolte a été réduite de 45% à 30% et les pertes (probablement en forme de gaz) ont augmenté de 7% à 25%. Du fait que le Centre ICRISAT se trouve au bord de la région de précipitations assurées, ces résultats sont encore plus pertinents dans toute la région où les précipitations annuelles s'élèvent jusqu'à 1300 mm a*$^{-1}$*.*

Des recherches préliminaires sur le phosphore ont confirmé des expériences agronomiques antérieures indiquant une demande plus faible pour l'engrais P sur les Vertisols. Les indications de la nécessité de réévaluer des procédés d'analyse des sols, et le faible taux de fixation du phosphore par les Vertisols sont d'un intérêt tout particulier.

Une attention particulière a été portée à la détermination des besoins des éléments nutritifs en culture pure. Dans l'avenir, deux types d'approches seront nécessaires : (1) des études sur la variabilité annuelle dans les réponses, surtout due aux interactions eau × sol × culture et (2) des études à longue échéance visant à estimer les stratégies pour maintenir la fertilité. Des sujets spécifiques nécéssitant une recherche urgente sont des études sur N, relatifs à l'éfficacité de l'engrais et les bénéfices potentiels des légumineuses, et les besoins en phosphore, surtout en rapport avec les systèmes de culture à long terme (plutôt que pour les monocultures). Elles sont toutes les deux appropriées pour les activités de réseau, aussi bien en Inde qu'à l'extérieur, à cause de la combinaison d'environnements semblable et dissemblable au sein des tropiques semi-arides.

Introduction

The low nutrient status of most SAT soils has been recognized for several decades, but fertilizer use in rainfed agriculture across the SAT is very low, especially on the staple food crops. This low usage contrasts with the widespread realization by farmers of the benefits of nutrient inputs in irrigated agriculture in India (Tandon and Kanwar 1984); and, for Vertisols, the contrast is most marked, because nutrient inputs were identified very early as an important component of improved farming systems for deep Vertisols in the assured rainfall areas of India (Virmani et al. 1989; Willey et al. 1989). Even on Vertisols, farmers have been very cautious, however, in their adoption of fertilizer inputs for dryland agriculture. In this paper, we discuss some historical developments leading to the currently increasing awareness of the importance of nutrient inputs in dryland agriculture, and we show the effectiveness of nutrient inputs in the improved double cropping technology for Vertisols. Finally, we indicate the needs for future research on Vertisols, especially for network activities.

Nutrient Status of Indian Soils

Nitrogen, phosphorus, and zinc are the main elements that need to be added to soils to ensure satisfactory crop production in the SAT of India. These needs have been clearly demonstrated by many thousands of agronomic experiments, both at research centers and in farmers' fields (Kanwar 1972; Randhawa and Tandon 1982). Supporting evidence has been provided by extensive surveys involving tissue analyses of crops and the available nutrient status of the soils (IARI 1982). These complementary studies indicated that nitrogen deficiency in the staple cereal crops was almost universal, that phosphorus fertilizer was needed on about 50% of soils, and that zinc was the third important nutrient. The impetus for such extensive surveys of soil and crop nutrient status arose from the need to establish nutrient requirements of crops in extensive irrigated schemes.

Irrigated Agriculture

The combination of nutrient inputs, improved cultivars, and an assured soil moisture regime through irrigation have been the basis of the "green revolution" that has so markedly improved grain production in India. The acceptance of the importance of nutrients led to India being the third largest consumer of fertilizer-N in the world in 1981 (FAO 1985). Consumption in India was then 4.1 million tonnes (Sahai et al. 1982). Most of this fertilizer is applied in irrigated agriculture, and will be so in the short-term future because nutrient inputs are still less than the estimated needs in many irrigation areas (Jha and Sarin 1984).

Most of the research associated with irrigation schemes of the original green revolution aimed at increasing the production of rice or wheat, the premier food grains in India. Relevant to dryland agriculture, however, is one excellent example (Fig. 1), which shows the benefits of improved seed and fertilizer for grain sorghum—one of the two staple cereals grown by subsistence farmers in the drier agroclimates of the tropics. The yield of the traditional (local) long-duration and long-strawed sorghum cultivar was only about 1200 kg ha^{-1} without fertilizer-N, which contrasted with the satisfactorily high yield (>3500 kg ha^{-1}) with N fertilization from the short-statured, short-duration, improved cultivar (Swarna) and hybrids (CSH 1 and CSH 2); even without inputs of N, the yield of the improved cultivars was 50% more than that of the local; and the improved cultivars were much more responsive to inputs of N than the local cultivars.

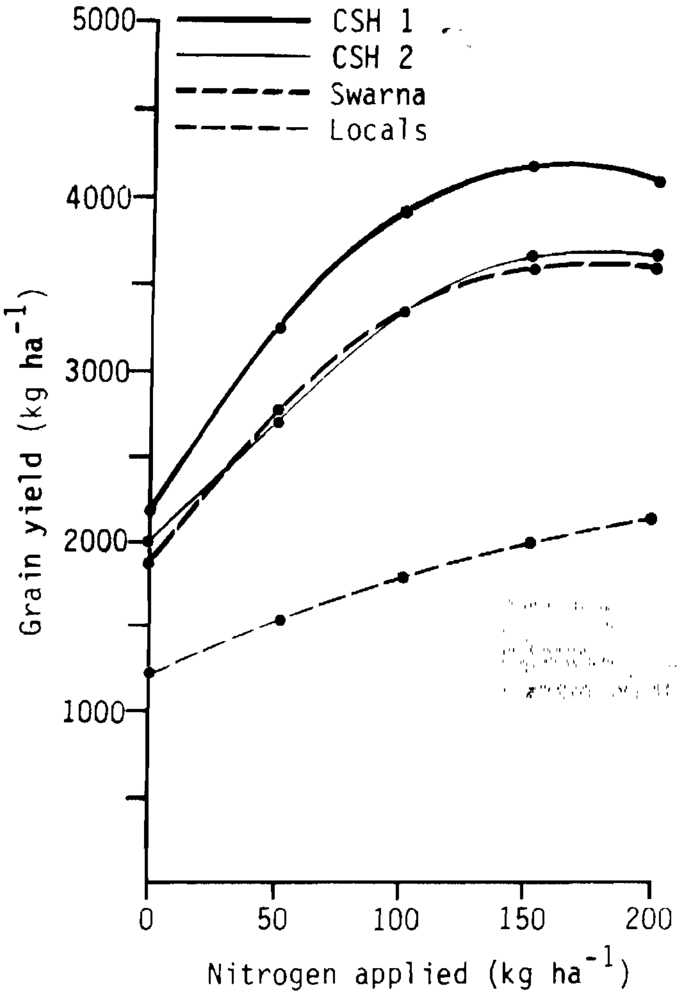


Figure 1. Comparative yield response of four sorghum cultivars to nitrogen application during the rainy season. Yield values given represent an average of 25 experiments conducted at various locations by the All India Coordinated Sorghum Improvement Program, during 1965-70 (Source: Singh et al. 1972).

These results, and many others since, have amply demonstrated the excellent response of improved cultivars to nitrogen inputs when the soil moisture regime is assured throughout the life of the crop; but the responses are much less certain under the variable moisture regimes of dryland farming areas.

Rainfed Agriculture

The potential benefits of nutrient inputs in dryland agriculture have come to be recognized only within about the past 10–15 years; their recognition was much earlier in irrigated agriculture. Perhaps the major reason for this slow recognition was the essentiality of irrigation for the heart of the green revolution in India – in the near-arid environment of the Punjab. Regardless of the cause, the view prevailing earlier was that the major factor limiting improved productivity in rainfed agriculture was the lack of a reliable moisture regime, due to unreliable rainfall. Drought was perceived to limit productivity much more than nutrient deficiencies. The recent change in views is indicated in the conclusion that nutrients are the most important component of improved systems for rainfed agriculture, and that their importance had not been adequately recognized (Kanwar 1981).

Acceptance of the need for nutrients is derived from many experiments showing good responses (e.g., Table 1). Similarly, at ICRISAT Center, initial attempts at developing an improved system for deep Vertisols showed the additive effect of improved nutrients, agronomy, and cultivars on yields of rainy-season cereals (Table 2). Nevertheless there remains some caution over the use of fertilizers, because of variability in responses between years and locations (Table 3). In interpreting these results, a response of about 3 kg grain $(\text{kg N})^{-1}$ applied is required to cover the costs of fertilizer, and farmers require a 2.5–3.0 fold return (i.e., 8–9 kg grain $[\text{kg N}]^{-1}$) to interest them in making an input (Tandon 1980).

Table 2. Effects of step-by-step improvement in cultivar, fertilizer, and land management on yields of maize grown in the rainy season on a deep Vertisol, ICRISAT Center, 1976 (ICRISAT 1977, pp.172).

		Fertilizer	
Variety	Land management	Traditional (FYM)[1]	Improved (NPK)
Traditional	Traditional	450	1900
	Improved	660	2610
Improved	Traditional	630	2220
	Improved	960	3470
LSD P = 0.05		474	

1. FYM = farmyard manure.

Table 1. Responses of rainfed sorghum to optimum or near-optimum levels of nitrogen application in field experiments in India in the rainy season (Tandon and Kanwar 1985).

No	Soil (trials averaged)	Location (cultivars)	Yield of zero N plots (t ha^{-1})	N level (kg ha^{-1})	Response (kg grain $[\text{kg N}]^{-1}$)
1	Alfisol (8)	Hyderabad (Hybrids)[1]	1.35	80	21.6
2	Alfisol (3)	Vizianagaram (CSH 1)	2.67	100	21.9
3	Vertisol (2)	Hyderabad (CSH 6)	1.18	120	28.5
4	Vertisol (2)	Dharwar (CSH 1)	2.39	100	14.2
5	Vertisol (8)	Akola (CSH 1)	1.35	60-80	24.2
6	Vertisol (5)	Akola (CSH 1)	1.47	100-120	16.7
7	Vertisol (3)	Dhule (CSH 1)	2.97	100	12.7
8	Vertisol (2)	Kohlapur (CSH 1)	2.39	100	17.2
9	Vertisol (2)	Nagpur (CSH 1)	1.88	75	24.2
10	Vertisol (3)	Parbhani (CSH 5)	3.11	120	20.6
11	Vertisol (3)	Kota (CSH 1)	0.77	75	10.1
12	Vertisol (3)	Rajkot (CSH 1)	1.37	90	14.8
13	Vert-Alf (5)	Jhansi (Mau T1, T2)	1.22	60-80	13.6
14	Mollisol (6)	Pantnagar (CSH 1)	2.60	80-100	11.9
15	Entisol (6)	New Delhi (CSH 1)[2]	2.66	60	24.3
16	Entisol (4)	New Delhi (CSH 1)[2]	0.82	100	16.0

1. Hybrids CSH 1, CSH 5, CSH 6.
2. Protective irrigation when needed; Inceptisols/Entisols both occur.

Table 3. Summary of response of rainy season crops to fertilizer-N (Rao and Das 1982).

Crop	Range of response (kg grain [kg N]$^{-1}$)
Sorghum	3.4-43.4
Pearl millet	2.1-24.8
Finger millet	5.0-42.4
Maize	4.1-67.4
Rice	4.5-33.9
Setaria	5.9-17.9
Sunflower	1.5-22.6
Castor	2.9-7.2
Groundnut	1.3-6.0
Linseed	1.2-11.5
Sesamum	1.3-5.0

Fertilizer Use in Rainfed Agriculture

Despite the encouraging results shown in Tables 1 and 2, the adoption of fertilizer in dryland agriculture in India has been particularly slow. Over 1977–79, the average input of nutrients in the dryland districts of the country was only 18.5 kg ha^{-1}a^{-1} (Jha and Sarin 1984); the inputs are expressed in the oxide form, i.e., N + P_2O_5 + K_2O, and a dryland district is one in which less than 25% of cultivated land was irrigated. But these average rates of fertilizer application did not reflect the fertilizer applied to the staple food crops (sorghum, millet) of the drylands. Of the total nutrients applied over a district, most, sometimes all, was applied to either cash crops (for example, groundnut, cotton, castor, chillies, tobacco,) under rainfed agriculture, or to small areas of irrigated land (e.g., paddy rice, sugarcane) within the rainfed area; in both these situations, farmers may apply large rates of fertilizer. The amount of fertilizer applied by the subsistence farmer in the Indian SAT to his dryland staple food crops—sorghum and millet—is indeed very small.

The reasons for the slow adoption of fertilizers in the cultivation of dryland cereals are not well understood, although some factors are fairly obvious. First, dryland agriculture has been given research emphasis only in recent years, because of the earlier views that low and variable rainfall was a major constraint. Second, fertilizer inputs are most effective only when several improved components are introduced concurrently, e.g., improved cultivars and a range of factors that fall within the umbrella of improved agronomy. Third, and most important in the view of Jha and Sarin (1984), is the uncertainty of the responses of crops to fertilizer additions; variability in responses had earlier been clearly demonstrated (Kanwar et al. 1973) though inadequate attention has been given to its effects on the adoption of fertilizers. Our research over the past few years has aimed at improving understanding of the factors causing variability in responses, to allow a better delineation of the conditions under which nutrient use would be most effective, and therefore reduce the uncertainty currently attached to the use of fertilizer in dryland agriculture, especially on Vertisols. Pertinent results are given in the sections that follow.

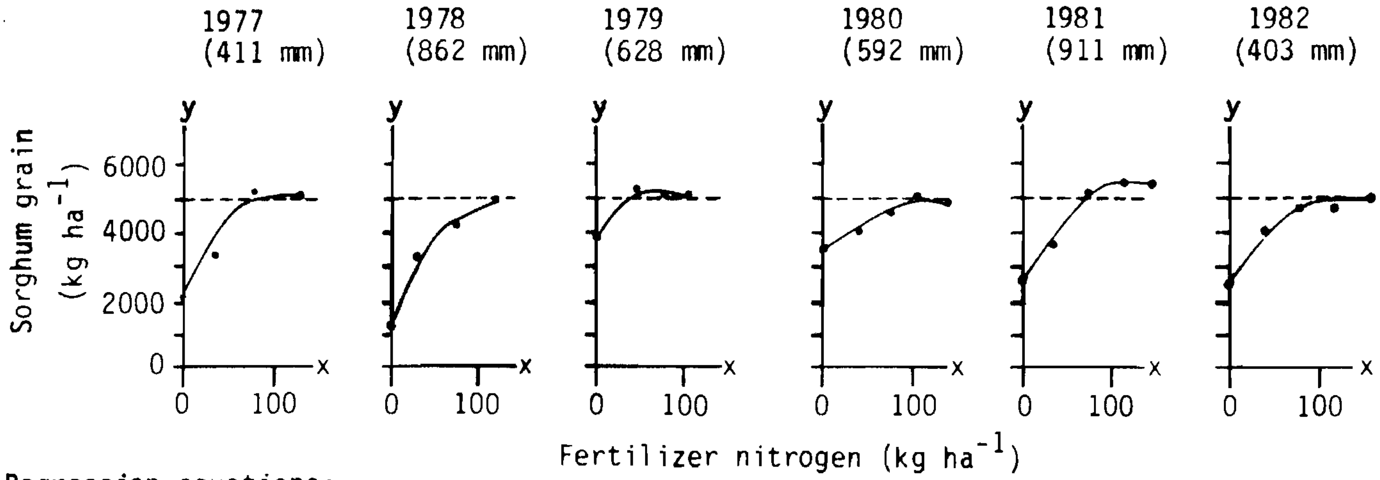
Nutrient Inputs for Deep Vertisols in the Rainy Season

Nitrogen has been given most emphasis in our studies of nutrient management on deep Vertisols, because of the prevailing view that phosphorus inputs were less important for crops on Vertisols than on lighter-textured soils such as Alfisols and Entisols (Arakeri 1980; Tandon and Kanwar 1984). An additional reason for giving priority to nitrogen is that an assured moisture regime is essential for maximum responses to fertilizer-N; and, the most important attribute of Vertisols—their high water-holding capacity—should minimize the effects of dry periods during the rainy season. Therefore, it is on Vertisols under moderately assured rainfall that we would expect to get the most consistent responses to the total nitrogen supplied to a crop (from soil and fertilizer sources). ICRISAT Center provided a useful benchmark site for studying such nutrient responses in detail.

Nitrogen

Sole Sorghum

A summary of responses of sole-cropped sorghum to applied N on deep Vertisols over six successive years at ICRISAT Center provides a good example of the year-to-year variation in responses in rainy-season cropping (Fig. 2). The first increment of applied-N (usually 40 kg N ha^{-1}) always gave worthwhile responses. Even in the particularly harsh year of 1979—when the rainy season commenced late and was notable for several prolonged droughty periods



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 2. Response of sole-cropped hybrid sorghum (CSH 6) to applied N on deep Vertisols, ICRISAT Center, rainy season 1977-82. Seasonal rainfall given in parentheses after year (Source: ICRISAT 1984).

up to sorghum anthesis in late August—the initial increment of N caused a response of 13.3 kg grain (kg N)$^{-1}$ applied which, at prevailing grain and fertilizer prices, represented a benefit:cost ratio of about 4:1.

Figure 2 clearly shows that seasonal conditions at ICRISAT Center did not appreciably restrict the maximum yield of rainy-season sorghum (CSH 6) on deep Vertisols, provided adequate nitrogen was supplied. With adequate N inputs, yields attained the quite satisfactory level of 5000 kg ha^{-1} in each year, even in the particularly harsh 1979 season. This contrasts with lower yields on Alfisols in this year (ICRISAT 1984, pp.255-259), and reinforces the observation by other workshop contributors that Vertisols are potentially among the most productive soils in the SAT, mainly because of their high water-storage capacity. The storage is sufficient to maintain crop growth during droughty periods within the rainy season, in addition to supporting growth for extended periods after the rains ease.

The area delineated as assured for rainy-season cropping on deep Vertisols was based on the high probability of a rainy-season crop to survive and produce grain (Virmani et al. 1989). This concept did not, however, extend to the next step of assessing the potential productivity of crops, and especially the responsiveness to nitrogen for which we might expect, *a priori*, that the assuredness of rainfall would need to be higher. Nevertheless, because ICRISAT Center is located on the edge of the area described as assured for crops' survival, we can predict with reasonable confidence (on the basis of the data in Fig. 2) that this assured area is also that in which rainfall is sufficiently dependable for moderately high and reliable grain production of rainy-season sorghum.

While the data in Figure 2 show a high reliability of responses to a first increment of nitrogen, they also indicate that the magnitude of responses and the amount of fertilizer needed varies considerably. These are inversely related to the yield without N inputs. Preliminary examinations indicate that these, in turn, may depend on a combination of seasonal rainfall and the nitrogen-supplying capacity of the soil; research on these aspects is needed.

The percentage of fertilizer-N absorbed by crops provides a useful guide to the efficiency of its use. For sole crops of rainy-season sorghum at ICRISAT Center—grown under the agronomic practices recommended for double-cropping deep Vertisols, especially dry seeding ahead of arrival of rainy season (see Virmani et al. 1989) and improved methods of fertilizer application – uptakes are usually greater than 50% (Moraghan et al. 1984; C.W. Hong, ICRISAT, personal communication). These are similar to results expected from experiments elsewhere in the world where fertilizer use by the crop is efficient. The uptake of fertilizer by sorghum crops was assessed by the "apparent N recovery" method, or was measured using isotopically-labeled ^{15}N fertilizer; the improved method of fertilizer-N application involved applying the fertilizer in bands below the soil surface, in split applications involving one-half of the total at seeding, and one-half at the first weeding (about 10 14 days after emergence of the crop).

Improved methods of fertilizer application appear to be essential in high rainfall years. In 1981, when the total rainfall was 1200 mm, application of all the fertilizer at seeding gave a low uptake by the crop of only 30%—a value which usually indicates inefficiency—and the unaccounted-for N (presumably lost as gases) was 26% (Table 4). The improved application method, involving split-application and band-placement of fertilizer, increased N uptake to >45%, and decreased the apparent losses to <7%. The improved application methods gave little or no advantage in drier years. This result, obtained in a very high rainfall year at ICRISAT Center, has considerable relevance for the Vertisols under higher average rainfall. The nitrogen losses appear to be caused by denitrification, as leaching through these heavy clay soils is expected to be very slow.

The ^{15}N-recovery data described here were the first to be obtained for Vertisols under dryland agriculture in India. They are particularly valuable because they counter earlier popular opinion that fertilizer-N is not efficiently used by cereals in the rainfed SAT of India. They also show the need for care in fertilizer application. The need for simpler—and cheaper—implements is clear (see von Oppen et al. 1989), but implement development should not ignore the need for research on timing and possibly placement of fertilizer-N.

Cereal/Legume Intercrops

The intercropping of pigeonpea with sorghum, with a regular row-arrangement of 1:2 (pigeonpea: sorghum), provides a highly successful means of increasing productivity by about 40–60%, compared with growing these two components as sole crops (Willey et al. 1989). The yield of such intercropped sorghum, maturing towards the end of the rainy season, is usually in excess of 90% of that of a sole crop; for medium-duration pigeonpea, maturing

Table 4. Effect of method of application of urea (72 kg ha^{-1}) to sorghum CSH 6 on grain yield, N uptake, and N recovery; Vertisol, ICRISAT Center, rainy season 1981 (Moraghan et al. 1984).

	Broadcast over soil surface			
	Left on surface	Incorporated[1]	Split band[2]	SE
Grain yield (kg ha^{-1})	4260	4110	5220	± 225 1
N-uptake (kg ha^{-1})				
From fertilizer	22	21	40	± 1.1
From soil[3]	40	39	45	[illegible]
Recovery of fertilizer-N (%)[4]				
Plant	31	30	55	± 1.6
Soil	42	45	39	± 2.7
Plant + soil	73	75	94	± 2.4
Assumed losses	27	25	6	-

1. Immediately prior to seeding.
2. Half the total fertilizer-N applied at seeding, and half 14 days after emergence.
3. Calculated from ^{15}N content of plant.
4. Determined by ^{15}N.

several months later, yields are about 60% of the sole crop. The sorghum/pigeonpea intercrop gives about the same productivity as sorghum (or maize) and chickpea sequential crops grown in the rainy and postrainy seasons, respectively; but the intercrop is more reliable because it avoids the need to establish the second crop when reliability of rainfall is declining (Willey et al. 1989). But there had been no systematic study of the effectiveness of fertilizer-N applied to the cereal; because of competition between the two components of the intercrop, fertilizer application was expected to be less efficient than with the sole crop. Comparisons over 3 years show that the responsiveness of sorghum was decreased only slightly by the introduction of the pigeonpea as an intercrop (Fig. 3); and, although the stimulation of the growth of sorghum by fertilizer-N caused some depression of pigeonpea yields, the overall increase in productivity was still 40% with N-inputs as high as 120 kg ha^{-1} (Fig. 4).

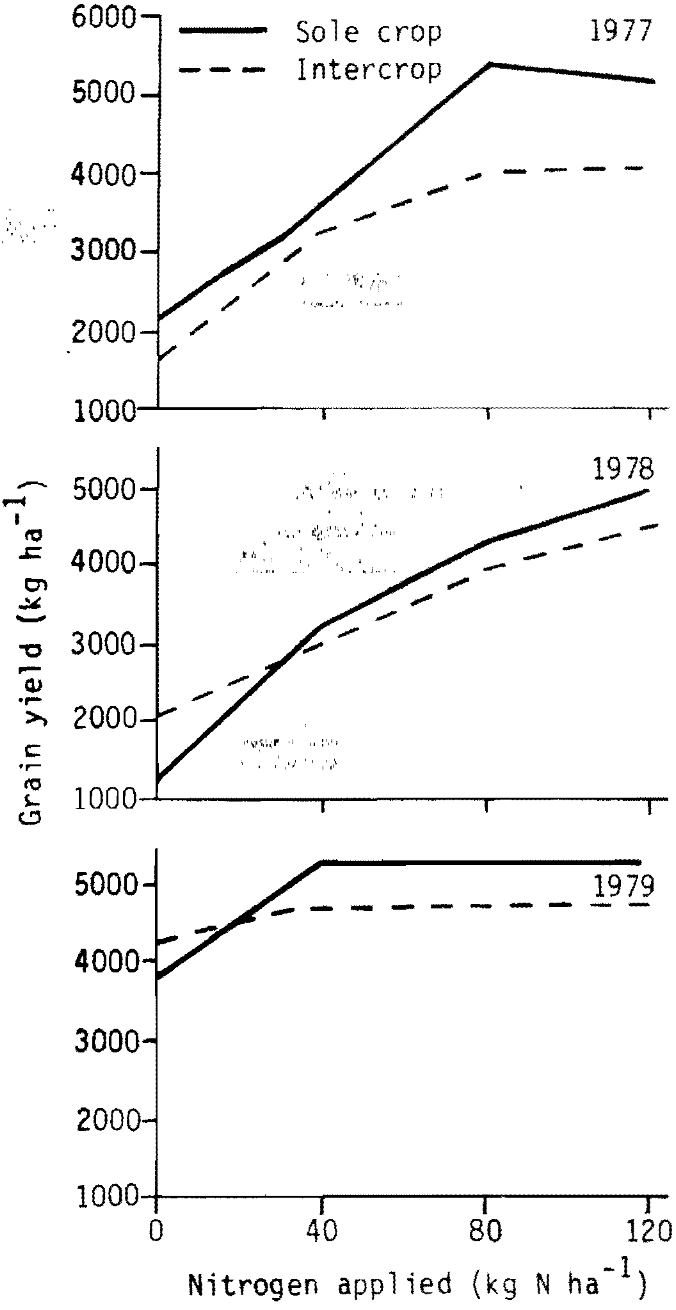


Figure 3. Response of sole and intercropped rainy-season sorghum to nitrogen on Vertisol at ICRISAT Center, 1977-79 (Source: ICRISAT 1981).

Residual Effects in Cropping Systems

The proportion of fertilizer-N, applied to rainy-season cereal crops, that became incorporated into the soil was quite high (up to 45%, see Table 4). Availability of this incorporated-N for subsequent crops was, however, low. Only 1-3% was taken up by a subsequent crop, either safflower grown in the postrainy season or sorghum in the rainy season of the following year (Moraghan et al. 1984). This result is in accord with data showing the very slow release of fertilizer-N once it is incorporated into the soil matrix (Jansson 1963; Westerman et al. 1972; Dowdell et al. 1984).

Legume-Based Cropping Systems

Until recently, agricultural research in India had given emphasis to the use of fertilizer-N for the alleviation of nitrogen deficiency in cereals. While this reflects the ready acceptance of fertilizer use by farmers in irrigated agriculture, the lack of ready adoption of fertilizer-N use in rainfed agriculture leads to speculation of the possible role of legumes in providing "free" inputs via the biological fixation of N by legumes.

Legume-based systems have been particularly successful for providing N-inputs where fertilizer was of marginal economic benefit (Donald 1964; Russell 1984). These systems used grazed pastures for the legume phase. But, in India, there is no tradition of pasture development for animal production; legumes are grown for their grain as part of the crop-production system. Their produce thus removes a substantial proportion of the N fixed, especially by improved cultivars with a 'high harvest index', i.e., the proportion of grain to total biomass. Improvements to cultivars by plant breeders are usually directed at least partly to improving the

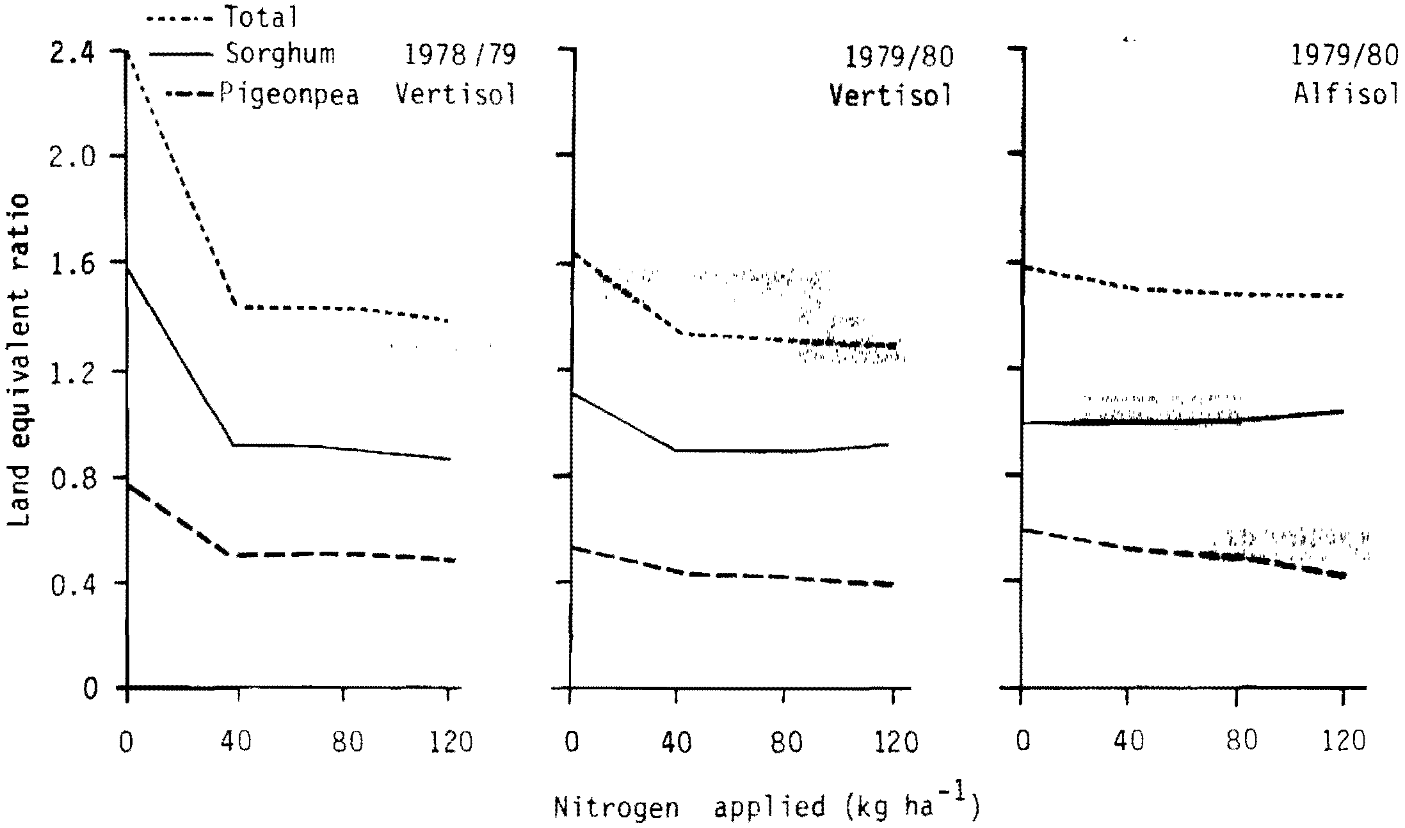


Figure 4. Effect of nitrogen fertilization on the land equivalent ratios in sorghum/pigeonpea intercrops at ICRISAT Center, 1978-80 (Source: ICRISAT 1981).

harvest index. This can lead to the removal of more nitrogen in grain than has been fixed during the crop growth (Henzell and Vallis 1977).

Perhaps it was such logic that led to a lower priority being given to research on the possible beneficial effects of biological N fixation by grain legume crops. Ignored was the fact that pigeonpea has only a low harvest index, sometimes less than 0.20 for the medium- to long-duration types, and that it also sheds its senescing leaves from flowering onwards. Although the farmer removes the stalks from the field, he removes relatively little nitrogen in this process, because the stalks have a very low N content.

Addition of nitrogen by fallen leaves may add 40-60 kg N ha^{-1} to the soil (Sheldrake and Narayanan 1979). These, plus root material and nodules remaining in the soil, have been shown to have good residual effects on a subsequent cereal crop (Kumar Rao et al. 1983), which are equivalent to an application of fertilizer-N of about 30-40 kg N ha^{-1} (Fig. 5). While this is not large, even a moderate input is valuable for a crop as responsive as sorghum to N inputs; this input could double yields, because the

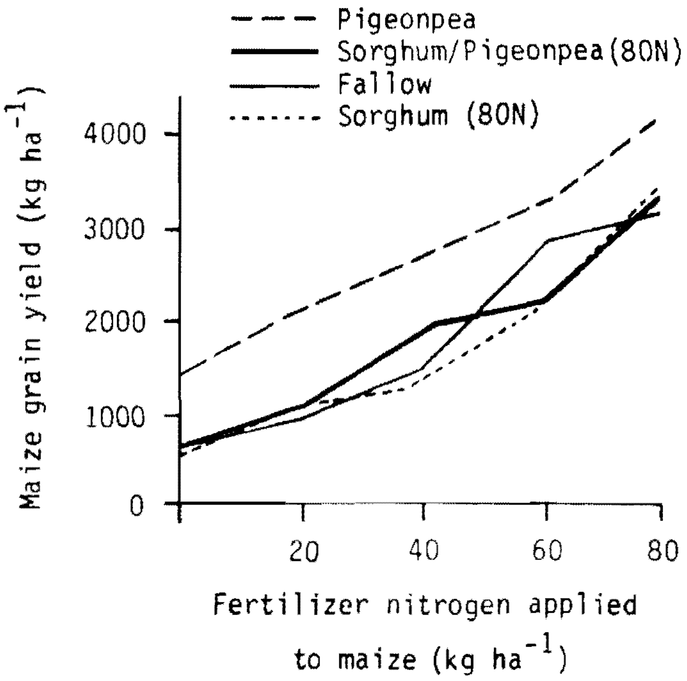


Figure 5. Effect of pigeonpea grown in the previous season as a sole crop, or in sorghum/pigeonpea intercrop, on the response of maize grain yield to fertilizer nitrogen application (Source: Kumar Rao et al. 1983).

soil appears to supply as little as 30 kg N ha^{-1} to cereal crops.

Such results have led to the establishment at ICRISAT of long-term experiments that examine the yields and residual effects of various combinations of crops, to assess the optimum combinations of legumes and cereals for maintaining productivity. Such experiments are urgently needed for the various agroclimates and soils in the Indian SAT, because their results will provide the basis for planning an optimum balance of fertilizer-N and legume-N inputs.

Phosphorus

The need to establish the phosphorus requirements of crops grown on Vertisols has received much less research attention than that given to nitrogen, for two reasons. First, phosphorus is given a lower priority in India than nitrogen, as it generally appears to be less necessary on Vertisols than on other soils (Arakeri 1980). Second, strategies for phosphorus application can be much simpler to develop, because of the strong residual effects of previous applications and because it is often possible to make general recommendations on a soil basis, which apply over quite wide areas (Smith 1967).

Preliminary experiments at ICRISAT have indicated that Vertisols differ from other soils as regards the behavior of P in the soil. Pigeonpea may respond to phosphorus applications on Alfisols of low available P status (<3 ppm Olsen P in the 0–15 cm soil depth); but it has not yet responded on Vertisols at ICRISAT Center, even when soil available-P (Olsen) levels were extremely low (<1.5 ppm). Further, sorghum—much more responsive than pigeonpea to P applications (ICRISAT 1981, pp.178-185)—usually responds to P application on Vertisols only when the Olsen-P value is less than 2 ppm (Fig. 6). This is a very low critical level; in India 5 ppm is generally considered as possibly adequate, and 10 ppm as sufficient.

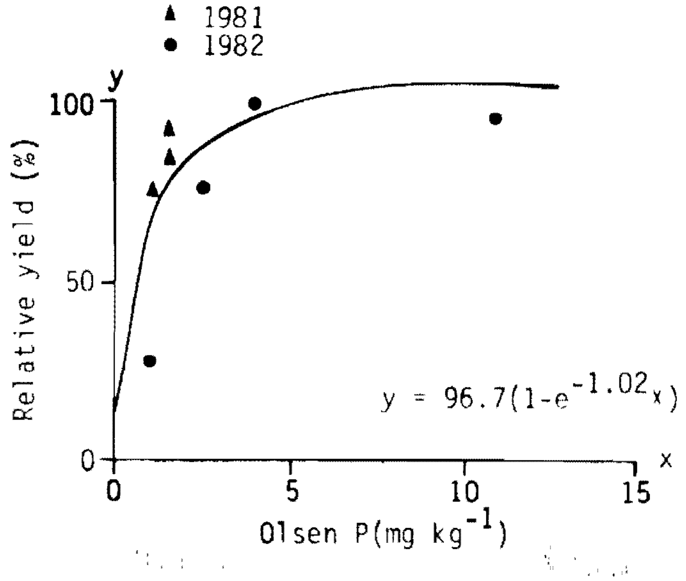


Figure 6. Relationship between relative grain yield (Y-Po/Y-Pmax) of rainy-season sorghum CSH 6 and available P (Olsen) in 0–15 cm depth of Vertisols; field experiments, ICRISAT Center, 1981 and 1982.

What causes the apparent difference in the behavior of P in Vertisols, from that in other soils, is not immediately clear. Studies under more closely controlled conditions, in pot experiments involving soils from carefully selected sites on Alfisols and Vertisols, failed to demonstrate a difference between the soil-test/crop-response relationships for the two soils when the Olsen test was used to assess soil P status. But a wide divergence was shown when the more-exhaustive Colwell adaptation of the Olsen test was used. This was surprising because the Vertisol, with its higher buffering capacity, was expected to release more "sorbed" P than the Alfisol. Although Vertisols in India are reputed to have a high P-fixation capacity, relatively little difference was found in the fixation rate of benchmark Vertisols and Alfisols at ICRISAT Center (ICRISAT 1985, pp.255-257).

Other evidence indicates that the P status of Vertisols may vary substantially across the SAT. Some Vertisols in Australia have not required P inputs even after many years of continuous cropping, and those in India and Sudan appear to require only small inputs, but some Ethiopian Vertisols appear to require substantial inputs (Tamirie Hawando, Ethiopia, personal communication). Further research is needed on the various issues raised about the behavior of P in Vertisols, mainly because recommendations for nutrient additions to soils must be derived from known data about the highest and most reliable benefit:cost ratio options.

Other Nutrients

Apart from nitrogen and phosphorus, zinc is the only nutrient required over substantial areas in

India. The high clay content and alkaline pH of Vertisols is undoubtedly responsible for the widespread occurrence of Zn deficiency. Sorghum is much less susceptible than maize, but current remedial measures are not very satisfactory. Soil applications are most effective, but they are costly and wasteful because the amount of zinc sulfate needed for improved cropping systems is about 20 kg ha^{-1} applied perhaps as often as every 3 years. Deficiencies can be alleviated, or completely ameliorated, by spraying 0.5% zinc sulfate solution onto the crop; but, with severe deficiencies, the application may need to be repeated 2 or 3 times. Temporary waterlogging of Vertisols may initiate or intensify some nutrient deficiencies, as for example, zinc deficiency on maize and iron chlorosis on groundnut.

Vertisols: Postrainy-Season Cropping

The nutrient requirements of postrainy-season crops have received much less attention than those of rainy-season crops. Responses are smaller in postrainy-season crops than in rainy-season crops (Tandon 1980; Tandon and Kanwar 1984) and the frequency of profitable responses appears to be lower (Kanwar et al. 1973). The main reason for this smaller reward is undoubtedly that postrainy-season crops usually rely on water stored in the soil profile for most (or all) of their water requirements. These crops usually approach maturity with their moisture supplies approaching exhaustion; drought stress during their growth is common. Additionally, nutrients placed at the usual depth (5 cm) in the soil may be easily accessible to plant roots for only a short time, because of increased nutrient uptake and yield (Rao and Das 1982; Moraghan et al. 1984), but the magnitude of nutrient response will still be limited by the water available to the crop.

Research is urgently needed on nutrient requirements of postrainy-season crops on Vertisols. As indicated, complex nutrient-water interactions may be involved. Systematic approaches, involving studies of the mechanisms involved, would appear to be more promising than empirical approaches.

Further Research Needs

Findings on the nutrient requirements of crops on Vertisols from the research at ICRISAT Center can be applied to the watershed-based double cropping technology for deep Vertisols in the assured rainfall areas in India. We can extrapolate with some confidence, especially for nitrogen, because (1) ICRISAT Center is located on the 'dry' edge of the assured rainfall area, (2) responses to nitrogen are especially dependent upon an assured moisture regime, and (3) the Vertisols in India appear to be reasonably homogenous (Swindale 1989). We may conclude, from the data in Figure 2, that lack of nutrients (especially N) is a much more important constraint to production than drought in this target area. This finding clearly indicates the need for further research to determine the best means of improving and maintaining the nutrient status of these soils; this may involve fertilizers, legumes, or a combination of both.

For cereals grown in the rainy season, fertilizer-N is used efficiently under the moderate rainfall conditions at ICRISAT Center. But, because of the higher probability of waterlogging, and losses by denitrification, more research is needed on the application methods under higher rainfall. More research is also needed on postrainy-season cropping, as this has been a neglected area. The reliability of responses to nutrient inputs in this season has not yet been given serious consideration.

Although the advantages of legumes are known, more emphasis needs to be given to legume-N inputs. The preliminary results shown here from ICRISAT Center are being substantiated in more detailed work. Clearly, there is a need to develop general relationships that permit the planning of crop sequences and crop combinations, which will maintain fertility for a range of soils and rainfall environments.

For phosphorus, initial results shown here indicate the need for a reassessment of the behavior of P in Vertisols. It does not seem generally recognized, yet, that a lower critical limit is needed for a soil test for sorghum on Vertisols. Additionally, variations in P status across the SAT appear to have received little attention.

In summary, there exists a full agenda of research topics that justify attention within a Vertisol network. Commonalities and contrasts in Vertisol climates and soil characteristics provide a challenging research framework. A network approach offers the potential of a faster solution to crop production problems than is achievable by researchers working in relative isolation in their own countries.

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Discussion

Cooper: (1) We observed large responses to phosphate in Vertisols in Syria (anything below 6-9 ppm of Olsen available P guaranteed the response); but the response depended on the method of application—banded vs. placed. (2) Have you studied methods of application?

Burford: (1) In discussing responses in relation to soil test values, we are referring to experiments in which all efforts have been made to optimize responses: e.g., good agronomy (optimum plant populations and spacing, good weed control, good pest control, etc.); improved cultivars (CSH 6 hybrid sorghum, for example); and appropriate placement of P fertilizer. (2) No, because this aspect has been covered fairly extensively by the national programs in India, such that Tandon gives general recommendations on the best application methods for the different sources of P for several different groups of soils.

Blokhuis: With respect to Dr. Burford's comment that some Ethiopian Vertisols fix appreciable amounts of P, and exhibit very large responses to P application, some Ethiopian Vertisols have received appreciable amounts of volcanic ash.

Hawando: Ethiopian Vertisols—whether they are developed from limestone, basalts, or volcanic ash mixed with Vertisols—responded highly to applied P and N.

Ahmed: (1) On Caribbean Vertisols (that test very low for available P by chemical methods) grass crops—sugarcane and maize, for instance—do not respond to P but other crops may; all scientists have interpreted this phenomenon as due to differences in root/soil relationships for various crops. Do you have any experience with response of P to crops other than cereals? (2) With respect to your comments about P deficiency on Ethiopian Vertisols, I have to point out that these are overlain to varying depths by andisolic materials and this may explain their behavior with respect to phosphorus.

Burford: (1) At ICRISAT Center, we have found that sorghum and millet respond to applied P much more than pigeonpea and chickpea.

Rasheed: In your last slide, you showed us some Zn deficiency symptoms. I would like to know what the pH was, and whether you observed any other micronutrient deficiencies.

Burford: The reaction of the surface soil was about pH 7.5-8.0. No other consistent micronutrient deficiencies were found, although transient iron deficiency may occur during periods of temporary waterlogging in cool weather.

Effective Tillage Practices for Conserving Soil and Water Resources

Paul W. Unger and Ordie R. Jones[1]

Abstract

Soil erosion by water and wind is a problem on most soils, including Vertisols. It is widely known that a permanent cover of grasses and trees is highly effective for controlling erosion and conserving water, but such cover does not allow crop production; hence, tillage and support practices are relied upon to control soil and water erosion. Conservation tillage, which retains residues of crops on the soil surface, is more effective than clean tillage for conserving soil and water. However, soil and water can also be conserved through proper use of clean tillage alone or by tillage in conjunction with suitable support practices, such as contouring, terracing, stripcropping, furrow diking, and so on. This report discusses the effect of conservation tillage, clean tillage, and support practices on conserving soil and water resources.

Résumé

Pratiques effectives de labour afin de préserver les ressources du sol et de l'eau : *L'érosion du sol par l'eau et le vent est un problème dans la plupart des sols, y compris les Vertisols. On sait très bien qu'une couverture permanente de graminées et d'arbres est très éfficace pour contrôler l'érosion et conserver l'eau, mais une telle couverture ne permet pas de production agricole. Par conséquent, le labour et les pratiques d'appui sont nécessaires afin de contrôler l'érosion. Le labour de préservation, où l'on conserve les résidus des récoltes à la surface du sol, est plus efficace que le labour intégral, où l'on enlève les résidus. Néanmoins, le sol et l'eau peuvent être également protégés par l'utilisation adéquate d'un labour sans résidu ou en l'utilisant en combinaison avec des pratiques d'appui adéquates, comme par exemple des courbes de niveau, des terrasses, des cultures en bandes, le drainage de sillons etc. Cet article traite de l'effet du labour de préservation, du labour intégral et des méthodes d'appui pour maintenir les ressources du sol et de l'eau.*

Introduction

Most of the world's soils, including Vertisols, are subject to erosion by water and wind. Although Vertisols cover only about 1.8% of the world's land surface (Donahue et al. 1977), they are highly important agriculturally and must be conserved to sustain crop production. There is also an urgent need to conserve water, because Vertisols commonly occur where limited precipitation often limits crop yields.

The effectiveness of vegetative covers for controlling erosion is well known; permanent covers of grasses and trees, however, are usually not compatible with crop production. Consequently, alternate

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conservation practices must be employed. A practice that is essentially as effective as a permanent cover of grasses or trees is conservation tillage, which retains a cover of residues on the soil during critical erosion periods. A complete cover of surface residues gives the most protection. Lesser amounts, however, provide enough protection so that annual erosion does not exceed 11.2 t ha^{-1}, the tolerable level for many soils (Wischmeier and Smith 1978). Approximate amounts needed to maintain erosion below this tolerable level are given in Table 1.

The residue amounts shown in Table 1 are relatively low. However, such amounts often are not produced by rainfed crops in many areas, and residues of some crops, such as cotton (*Gossypium hirsutum* L.), provide little protection against erosion. In addition, residues are often used for animal feed or fuel. When crop residues are not available, whatever the reason, alternate measures must be employed. This report discusses (1) conservation tillage methods for situations where crop residues are available, (2) clean tillage methods for situations where residues are limited or it is not desirable to use conservation tillage, and (3) support practices that provide additional protection against soil and water losses.

Tillage Methods

Conservation Tillage

Conservation tillage is commonly defined in the United States as any system that leaves at least 30% of the soil surface covered with crop residues after a crop is planted. This definition implies that such an amount or more would be present at all times during the interval between crops. Following is a short discussion of some methods of residue-management systems.

Stubble-mulch tillage. Stubble-mulch tillage is accomplished with implements (sweeps or blades) that undercut the soil surface, thereby retaining most crop residues on the surface. Stubble-mulch tillage can also be performed with a chisel plow, but a rotary rodweeder may be needed to improve weed control.

Stubble-mulch tillage was developed to control wind erosion in the Great Plains of the United States, but it also reduces water erosion and enhances water conservation. Because stubble-mulch implements reduce surface residues only about 10% for each operation, they usually maintain adequate residues to control erosion, provided sufficient residues are produced by the preceding crop.

One disadvantage of stubble-mulch tillage is poor weed control when tillage is performed while the soil is moist or when precipitation occurs soon after tillage. Some grassy weeds may be especially hard to control. To improve control and to firm soil before planting, shallow tillage with a rodweeder is often used in a stubble-mulch system.

Stubble-mulch and one-way disk (clean) tillage were compared by Johnson and Davis (1972) for winter wheat (*Triticum aestivum* L.) on a Mollisol (Pullman series) at Bushland, Texas. The soil has 30% clay in the surface horizon and a high shrink-swell potential, with a coefficient of linear extensibility (COLE) of 0.078 in the Bt1 horizon (unpublished data, US Department of Agriculture, Soil Conservation Service, National Soil Survey Laboratory, Lin-

Table 1. Approximate amounts (kg ha^{-1}) of residue needed to maintain annual erosion at below a tolerable level of 11.2 t ha^{-1} on various types of soil (from Anderson 1968, Fenster 1973).

	Water erosion	Wind erosion					
	Wheat residue	Wheat residue		Growing wheat		Sorghum residue	
Soil Texture[1]	Flat	Standing	Flat	Standing	Flat	Standing	Flat
Silts	1600	500	1000	560	480	2000	2900
Clays and silty loams	2100	900	1800	1100	930	3700	5300
Loamy fine sands	1000	1200	2400	1300	1000	4700	6900

[1] Silts with 50% nonerodible fractions greater than 0.84 mm in diameter. Clay and silty clay with 25% and loamy sand with 10% nonerodible fractions.

coln, Nebraska). Although water storage and yield increases were small (Table 2), the stubble-mulch system provided protection against erosion.

Where weed control is difficult with stubble-mulch tillage, improved weed control can be achieved through use of herbicides to replace some tillage operations. Wicks and Smika (1973) in Nebraska found that no-tillage (herbicide-treated) plots had the fewest weeds, the greatest amount of soil water, the most surface residues, and the highest yield of sorghum [*Sorghum bicolor* (L.) Moench]. Sorghum grain yields were 2690 kg ha^{-1} with clean tillage, 2890 with stubble mulch, and 3160 with no-tillage. In another study, sorghum grain yields were 3200 kg ha^{-1} with stubble mulch and 4580 with tillage-herbicide treatments (Fenster 1977). The tillage-herbicide treatment may be especially suited to Vertisols, which become very sticky when wet and, hence, difficult to cultivate for timely weed control.

Disk tillage. Disk-type implements bury from 30 to 70% of surface residues during each operation, depending on the implement used and how it is operated (Fenster 1977). Disk-type implements provide good weed control, but are useful for conservation tillage only if sufficient residues are retained on the soil surface. Where residue production is low and the potential for erosion is high, disk-type implements should not be used. In addition to greatly reducing residues left on the surface, disk implements pulverize soils and reduce surface roughness. Pulverized, smooth-surfaced soils are more susceptible to erosion and allow less water infiltration than residue-covered or rough-surfaced soil.

Ridge planting. Ridge planting is a once-over tillage-planting operation. The planter units are operated on ridges made by cultivation of the previous crop or after crop harvest. At planting, till-plant units remove the ridge tops with wide sweeps that shove old stalks and root clumps into the inter-row area. Seed is planted in the cleared area and covered with loose soil. Ridges are re-formed with rolling or disk-hiller cultivators (Griffith et al. 1977). Although developed for maize (*Zea mays* L.), the system is also suitable for other row crops. Conservation benefits result from the soil being covered with residues or a growing crop during most of the year. Additional runoff-control benefits occur if the ridges are on the contour. Ridge planting benefits poorly drained soils, such as Vertisols, because ridges are usually drier and better aerated than furrow bottoms or land that is managed in a flat condition.

No-tillage. No-tillage (or zero tillage) has been widely acclaimed as a highly effective conservation practice. No-tillage requires no seedbed preparation other than opening soil for seed placement, usually with a coulter operated in front of a planting unit equipped with disk or chisel openers (Mannering and Fenster 1983).

With no-tillage treatments, herbicides are used to control weeds. Consequently, all crop residues are maintained on the soil surface, which improves erosion control and enhances water conservation through improved infiltration and reduced evaporation. For no-tillage to be effective, adequate residues must be available. No-tillage is not and cannot be expected to be effective on seriously degraded soils or where residue amounts are low. Where residues ranged from about 1500 to 2500 kg ha^{-1} and weeds were controlled with herbicides, water storage and crop yields were similar to those with stubble-mulch tillage (Wiese and Army 1958, Wiese et al. 1960).

Table 2. Plant-available soil-water contents at time of planting and grain yields for a long-term (1942-1969) study for rainfed winter wheat on a Mollisol at Bushland, Texas (from Johnson and Davis 1972).

Cropping system	Tillage method	Soil water content (mm)	Grain yield (kg ha^{-1})
Continuous wheat	One-way disk	91	580
	Stubble mulch	103	690
Wheat-fallow	One-way disk	128	930
	Stubble mulch	154	1060
	Delayed stubble mulch[1]	144	1030

1. Tillage delayed until weeds needed control in the spring (about 10 months after wheat harvest).

When more residues were present, Unger and Wiese (1979) obtained greater water storage and higher sorghum grain yields with no-tillage than with other treatments on the Mollisol at Bushland, Texas (Table 3). Higher infiltration and lower evaporation undoubtedly were responsible for greater water conservation with no-tillage. In another study at Bushland, Texas (Unger 1984), both water storage during fallow and average sorghum yields were highest with the no-tillage treatment (Table 3). The treatments, applied during fallow after wheat, had no residual effects on subsequent sunflower (*Helianthus annuus* L.) or wheat yields.

On a Mollisol (Austin series) at Temple, Texas, where annual precipitation is 840 mm, Gerik and Morrison (1984) obtained similar soil-water storage and grain yields of sorghum by using no- and conventional-tillage treatments. However, no-tillage has greater potential for the region for several reasons: first, production costs are lower; second, sorghum can be grown on narrow rows (a practice that has potential for higher yields), whereas clean tillage requires wider rows to permit cultivation for weed control. The effect on erosion was not reported, but leaving wheat residues on the soil surface and using no-tillage undoubtedly greatly reduced erosion on this highly erosive soil. Also on the same soil, wheat yields in a 3-year study with wide beds were not significantly different in 2 years, but were significantly lower with no-tillage in a droughty year because of less tillering (Gerik and Morrison 1985).

Jones and Benyamini (1984) applied water with a rainfall simulator to the Mollisol at Bushland, Texas. The plots were in a cropping system of winter wheat-fallow-grain sorghum-fallow, with no- or stubble mulch-tillage used for weed control. Both tillage treatments resulted in similar infiltration rates during fallow after wheat and for sorghum with full canopy; infiltration decreased much more rapidly with no-tillage during fallow after sorghum. However, runoff from a 110-mm natural rainstorm (June 1984) was 81 mm from no-tillage, and 85 mm from stubble-mulch tillage watersheds. Soil loss with stubble-mulch tillage was 6.56 t ha^{-1}, but only 2.15 with no-tillage. Soil loss from no-tillage plots in fallow after wheat was 0.24 t ha^{-1} from the storm.

The vast potential of no-tillage practices for controlling erosion by water on sloping watersheds is illustrated by the data (Table 4) for a storm in Ohio that had an expected recurrence frequency of over 100 years (Harrold and Edwards 1972). Maize was grown on all watersheds. Rainfall and slopes were similar for clean-tilled watersheds, but runoff and soil loss were much less from the contour-row than from the sloping-row watershed. On the no-tillage watershed, rainfall was slightly lower, and about 60% of the water was lost as runoff. However, soil

Table 3. Effect of tillage method on average soil-water storage, on sorghum grain yield, and on water-use efficiency (WUE) of the sorghum crop. Data from a cropping system of irrigated winter wheat, followed by fallow, followed by dryland sorghum on a Mollisol at Bushland, Texas (from Unger and Wiese 1979, Unger 1984).

Years	Tillage method	Water storage[1] (%)	Sorghum grain yield (kg ha^{-1})	WUE[2] (kg m^{-3})
1973-77[3]	No tillage	**35 a[5]**	3140 a	0.89 a
	Sweep	**23 b**	2500 b	0.77 b
	Disk	**15 c**	1930 c	0.66 c
1978-83[4]	No-tillage	**45 a[5]**	3340 a	-
	Sweep	**36 ab**	2770 b	-
	Disk	**34 ab**	2370 cd	-
	Moldboard	**29 b**	2560 bc	-
	Rotary	**27 b**	2190 d	-

1. Soil-water storage during fallow after wheat. Based on fallow-period precipitation stored as soil water.
2. Grain-yield WUE for sorghum. Based on total water use (precipitation plus soil water extraction) during the sorghum growing season. WUE not reported for 1978-83 cropping.
3. Precipitation for all treatments was 348 mm during fallow, and 264 mm during the growing season.
4. Precipitation for all treatments was 316 mm during fallow, and 301 mm during the growing season.
5. Within each experiment, column values followed by the same letter or letters are not significantly different at the 5% level, based on the Duncan multiple-range test.

Table 4. Effect of tillage method on water runoff and soil loss from watersheds planted to maize at Coshocton, Ohio, during a severe rainstorm on July 5, 1969 (from Harrold and Edwards 1972).

Tillage method	Slope (%)	Rainfall (mm)	Runoff (mm)	Soil loss (t ha^{-1})
Plowed, clean-tilled, sloping rows	6.6	140	112	50.7
Plowed, clean-tilled, contour rows	5.8	140	58	7.2
No-tillage, contour rows	20.7	129	64	0.17

loss with no-tillage was much lower than that from the clean-tilled watersheds (whether cultivated on a contour or sloping row) even though the slope was much steeper on the no-tillage watershed.

No-tillage is also highly effective for controlling wind erosion, as illustrated by the data in Table 5 for a sandy soil. Undoubtedly, losses from a Vertisol would be different, but wind erosion does occur on bare, smooth, unprotected Vertisols, and surface residues would reduce wind erosion and protect crops.

Paraplow tillage. The paraplow is an implement that retains most crop residues on the soil surface. In Iowa, surface residues after planting averaged 75% with the paraplow, 83% with no-tillage, and 12% with moldboard plowing (Erbach et al. 1984). Soil-water contents were similar, but maize yields were 5.6 t ha^{-1} with moldboard plowing, as compared with 4.4 with no-tillage and 4.9 t ha^{-1} with the paraplow treatments. In England (Davies et al. 1982) and the United States (personal communication, John F. Dougherty, Howard Rotovator Co., Inc., Muscoda, Wisconsin), runoff was lower with the paraplow than with no-tillage or plowing treatments. Reducing runoff reduces the potential for erosion. From the limited data available, it appears that paraplowing has potential for conserving soil and water on dense, high-clay soils, such as Vertisols, by maintaining surface residues and favorable infiltration rates.

Table 5. Effect of tillage system and surface residues of maize stalks on soil loss by wind erosion from land in Ohio (from Woodruff 1972).

Tillage method	Surface residue of maize (t ha^{-1})	Soil loss (t ha^{-1})
Experiment I		
Fall plow	0.28	26.1
Spring plow	0.12	8.5
No-tillage	5.60	1.2
Experiment II		
Plow, normal residues	0.14	3.5
Disk, normal residues	0.54	5.1
Disk, double residues	1.76	0.8
No-tillage, residues removed	0	3.0
No-tillage, normal residues	1.82	0.6
No-tillage, double residues	2.85	0.5

Clean Tillage

When conservation tillage is not used, either by choice or because of inadequate crop residues, then other practices must be relied upon to conserve resources. Wind erosion on clean-tilled Vertisols can usually be controlled by any tillage that produces an adequately rough, cloddy surface. Secondary operations (disking, leveling, smoothing, etc.) and weathering (rainfall, drying, etc.) may decrease surface ridges and cloddiness to the point that they no longer afford protection against the wind. Unless soil is pulverized, any operation to ridge it or increase its surface cloddiness usually is adequate as an emergency measure to control wind erosion on a Vertisol.

To control water erosion on Vertisols where clean tillage is used, infiltration should be increased or water should be conveyed off the land at nonerosive velocities. To achieve this, soil ridging or roughening tillage is often used in conjunction with graded furrows, contouring, furrow diking, terracing, or other practices.

The influence of tillage *per se* on runoff and, consequently, on water erosion is related to the stability of surface soil aggregates and to the roughness, surface-retention storage, and pore space that result from tillage with different implements. To maintain high infiltration rates, water-stable surface aggregates are desirable. These normally result from maintaining organic materials at or near the soil surface. Low-stability soils are readily dispersed by water, which causes surface sealing and increases runoff and erosion.

When precipitation rates exceed infiltration rates, temporary surface storage of water can reduce runoff and aid in controlling erosion. Ridge-forming tillage on the contour is a proven conservation practice (Dickson et al. 1940, Fisher and Burnett 1953, Harrold and Edwards 1972). Runoff was also eliminated by furrow diking of gently sloping land, and all water from a 114-mm rainstorm during a 24-hour period was retained on the Mollisol at Bushland, Texas (Clark and Jones 1981).

In addition to lister tillage, implements such as moldboard plows, sweep plows, disks, chisels, rotary tillers, cultivators, and so on affect soil pore space and surface roughness and, therefore, runoff and erosion. Burwell et al. (1966) evaluated effects of porosity and roughness resulting from tillage on infiltration of simulated rainfall (Table 6). For the plow treatment, runoff started only after cumulative infiltration approached plow-layer total pore space and surface-retention volumes and exceeded those volumes before 25 mm of runoff occurred. For the other treatments, though 50 mm of runoff occurred, storage volumes were not filled. Smoother surfaces with treatments other than plowing apparently resulted in more rapid soil dispersion and surface sealing, which reduced infiltration.

One practice that involves clean tillage, but which has considerable potential for controlling erosion, is the plow-plant system for which plowing is delayed until 12 to 24 hours before planting. Consequently, the soil remains residue-covered for a major part of the erosion period. Planting may be in tractor or planter wheel tracks (Griffith et al. 1977). Variations of this system are disking and planting; fall chiseling, then disking, cultivating, or rotary tilling before planting; or rotary tillage (strip or full width) and planting (Griffith et al. 1977).

Support Practices

By using conservation tillage methods, especially no-tillage, lands that are otherwise highly susceptible to erosion can be safely cropped in many cases because of the protection afforded by surface residues. Other lands, however, are highly susceptible to erosion when clean-tillage methods are used and, therefore, require additional support practices to conserve soil and water. In this section, we discuss practices that can be used for that purpose. For this report, support practices are engineering-type practices and cultural practices (other than tillage) that aid in conserving soil and water resources.

Contouring

Contouring involves performing tillage and cultural operations so that elevations along rows are as level as practical. When lister tillage or ridge planting is done on the contour, the potential for erosion by surface water flow is greatly decreased (Stewart et al. 1975). Contouring provides almost complete protec-

Table 6. Effect of tillage-induced plow-layer porosity and surface roughness on cumulative infiltration of simulated rainfall (from Burwell et al. 1966).

	Potential water storage volume (mm) due to		Cumulative infiltration[3] (mm) to		
Tillage method[1]	Pore space[2]	Roughness	Initial runoff	25-mm runoff	50-mm runoff
No-tillage	81	8	9	21	24
Plow	137	50	171	217	230
Plow-disk-harrow	124	25	53	73	84
Cultivation	97	29	57	83	91
Rotovation	117	15	24	38	41

1. Plowing and rotovating performed to a 15-cm depth, cultivating to a 7.5-cm depth on untilled soil.
2. Measured to tillage depth.
3. Water applied at a rate of 127 mm h⁻¹.

tion against erosion from low to moderate intensity storms, but little or none against intense storms that overtop and break the contoured ridges. In such cases, water conservation is also reduced. However, with lesser storms and proper use, contouring promotes uniform water storage on the entire field. With lister tillage, each ridge serves as a miniature level terrace and, thus, holds water on the land. Contouring has no direct value for controlling wind erosion unless the ridges increase surface roughness perpendicular to the wind direction.

Stripcropping

Stripcropping reduces water and wind erosion. To reduce water erosion, it is useful to alternate protective and cropped strips, usually of equal width, and more effective to plant sod and winter small grains than spring grain crops. Soil eroded from cropped areas is then trapped in the protective strip. Stripcropping reduces soil losses from a field, but may not prevent movement within a field (Wischmeier and Smith 1978).

In the United States, stripcropping is widely used for wind erosion control with the alternation of fallow and cropped areas perpendicular to prevailing winds. On fallow areas, residues from small grain crops provide some protection against wind erosion by reducing field length in the direction of prevailing winds. In other areas, narrow strips of tall plants have given some control of wind erosion and conserved water (Black and Siddoway 1971, Hagen et al. 1972).

Terraces

Terraces are constructed across the slope to conduct runoff from fields at nonerosive velocities. They also retain water on fields until infiltration occurs, thus making more water available to plants. Terraces are generally combined with waterways or underground outlets that safely dispose excess water (ASAE 1981). The effectiveness of terraces for conserving soil and water can be enhanced by such complementary practices as contouring, stripcropping, diking, and conservation tillage.

Terraces are classified by alignment, cross section, grade, and outlet. Terrace alignment is parallel or nonparallel. Parallel terraces require more soil movement during construction but are easier to farm with mechanized equipment; nonparallel terraces may result in odd-shaped areas that are difficult to farm.

Terraces commonly used on gentle slopes have broad bases, which permit crops to be grown and machinery to be operated over the entire terrace. On narrow-base terraces, ridges should be seeded to permanent vegetation. On steep-backslope terraces, backslopes should be vegetated. Ridgeless channel terraces can be used on nearly flat or gently sloping fields. Soil excavated from channels is used to smooth the interterrace intervals.

Maximum water retention for crop use is obtained with bench or conservation bench terraces (Fig. 1), which require land leveling. With bench terraces, the entire terrace interval is leveled and water is retained on the bench with permanently vegetated ridges. With conservation bench terraces,

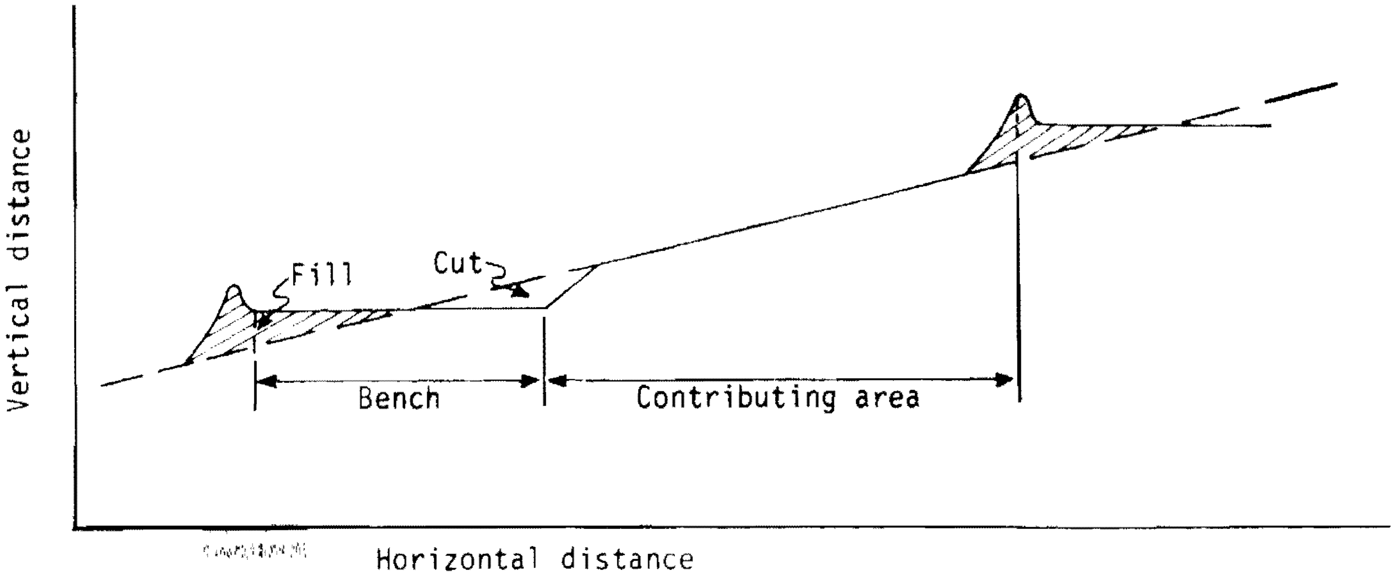

Figure 1. Schematic diagram of a conservation bench terrace system (from Hauser 1968).

on the other hand, only a portion of the interterrace interval is leveled, usually the lower one-third or one-half; thus, costs for construction are less than for bench terraces. Bench, conservation bench, and minibench terraces (Fig. 2) are effective for reducing erosion and increasing crop yields on slowly permeable soils in semi-arid climates. Minibench terraces are only one- or two-equipment widths wide (Hauser 1968, Jones 1981).

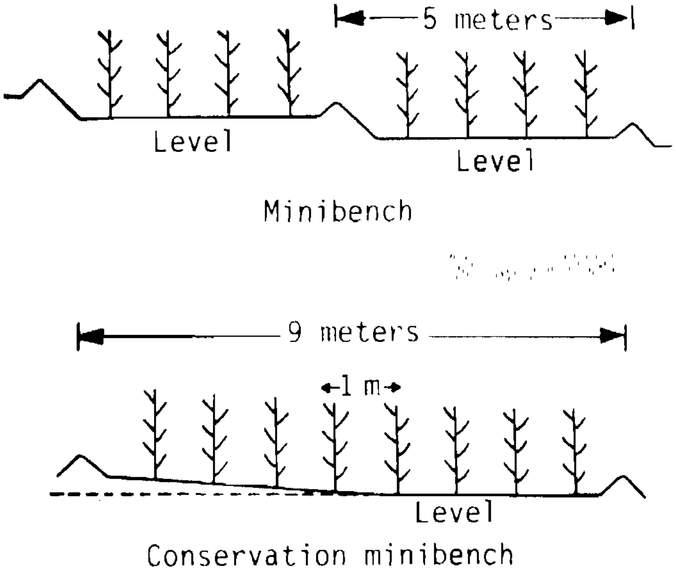

Figure 2. Schematic diagram of minibench and conservation minibench terraces (from Jones 1981).

Graded terraces slope toward the outlet and are constructed to reduce field slope length and water flow velocities, which also reduces erosion. The grade to the outlet may be uniform or variable. Level terraces are built in low-rainfall areas to conserve water and to control erosion. Channel ends are often blocked to retain runoff on the field.

Terrace outlets are classified as (a) blocked, where surface water is retained in the terrace channel; (b) grassed waterway, where water is drained into vegetated waterways; or (c) underground outlet, where water is removed from terrace channels by an underground pipe. The latter outlets aid in erosion control and remove less land from production. Combinations of the various outlet systems may be used.

Diversions

Diversion terraces are individually designed channels and ridges across the slope, which are used to protect field areas against runoff from unterraced areas, to divert water out of active gullies, and to protect farm improvements. Diversions are often used to prevent outside runoff from entering terraced fields.

Graded Furrows

In contrast to contour furrows, which minimize runoff and erosion, graded furrows convey runoff water from fields at nonerosive velocities. Each furrow functions as a small graded terrace. Although designed to remove excess water, graded furrows also conserve water. Runoff was 187 mm from graded-furrow, and 236 mm from terraced watersheds during a 32-month period at Temple, Texas (Richardson 1973). Runoff was less with graded furrows because the excess water was more uniformly distributed over the entire field, which provided more time and area for infiltration.

Furrow Dikes

Furrow dikes (tied ridges) can effectively conserve water by retaining potential runoff on field areas until it infiltrates. With this practice, small earthen dams are constructed between cropped ridges that are formed with a lister (bedder). The dikes are built across the furrow at intervals of 1-4 m, depending on slope and available equipment. With furrow dikes, sorghum yield increased 1550 kg ha^{-1} at Etter, Texas, in 1980, but averaged only a 230 kg ha^{-1} increase at Bushland, Texas, from 1975 to 1979 (Clark and Jones 1981). The soils were similar at the two locations, but the distribution of rainfall was different.

Drainage

The emphasis in the foregoing sections has been on soil and water conservation, but too much water can also be detrimental to crop production due to flooding and poor drainage. Where drainage is necessary, water must be conveyed from the field at nonerosive velocities.

For fields with nonuniform slopes, rows should drain into low areas or waterways within a field to improve overall drainage. If low areas are not connected, drainage can be improved by connecting the areas with ditches that discharge into established waterways, into low areas in the field, or into a pond. Minor low areas can be filled by smoothing the surface, thus improving drainage in the field.

For nearly level fields, drainage has been improved by using systems of beds and furrows (Krantz et al. 1978, El-Swaify et al. 1985), which provide drainage of the seed zone and result in slightly higher yields, for example, 2800 kg ha^{-1} of maize on 150-cm broad beds compared to 2690 on flat (Krantz et al. 1978). Planting on beds to improve drainage was also recommended by Bradfield (1969) for an intensive cropping system under high-rainfall conditions in the Philippines.

Time of Tillage and Planting

Vertisols are difficult to till, both when too wet and too dry. Consequently, timing of cultural operations is critical to assure favorable soil conditions at planting time. Some management options with respect to increasing production on Vertisols were discussed by El-Swaify et al. (1985). A major benefit results from performing primary tillage before the soil becomes too dry (immediately after harvest of the postrainy-season crop). With early soil preparation, a rainy-season and a postrainy-season crop could be grown, provided climatic conditions are favorable. Where drainage is poor, the rainy-season crop may need to be dry planted on raised beds, which results in the crop being started as soon as sufficient rainfall occurs. Planting after rains is difficult in wet, sticky soils. Raised beds permit better crop growth on poorly drained soils during the rainy season, and they permit earlier establishment of the postrainy-season crop because beds dry faster than nonbedded soils. Earlier establishment of the postrainy-season crop in itself could increase yields, because crops would use more of the rainfall rather than depending solely on stored soil water.

Planting Method

Row crops (cotton, maize, sorghum, sunflower, etc.) are commonly planted with unit planters in rows 50 to 100 cm apart; this spacing allows interrow cultivation during the growing season. In drier climates, a sweep or lister may be operated in front of the unit planter to kill weeds and shove aside dry soil, thus allowing placement of seed in moist soil. In wetter climates, a well-drained seedbed can be obtained by placing seed in the top of a ridge that was formed with a lister during seedbed preparation. Drills used for seeding small grains can also be used to seed row crops by plugging unneeded spouts to achieve the desired row spacing (Jones and Johnson 1983).

Two basic types of drills, disk and hoe, are used to sow small grains. Disk drills, with single- or double-disk openers, are used for seeding on smooth, well-prepared seedbeds that have favorable water contents near the surface. High-clearance deep-furrow hoe drills are adapted to seeding in drier soils and in crop residues, but both types of drills can sow through crop residues if coulters are mounted in front of the disks or hoes. Drill-row spacings vary from 20 to 35 cm. The narrow-row spacings are commonly used in higher rainfall areas (Jones and Johnson 1983). When seeds are sown deeper than about 4 cm, poor emergence has been observed for some of the new short-stemmed crops, such as wheat. Proper planting increases the need for timely and uniform plant establishment, thus decreasing the potential for replanting, increasing the potential for more efficient use of water resources, and decreasing the potential for erosion.

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Discussion

Hawando: Under zero-tillage, how do you control insects and diseases in Texas conditions?

Unger: At our location where we have a cold winter, we have not encountered any greater insect or disease problems with no (zero)-tillage than with conventional tillage methods. However, I realize there could be greater problems with no-tillage under other conditions or environments.

Saunders: The no-till system certainly seems attractive from what you have presented. However, it seems that this system can cause a buildup of certain soilborne diseases, e.g., *Sclerotium rolfsii*, particularly in more humid environments. Do you have any information on this factor?

Unger: There have been reports indicating a buildup of diseases under certain conditions. However, our environment is relatively dry, and we have not had a problem with either pests or diseases.

Sharma: We noticed that turning in of sorghum and pearl millet residues causes serious problems of *Sclerotium rolfsii* to the succeeding crop of pigeonpea at ICRISAT Center.

Hong: Under no-tillage, soil and water can be better conserved. But, I think, in a low-fertility soil at least, fertilizer should be well mixed with soils. Tillage seems to be needed to mix the fertilizer well with the soil. Where soil fertility is high, this aspect may not be important. But in soils with low fertility, this aspect should receive due attention.

Unger: Our soils do not require added phosphorus, but we do apply nitrogen fertilizer by chiseling anhydrous ammonium into the soil at some time in the cropping sequence, usually at the time that we do a limited amount of tillage to reestablish the beds and furrows in preparation for the irrigated crop. This would be the case where we use the cropping sequence of irrigated wheat, followed by fallow, dryland grain sorghum, and fallow.

Adoption of Improved Vertisol Management Technology in Karnataka State, India: A Case Study

T.V. Sampath[1]

Abstract

The traditional technology for crop production in the Vertisol tract of Karnataka, with a mean annual rainfall of 620 mm, is now barely able to meet the needs of a continually increasing population. Rainfall unreliability has led to the development of traditional farming systems in which the emphasis on stability does not allow flexibility for improved productivity.

Recent advances in technology, through adoption of ICRISAT's improved systems of land management and crop production, have increased yields in operational research blocks during 1982/83 and over a much larger area of 277 ha during 1983/84. This has led to their wider acceptance among farmers in this tract. During 1984/85, 961 ha in nine districts (31 locations) were brought under this advanced technology. The technology influenced not only the farmers involved within the watersheds but also those outside. The primary need of both sets of farmers was the adoption of land management and cropping systems; both measures met with a fair degree of success.

A twofold to threefold increase in productivity was obtained by adopting the new technology; this process was assisted by scientists from ICRISAT and the University of Agricultural Sciences (UAS), Karnataka. ICRISAT's inputs emphasized analysis of crop phenological stages, characterization of moisture availability and periods of moisture deficiencies, and introduction of appropriate crops and varieties in relay or sequential cropping systems. Cropping systems were chosen on the basis of optimum sowing times, so that a crop would not encounter severe water stress during its growth. Introduction of innovations such as improved implements for land management, fertilizers, and seed placement were given priority.

Résumé

Adoption de la technologie améliorée de la gestion des Vertisols dans l'Etat de Karnataka en Inde—une étude de cas : *La technologie traditionnelle utilisée pour la production alimentaire dans les régions de Vertisols du Karnataka (pluviométrie annuelle moyenne : 620 mm) peut à peine satisfaire les besoins d'une population en augmentation continue. La pluviométrie aléatoire a obligé les cultivateurs d'adopter des pratiques qui mettent l'accent sur la stabilité des rendements sans permettre l'amélioration de la productivité.*

De percées récentes dans la technologie, grâce à l'application des systèmes de production améliorés mis au point par l'ICRISAT, ont multiplié des rendements au niveau opérationnel de recherche au cours de 1982/83 et sur une superficie plus grande de 277 ha au cours de 1983/84. Ce résultat a entraîné une plus large acceptation parmi les paysans dans cette région. En 1984/85, cette technologie avancée a été adoptée sur 961 ha dans neuf districts (31 emplacements) de l'Etat. La technologie a eu un impact positif sur les paysans disposant des bassins versants aussi bien que ceux qui n'en ont

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pas. Les deux éléments de la technologie—la gestion du sol et les systèmes culturaux—ont été adoptés avec un certain degré de succès par les deux groupes de cultivateurs.

La productivité a augmenté deux ou trois fois grâce à cette technologie. Cette expérimentation en milieu réel a été assistée par les chercheurs de l'ICRISAT et de l'Université des sciences agricoles du Karnataka. Les composantes des intrants soulignées par l'ICRISAT consistaient en l'analyse des stades phénologiques de la plante, la caractérisation de la disponibilité en humidité et des périodes de stress hydrique ainsi que l'introduction des cultures et variétés appropriées dans les systèmes séquentiel ou de relai. Les systèmes de cultures ont été choisis en fonction des dates de semis optimales afin qu'une récolte puisse échapper au stress hydrique sévère pendant sa croissance. La priorité a été accordée à l'introduction des éléments comme des outils améliorés pour la gestion du sol, des engrais et des pratiques de semis.

Introduction

The total area under cultivation in the State of Karnataka is 10.3 million ha, and 8.2 million ha of this is dryland, much of it without any prospect of irrigation. Forty percent of the dryland area is covered with deep, medium, and shallow black soils, which are mainly Vertisols and associated soils.

Although these soils are said to be productive, there always is a risk of crop failure due primarily to climatic factors. The tropical climate—with its high incidence of solar radiation, high temperatures, and unreliable rainfall with spells of drought and flood—determines agriculture in most of the Vertisol tracts of Karnataka.

This tract receives a mean annual rainfall of 620 mm, ranging from 470 mm in parts of Chitradurga to 785 mm in Dharwad and Belgaum districts. Rainfall during the longest part of the rainy season, May to August, is unreliable. And some 50% is received during the months of September-October; this rainfall is commonly of very high intensity, resulting in very high runoff. Rainfall unreliability during the first part of the rainy season often deters farmers from attempting rainy-season crops. The high moisture retention capacity of Vertisols, however, and the concentration of rainfall towards the end of the rainy season, have led to the farmers' traditional practice of generally growing crops in the postrainy season, using moisture stored in these soils.

The most serious problems of these medium-to-deep, calcareous, smectitic soils is a low infiltration rate, which causes loss of water from high-intensity rains as runoff and thus reduces the amount of moisture stored in the soil. Other problems are related to the Vertisols' clay content: these soils can be difficult to cultivate because they are extremely sticky when wet and hard when dry. The heavy soil texture, the primitive implements used, and the weak draft animals used to pull them, make timely soil-tillage operations difficult. The soils commonly have a low hydraulic conductivity in the subsoil, thus resulting in waterlogging and erosion during short spells of high-intensity rainfall. Finally, fertilizer inputs are needed to correct serious deficiencies of nitrogen, phosphorus, and zinc.

The major crops grown in Vertisol areas are sorghum, mung bean (greengram), pigeonpea, chillies, and cotton. Traditional systems of land management and crop production give only a low productivity; average yields (kg ha^{-1}) are 880 for cereals, 400 for pulses, and 470 for oilseeds.

Such a level of productivity is barely sufficient to meet the food requirements of the population in these areas. There are several problems related to soil moisture, such as the fact that crops are generally grown under receding moisture conditions; soils develop cracks about 6 weeks after the last rains. The rainfall pattern limits the flexibility of average farmers to improve productivity through their traditional farming systems. The farmers' operations have insufficient potential for productivity increases to support their requests for credit, particularly of the small and marginal farmers who constitute the majority of the farming community in this area; the vicious circle has long remained unbroken, and farmers in these areas have remained the most neglected unit of economic strata.

Major constraints to increasing the productivity in these areas include:

1. scanty and variable distribution of rainfall;
2. lack of readily available, location-specific, improved technologies for extension personnel to recommend strongly to the farming community;

3. farmers' lack of confidence in improved seeds, fertilizer application, and plant-protection measures; and
4. low economic status of farmers because of the low level of land- and crop-management practices used.

Breakthrough in Vertisol Management in Karnataka

Recent advances in technology—as a result of research by scientists at ICRISAT, the Indian Council of Agricultural Research (ICAR), and UAS, Bangalore—have brought new hope to farmers in these areas. Improved cropping systems play a dominant role in the technology and have increased yields twofold to threefold. These systems generally focus on the most efficient use of available rainwater for crop growth. Improved land and water management, in addition to appropriate cropping systems development, is now perceived to be critical in minimizing the destabilizing effect of adverse seasonal conditions. Dry spells during the main cropping season, through the failure of rain, determine the success or failure of the crop. The incidence of dry spells recorded during the past 30 years (1944-1974) is presented in Table 1, emphasizing the likelihood of moisture deficits for crops grown during the rainy season.

For growing crops during the postrainy season, it is essential that moisture be conserved in the profile during the rainy season. Therefore, the main emphasis in technology development for Karnataka has been on soil-moisture conservation techniques and on suitable crop varieties for minimizing risk. In addition, we urge that farmers invest in seeds of high-yielding varieties and in recommended doses of fertilizer to obtain significant increases in yield levels.

Improved Management of Vertisols

The dryland agricultural production technology, evolved by ICRISAT, was initially introduced in Karnataka on a pilot basis during 1982/83, over a small area of 16 ha at Farhatabad village in Gulbarga District, and over 8 ha at Andura village in Bidar District. Assistance, training, and supervision was provided by ICRISAT scientists.

Results indicate that sorghum, groundnut, maize, and sesame intercropped with pigeonpea or mung bean, followed by postrainy-season sorghum or safflower, gave excellent results, despite moisture deficits and dry spells. Experience from this first operational research project at Farhatabad and Andura instilled confidence in the staff of the State Department of Agriculture to expand the activity further during 1983/84. We planned to cover 500 ha in six districts (Gulbarga, Bidar, Dharwad, Bellary, Raichur, and Belgaum), and we succeeded in covering 277 ha in five districts.

Components Adopted

The main components of the improved technology adopted in these districts included the following:

Land development on watersheds. Using the expert advice of scientists, farmers were taken into confidence through various extension methods. Land was smoothed, undulations were removed, waterways were provided, land was laid on broadbeds and furrows, and provision was made for rainfall recycling systems in the holdings of farmers within the watershed.

Evolution of suitable cropping systems. After analyzing the rainfall data over 30 years, a rainfall probability chart was prepared for each location. Based

Table 1. Incidence of dry spells during the main cropping season (May to August) in selected locations in Karnataka in a 30-year period (1944-1974).

	Frequency of incidence (% of years)			
Nature of dry spell	Bangalore	Kolar	Tumkur	Chitradurga
More than 15 days, once a year	19	27	18	18
More than 15 days, twice a year	4	17	4	3
More than 30 days, once a year	4	11	4	10

on the total moisture availability and the water-holding capacity of the soil, cropping systems that allowed crops to be successfully grown with least risk were selected. Since moisture is the primary limiting factor, it was essential to have a proper choice of crops and varieties to suit each district, keeping in view differences in the amount of rainfall and moisture-holding capacities of the soils. Different crop phenological stages were analyzed and identified to arrive at typical moisture availability and periods of moisture deficiencies. Crops and varieties were identified, and their optimum sowing times were determined so that plants would not encounter severe water deficits. Care was taken to design intercropping, relay cropping, or sequential systems to provide for the various combinations of moisture available from precipitation.

Design of land management systems. The practice of early land preparation, by plowing immediately after the previous crop and taking advantage of early showers and premonsoon rains for raising a rainy-season crop, was followed.

Introduction of improved implements. Improved implements (such as the Tropicultor) were used to facilitate land preparation, reduce strain on the animals, and improve conservation and retention of soil moisture. Appropriate tools and machinery were used to place seed and fertilizer at the proper depth for effective plant population control and germination. Appropriate plant protection equipment was also used.

Dry seeding of crops. The selected crop was planted before the rainy season to ensure moisture availability for crop growth. (If, however, rainfall analysis indicated uncertainty of the initial rains, we advocated planting only after the rains arrived).

Fertilizer. An adequate amount of fertilizer was applied, based upon soil chemical analysis, the crop's requirement, and the availability of moisture. We improved the organic-matter content of the soil to increase both fertility status and moisture-holding capacity.

Moisture conservation systems. Crops were hoed, to minimize surface cracks and to break capillaries for moisture conservation. Weeds were removed to reduce competition for moisture and available nutrients.

Plant protection. Timely and need-based plant protection systems were adopted. Farmers were trained to identify pests and to adopt suitable recommendations for appropriate plant-protection measures.

Training/education. Formal training programs were provided to in-service personnel, at ICRISAT Center for subject-matter specialists and at our Training Centre for field-level staff. Farmers in the area were trained about all stages of the technology, from harvest of the previous crop to harvesting of the newly introduced crops.

Credit. Financial assistance was arranged through local cooperative credit societies and agricultural development banks. This credit was used to invest in inputs and land preparation and to support production activities.

Marketing. Market support through effective marketing systems was provied to farmers so they might derive maximum benefit from the investments made.

Review and evaluation. After harvest, we discussed all details of the previous year with the farmers so that they would be encouraged to continue to use the technological innovations. These discussions also provided feedback for further recommendations to other farmers in that area for sustaining adoption.

The 1984/85 Program

Motivated by success during 1983/84, we undertook advance planning to expand the system from those 277 ha to at least 1000 ha in nine districts (Bellary, Bidar, Chikmagalur, Chitradurga, Dharwad, Gulbarga, Hassan, Mysore, and Raichur) in the next year. We succeeded in covering 961 ha (Table 2). The results are quite encouraging. The major contributions of this advanced technology can be summarized as follows.

Hybrid sorghum (CSH 5) cultivation was introduced for the first time in this area during the rainy season; farmers harvested as much as 2100 kg ha^{-1} of cereals and 460 kg ha^{-1} of pigeonpea, despite dry spells during 1983/84. This compared to their best yield of 910 kg of cereals in any year using traditional varieties. High-yielding varieties of pigeonpea (PT-

Table 2. Vertisols brought under ICRISAT technology in Karnataka during 1984/1985.

District	Number of testing centers	Area (ha)
Belgaum	4	30
Bellary	2	22
Bidar	5	220
Bijapur	3	50
Chikkmagalur	1	10
Chitradurga	1	10
Dharwad	9	182
Gulbarga	4	410
Raichur	2	27
Total area		961

221, HYD-3C, TTB-7, ICPL 87) caught the imagination of the farmers involved. Not only did farmers fully adopt the watershed concept, but also they influenced farmers outside the watershed to adopt these varieties. Farmers in villages near the watersheds have realized that they can expect to harvest a grain yield of at least 1500 kg ha^{-1} even in the worst drought year, if only good land-management practices are followed and appropriate varieties are used. Use of improved agricultural implements for seed and fertilizer placement has become popular. Recommended doses of fertilizer under rainfed conditions are being applied to rainfed crops. Farmers have been able to evolve local methods and implements to meet the technological recommendations for land- and crop-management systems, both for moisture conservation and effective moisture use. Personnel from the credit banks have recognized the potential of this new technology on dryland farming as a bankable proposition, because the system has the intrinsic potential for minimum guaranteed returns.

The S-W-O-T Approach

We use our S-W-O-T analysis (Strengths-Weaknesses-Opportunities-Threats) to assist in formulating our extension approaches.

Strengths

1. The system can improve the economic conditions of the farming community by increasing yields twofold to threefold.
2. For every rupee spent, there is an assured return of Rs.2.00–5.50, depending upon the soil fertility and moisture-conservation system adopted and the rainfall.
3. The system improves the health of the soil by increasing its organic-matter and nutrient status.
4. Production of both cereals and pulses enables a better-balanced diet for the population at the village level.

Weaknesses

1. Dry seeding is not always successful.
2. The system requires heavy investment from an external source in the initial stage; there is a demand for credit input because dryland farmers themselves cannot initially generate the required financial resources.
3. Farmers need high-level, technically knowledgable personnel at the site to evolve cropping systems that can succeed at an 80% probability level.
4. Inputs must be available at the field level when the farmer needs them most; often fertilizer, seeds, and insecticides are not available at the village level.
5. High-level management is required to ensure linkages between availability of credit and supply of inputs.
6. There is need for reliable data, based on weather reports.

Opportunities

1. The system can provide a quick and lasting change in the economic system of the farming community.
2. It provides scope for scientists to evolve recommendations that can find quick adaptation.
3. It is an unexplored field for banking institutions to provide loans.
4. Benevolent governments should find the improved system an excellent means to better the lot of the rural population economically.
5. The state can satisfy food-production needs quickly, even through rainfed farming.
6. The system can provide an opportunity to introduce rural-based agroindustries in rainfed areas.
7. Industries manufacturing implements, fertilizers,

insecticides, seeds, and other inputs will find immense scope for increasing their activity in these areas.

Threats

1. Experiments with the unfamiliar technology without a proper database may fail to provide results, leaving doubts in the minds of farmers about the technology.
2. Ill-considered rural market conditions for the increased production might deter farmers from higher investment on their land in a sustained manner.
3. Recommending improved practices on a thumb-rule basis, without fine tuning by the specialists, may lead to failure.
4. Nonavailability of alternate varieties and crops may endanger sustained adoption of the system.

Discussion

Purnell: You mentioned "adapting to the climate." Do you also adapt to the soils?

Sampath: Yes, in some areas where the annual rainfall is less than 760 mm, and during the main rainy season it is less than 460 mm, we did not use the broadbed-and-furrow system. Under very low rainfall we tried the furrows; and under the lowest rainfall, we used the broad-block system.

Eswaran: I was very impressed by your sequential cropping system. You said that one of your problems was to provide a buffer stock of seed. This problem will increase as more farmers adopt the system.

Sampath: Yes, we are giving great attention to this problem of bringing seed and fertilizer at the right time to the right place.

Methods of Technology Transfer

Approaches to Agrotechnology Transfer, Particularly among Vertisols

L.D. Swindale[1]

Abstract

Greater efforts than at present are needed to transfer agricultural technology from place to place and country to country. Such transfer now occurs mostly by trial and error but more scientific approaches are being developed. Both (1) models that simulate biological processes and (2) regression equations relating crop performance to input and site-factor variables have great potential, but they have had only limited success to date. Methods of analogous transfer are currently more useful, particularly for transferring data for soil-based technologies.

In soil science, analogous transfer must be based upon a sound and accurate system of soil classification, such as Soil Taxonomy. In a fairly homogeneous soil order, such as the Vertisols, transfer of agricultural technology may be successful at the level of phases of subgroups or great groups, but care must be taken that characteristics important to their use and management are not overlooked. Transfer at the level of the soil family should be possible. Transfer to similar families in the same subgroup and to parallel families in related subgroups and great groups can be conjectured with considerable confidence, but empirical evidence is needed to test the hypotheses and to help refine the classification of these soils. Because Vertisols occur extensively in the semi-arid tropics and have production potentials well above their present levels of use, there would seem to be a fairly high priority for this research.

Vertisols occur extensively in central India, and their potential far exceeds their present use. Improved technologies have been developed on the same benchmark Vertisols and are currently being tested on others. The results of such tests on known kinds of soils can be combined with the average yields obtained by better farmers on soils of significant areal extent to develop soil suitability ratings. Once such ratings are available, soil suitability maps can be drawn for local development planning. Detailed and reconnaissance soil surveys provide a reasonable coverage of the pattern of soil distribution in a region, allowing soil suitability maps appropriate for large-scale regional planning to be drawn. Such maps can provide a basis for successful investment and ultimate improvement in agricultural production and the welfare of the people.

Résumé

Méthodes de transfert de technologie agricole, particulièrement dans les Vertisols : *De gros efforts sont nécessaires pour transférer la technologie agricole d'un endroit à l'autre et d'un pays à l'autre. Un tel transfert se produit maintenant, surtout par tâtonnement, mais des méthodes plus scientifiques sont à l'étude. Les modèles qui simulent des processus biologiques ainsi que les équations de régression qui lient la performance de la récolte aux variables d'intrants et de milieu ont un énorme*

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potentiel, mais n'ont eu que peu de succès jusqu'à présent. Des méthodes de transfert par analogie sont plus couramment utilisées, surtout pour ce qui concerne le transfert de données relatives aux technologies fondées sur le sol.

En pédologie, un transfert par analogie doit être fondé sur un système précis de la classification du sol, comme la "Soil Taxonomy". Dans un ordre de sol relativement homogène, comme les Vertisols, le transfert de la technologie agricole peut réussir au niveau des phases de sous-groupes ou grands groupes, mais il faut faire attention à ce que les caractéristiques importantes pour leur usage et aménagement à un niveau plus élevé ne soient pas négligées. Le transfert au niveau de la famille du sol devrait être possible. Le transfert à de telles familles dans le même sous-groupe et à des familles parallèles dans des sous-groupes et grands groupes connexes peut être considéré avec beaucoup de certitude, mais une évidence empirique est nécessaire afin de vérifier les hypothèses et d'aider à raffiner la classification de ces sols. Du fait que les Vertisols se trouvent de manière extensive dans les tropiques semi-arides et possèdent des potentiels de production bien en dessus de leurs niveaux actuels d'utilisation, il semblerait que cette recherche mérite une forte priorité.

Les Vertisols sont très étendus en Inde centrale. Des technologies améliorées ont été développées sur un Vertisol type et leur réussite sur d'autres Vertisols est en train d'être largement vérifiée. Les résultats de ces tests, sur des types de sols connus, peuvent être combinés avec les rendements moyens obtenus par de meilleurs agriculteurs sur des sols d'une étendue bien plus grande, afin de développer une classification d'aptitude des sols. Une fois que ces classifications sont disponibles, des cartes d'aptitude des sols peuvent être dressées en vue de la planification du développement local. Des cartes de sols de reconnaissance ou détaillées fournissent un aperçu raisonable du modèle de la distribution du sol dans une région permettant de dresser des cartes d'aptitude du sol qui conviennent à l'élaboration d'une planification régionale à grande échelle. De telles cartes peuvent fournir la base d'un investissement positif et d'une amélioration ultérieure de la production agricole et du bien-être de la population.

Introduction

Greater efforts than at present are needed to develop efficient methodologies for agrotechnology transfer from place to place and country to country. If present production and consumption trends continue, by 1990 the developing countries will face a deficit in staple food crops of 140 million tonnes—about three to four times the current deficit. Because such countries—except perhaps those with large oil resources—cannot afford to import so much of their basic foods and feeds, they must reverse the present trends by achieving greater increases in food production. Most of the increase must come from more intensive use of existing arable lands, and this means more efficient use of soils.

Because many soils are being used far below their potential, there is much scope for intensification. For example, in India, where almost all soils are already in use, current annual production is 2 billion tonnes of grain equivalent, but the potential is more than 4 billion tonnes. In India, and probably elsewhere, the greatest potential for increasing production lies in the savanna areas of the semi-arid and subhumid tropics. Although insufficient water is a problem, particularly in areas under rainfed cultivation, new technologies now exist or are being developed through agricultural research for wise and efficient use of these lands. Agricultural research contributes significantly to increases in production, but research costs are high and increased efforts are needed to make agricultural research more efficient. Many small developing countries do not have the research resources needed to solve all of their problems.

Concepts for Agrotechnology Transfer

The successful transfer of technologies from place to place, even within the semi-arid and subhumid tropics, is not easy. If we critically examine the successful transfer of agrotechnology in the world in recent years, we are struck by the fact that it is seed-based technology that has created the impact. Seed has been the vehicle of change. Furthermore, technologies have moved faster in irrigated areas or in areas with assured rainfall. The technologies have been based mainly on sole cropping under low risks. The commodities involved are well-known in the world market, and production and prices are influenced by world market trends.

Soil-based technologies—i.e., technologies to improve the productivity of certain soils—tend to be specific to the soils for which they are developed. They have high site-factor constraints (Swindale 1980). A soil, unlike a seed, is part of the landscape and cannot be moved physically from place to place. Spatial variability of soils is high, particularly in the tropics where soils are also less well understood. These factors make transfer of technology difficult.

In addition, technology transfer must take other environmental factors and socioeconomic differences into account. Agricultural technology cannot be successfully transferred without local adaptive research (Evenson and Binswanger 1979), and the amount and cost of such research is directly related to the magnitude of the site-factor constraints. If the site factors of the test location are not too different, the cost of the necessary adaptive research will not be so high.

In addition to the most common approach of using trial and error, three scientific approaches exist, in principle, to equate site-factor variables and constraints across locations. They are simulation models, statistical relationships, and analogous reasoning (Nix 1980).

Simulation Models

Simulation models attempt to mimic biological processes through physical laws and relationships, and, inherently, they should provide the best method for overcoming high site-factor constraints. For a single crop system on similar soils, climate-driven models should be successful because variations in climate essentially determine year-by-year crop yields (see, for example, Lemon et al. 1971).

The incompleteness of scientific knowledge and the complexity of the technologies and of the models themselves are barriers to the use of simulation, and there are few examples of its successful application. The successful development of simulation models requires an intensive multidisciplinary effort, and this is often difficult to achieve.

Although simulation models cannot yet be said to be usable for agrotechnology transfer, they are important aids to research (Innis 1975). They codify existing knowledge in highly systematic forms and help in the design of significant experiments. In developing and testing such models, we discern the minimum sets of data required at various levels of prediction. It is worth mentioning that minimum data sets for agrotechnology transfer by simulation invariably require data on climate, soil moisture (which is highly dependent upon the nature of the soil), and crop phenology. Seldom are these data collected in scientific experiments.

Empirical Statistical Relationships

Empirically devised statistical relationships are being used for agrotechnology transfer. The biological productivity—and, particularly, the yield—of a crop is empirically related to input and resource variables, usually by correlation and multiple linear regression. The data used to derive the statistical relationships are obtained from experiments or production records from a range of environmental conditions over time. The resulting correlations or regression equations, after validation, are used to predict productivity in future years or at new locations. Obviously, statistical predictions can be made with much more confidence at interpolated than at extrapolated sites.

Many examples of statistical predictions exist in the research literature, particularly in relating crop responses to applications of fertilizer and water. Some examples, in which soil-factor variables have been considered, are the equations developed by Voss et al. (1970), Runge and Benci (1975), and Culot (1981). Heady (1981), in referring to the many studies of this type with which his name is associated, has pointed out that they are limited in their application to several adjoining counties or states and cannot be used, except in principle, for intercountry transfer. Parametric methods of measuring the potential productivity of soil belong in this category. They are generally based on easily measured properties of the soil and tend to be rather site-specific (Beek 1978).

Analogous Transfer

In methods of analogous transfer, an attempt is made to stratify the environment sufficiently precisely to ensure successful transfer of technology (Swindale 1980). Areas analogous to the experimental site are identified by climate or soil classification.

Although climatic networks are extensive throughout the world, they have hardly been used for the purposes of transferring technology. The data gathered and hence the classifications are not sufficiently related to agriculture. Partial exceptions are the classifications made by Papadakis (1965, 1970). More recent efforts to use pattern analysis (Russell and Moore 1976) and reference climatic sites around the world (Shaw and Hill 1975) suggest that the usefulness of climatic classification for agrotechnology transfer is now being actively explored. No attempts have yet been made to validate climate classifications experimentally.

The development of soil classifications suited to agrotechnology transfer has been far more successful. The prime example of a general soil classification useful for such purposes is Soil Taxonomy (USDA 1975). Specific soil classifications for transferring a limited range of agricultural knowledge, such as probable crop responses to fertilizer have been developed—for example, the soil fertility capability classification by Buol et al. (1975).

Analogous Transfer in Soil Science

In Soil Taxonomy there are six taxonomic levels of classification: order, suborder, great group, subgroup, family, and series. Within each level the stratification of soils becomes narrower—i.e., the soils become more similar—and technology transfer can be made with greater confidence as one descends through the levels from order to series. Only in relatively homogeneous orders and suborders, such as Vertisols, Histosols, and Andepts, can useful interpretations be made at the order or suborder levels.

The **soil family** is the level in Soil Taxonomy most relevant to transfer of technology from place to place. By definition, the family groups soils within a subgroup having similar physical and chemical properties that affect their responses to use and management. The responses of comparable phases of all soils in a family are supposed to be nearly enough the same to meet most needs for practical interpretations of soil use.

In the United States, soils classified into the same phase of a family are placed in the same soil performance group or class. It must be noted, however, that there is an average of only five soil series in each soil family in the U.S., and that there are many families containing only a single series. The family is almost as narrow a stratification of soils as a soil series.

Most interpretations of soil use are currently made at the level of phases of soil series. The mapping units in detailed soil survey maps are usually identified as phases of soil series, and are the units the farm planner and extension worker normally use at the local level to advise farmers. Nichols (1988) has described in detail the many types of interpretations for technology transfer that are possible in the United States at the level of the soil series.

In Nichols' paper, high levels of inputs and management are presumed in making interpretative statements. Such an assumption cannot be made as a general rule in dealing with agricultural interpretations in tropical areas, and certainly not in the drylands of India where farmers' actual production is 25% or less of the potential yields revealed by research. To overcome this problem, the U.S. National Soil Handbook (USDA 1983) recommends three levels of management for soil survey interpretations of arable land: Level A is the combination of management practices used commonly by successful farmers for the soil being considered; Level B is a combination of superior management practices followed by farmers who obtain yields of crops well above the average; Level C is the optimum combination of management that can be defined as the full application of the current state of knowledge and techniques of crop production. Information for management levels A and B is obtained from surveys of farmer practices. For Level B the information gained from these surveys needs to be supplemented by agronomic research on farmers' fields. Data for Level C are generally obtained from agronomic research.

Agrotechnology Transfer Applied to Vertisols in India

In India most Vertisols occur on the Deccan plateau in central India, dispersed over a vast area from Gwalior in the north to Raichur in the south and extending through six States. The soils are developed *in situ* from the Deccan trap rocks (mostly augite basalts) and other base-rich rocks and from colluvium and alluvium derived from these. Most of the soils lie between 300 and 900 m above sea level on flat to undulating surfaces. Natural vegetation is dry deciduous forest, but most of the soils are now under cultivation.

Sorghum, maize, and pearl millet are the main cereal crops under dryland farming; pigeonpea, mung bean, and chickpea are the main pulses; safflower the main oilseed; cotton the main industrial crop. Soybean production is increasing on the wetter soils. Sugarcane, paddy rice, wheat, and cotton are grown under irrigation. Intercropping is common in rainfed agriculture (Jodha 1980). Although many crops are grown together, the major combinations are sorghum/pigeonpea, cotton/pigeonpea, and cotton/sorghum/pigeonpea. The mixtures usually combine crops with different maturity lengths, drought-sensitive with drought-resistant crops, cereals with legumes, and cash crops with food crops.

Much of the land is fallowed in the rainy season, because the rainfall is either erratic or so high that it causes problems in land management. Fertilizers and agricultural chemicals are seldom used in rainfed farming. Land preparation, using bullock-drawn implements, is usually limited to loosening the surface soil in February or March or before the soils dry out too much. The use of a blade harrow is common to break up the soil and remove weeds just before planting. Yields are low, about 800 kg ha^{-1} for nonirrigated sorghum.

The potential of these soils significantly exceeds current average yield, but new technologies are now available that better exploit this potential. Sorghum yields of 4600 kg ha^{-1} and maize yields of 3100 kg ha^{-1} have been obtained in intercrops with pigeonpea over 3 years without irrigation on Vertisols at ICRISAT. Higher yields, often exceeding 5500 kg ha^{-1} of sorghum, are obtained with sole crops. Over the last 10 years, ICRISAT scientists have evolved a technological package that can greatly increase the productivity of Vertisols in India. The package increases annual cropping intensities and decreases soil erosion during the rainy season (Virmani et al. 1989).

The Vertisol at ICRISAT, for which this improved technology was developed, is classified in the Kasireddipally series and is a member of the fine, montmorillonitic, isohyperthermic family of Typic Pellusterts. Some characteristics of this soil are shown in Table 1. Crops respond to the application of N, P, and Zn, and profitable responses by improved cultivars have been obtained with 80 kg N and 5 kg P ha^{-1}. Maize is more responsive to inputs than either sorghum or pearl millet.

Table 1. Some characteristics of the Kasireddipally soil[1] (from Swindale 1982).[2]

Horizon	Depth (cm)	Moist color	Particle-size analysis Sand (%)	Silt (%)	Clay (%)	Organic C (%)	pH (H_2O)	CEC[3] (C mol kg^{-1})	Base sat (sum) (%)	Volumetric water content[4] f.c. (cc cc^{-1})	w.p. (cc cc^{-1})
Ap	0-25	10YR3/1	22.0	19.1	57.4	0.96	8.1	56.5	90	0.40	0.27
A11	25-70	10YR3/1	18.6	17.2	64.0	0.69	8.2	60.8	97	0.44	0.27
A12	70-143	10YR3/1	15.8	17.9	65.8	0.60	8.0	54.9	99	0.44	0.27

1. Fine, montmorillonitic, isohyperthermic family of Typic Pellusterts.
2. See Table 3.
3. CEC = cation exchange capacity.
4. FC, Field capacity; WP, Wilting point.

The soil has high available water-holding capacity. In the first meter of the fully charged soil, 165 mm of water is available to crops; at a soil depth of 1.8 m, over 300 mm of water is available. Virtually all this water is available to plants, but lack of full root penetration below the 40-cm depth reduces water use by about 30% (ICRISAT 1978, pp. 185-186). The hydraulic conductivity of the soil is low—of the order of 1 mm day^{-1} at 100 millibars soil moisture tension—and vigorous root growth is necessary for plants to exploit the soil water at depth.

The infiltration rate of the dry soil is very high (70 mm h^{-1}) because of the many cracks; permeability drops to very low values (0.2 mm h^{-1}) once the soil is saturated. Under a transpiring crop, the surface cracks open after a few days without rain. For this reason, runoff from cropped Vertisols is usually less than runoff from cropped Alfisols.

The soil is very susceptible to erosion. The common traditional practice of fallowing the land during the rainy season leads to severe runoff and loss of soil. In a wet year as much as 10 t ha^{-1} of soil may be lost from fallowed land. Surface treatment, particularly the use of ridges, broadbeds, or bunds, can reduce soil loss by 50% or more, but crop cover even without land treatment reduces soil erosion much more (Binswanger et al. 1980). The use of ridges, broadbeds, or graded bunds also helps improve surface drainage, which is often a problem during the rainy season.

The improved technology developed for the Vertisols at ICRISAT should be well-suited to all soils in the Kasireddipally series, which are deep soils on slopes less than 3% and occupy some 26 000 ha in the State of Andhra Pradesh. It should also be well-suited to all soils more than 80 cm deep on similar slopes in the same soil family (fine, montmorillonitic, isohyperthermic family of Typic Pellusterts) wherever they occur in India or elsewhere. Moreover, this same technology should also be well-suited to soils in other families in the same suborder. For example, because the technology depends upon a minimum of 200 mm of water available in the soil, it should, other things being equal, be suited to soils in very fine-textured families, which should have larger amounts of available water than fine-textured families.

On the other hand, a technology suited to soils in isohyperthermic families may not be suited to soils in hyperthermic families because winter temperatures may be too low for some of the crops used in the improved technology.

The technology may also be successfully transferable to soils in parallel families—i.e., to fine, montmorillonitic, isohyperthermic families of other subgroups or even great groups. For example, the ICRISAT technology suited to Typic Pellusterts is likely to be applicable also to parallel families of Udic Pellusterts, which occur in slightly higher rainfall regions. On the other hand, it may not be as well-suited to parallel families of Typic Chromusterts, which have higher chromas indicative of more weathering and perhaps less montmorillonite—and which occur on better-drained or drier sites with less available water.

Land Suitability for Improved Vertisol Technology

The National Bureau of Soil Survey and Land Use Planning (NBSS and LUP) of the Indian Council of Agricultural Research (ICAR) and ICRISAT have embarked upon a cooperative research project to determine the suitability of the improved deep Vertisol technology to the Vertisols and associated soils in central India. The project is not complete, but some of the early results are of interest.

A target area of approximately 40 million ha has been included in the project, ranging from Gwalior in the north to Hyderabad in the south and from Jabalpur in the east to Aurangabad in the west (Fig. 1). The area contains most of the Vertisols that occur in India, including research sites which State departments of agriculture, ICRISAT, and ICAR have previously used in on-farm research and demonstrations of improved technologies.

At six sites within the area (see Fig. 1), soil scientists of the NBSS and LUP have made very detailed soil surveys at scales of 1:8000 or larger. Detailed information on current agricultural land use is being obtained for ten soil series (eight Vertisols and two Vertic Inceptisols) of significant areal extent in the region. The soils are classified in nine different families (Table 2).

The ten soils are remarkably uniform in their properties (Table 3). Coefficients of variation (%) for the eight Vertisols are 16.2 for depth of solum, 13.3 for percentage of clay, 10.3 for cation-exchange capacity, and 4.2 for mean annual soil temperature. Even when the two Vertic Inceptisols are added, the coefficients of variation for the last three characteristics remain small.

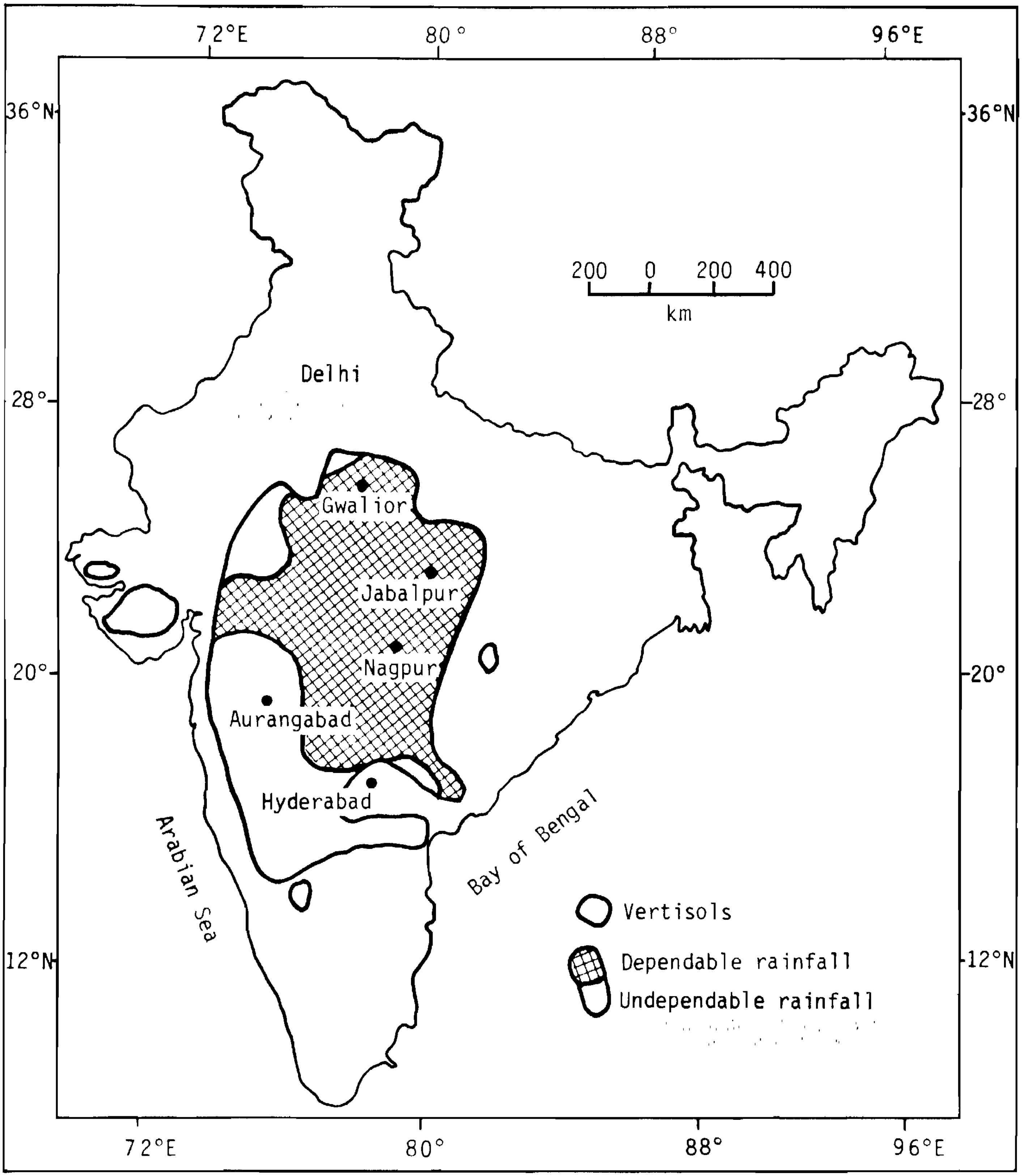

Figure 1. Target area for the improved Vertisol technology (Virmani et al. 1978).

Cropping patterns on the soils are complex (Table 4) and differ substantially among soil series (Table 5), particularly in the percentage of fallow in the rotation. Sorghum is grown on all the soils to some extent in either the rainy or postrainy season. Pearl millet is grown in the rainy season on soils in the west of the region where rainfall during the season is brief and irregular, and soybean in the rainy season on

Table 2. Description of 10 benchmark soils in central India[1].

Soil series	Locality	Area (ha)	MAR[2] (mm)	Mean air temp. Summer (°C)	Mean air temp. Winter (°C)	Soil family descriptors Texture	Soil family descriptors Mineralogy	Soil family descriptors Temperature	Subgroup name
Sarol	Indore	296 200	1050	32-33	17-18	fine	montmorillonitic	hyperthermic	Typic Chromusterts
Marha	Bundelkhand[3]	140 000	1330	32-34	16-18	fine	montmorillonitic	hyperthermic	Entic Chromusterts
Aroli	Nagpur	234 900	1125	32-37	20-21	fine	montmorillonitic	hyperthermic	Typic Chromusterts
Linga	Nagpur	293 300	1125	32-37	20-21	very fine	montmorillonitic	hyperthermic	Udic Chromusterts
Kamliakheri	Indore	255 800	1050	32-33	17-18	very fine	montmorillonitic	hyperthermic	Vertic Ustropepts
Kheri	Jabalpur	70 000	1440	32-34	15-17	very fine	montmorillonitic	hyperthermic	Typic Chromusterts
Sawargaon	Ahmadnagar	419 400	675	30-31	20-21	fine	montmorillonitic	isohyperthermic	Vertic Ustropepts
Nimone	Ahmadnagar	399 500	675	30-31	20-21	fine	montmorillonitic	isohyperthermic	Typic Chromusterts
Kasireddipally	ICRISAT	26 000	765	30-32	22-23	fine	montmorillonitic	isohyperthermic	Typic Pellusterts
Barsi	Sholapur	66 000	740	30-32	22-23	very fine	montmorillonitic	isohyperthermic	Typic Chromusterts

1. National Bureau of Soil Survey and Land Use Planning, ICAR.
2. MAR = mean annual rainfall.
3. Climatic data from Jhansi Research Center.

soils in the north of the region where rainfall is fairly high. Wheat and chickpeas are grown in the postrainy season in the more northerly soils.

Productivity obtained by the better farmers (30% of all farmers) under rainfed farming, measured in rupees, differs significantly between soil series. For two pairs of closely associated Vertisols and Vertic Inceptisols, where in each pair solum depth is the main discriminating characteristic, productivity under rainfed farming differed, but did not differ under irrigation (Fig. 2). Removal of the moisture-supplying constraint of the Vertic Inceptisols is obviously the reason for their improved performance.

Soil in the Nimone series, which is cropped mainly in the postrainy season, has lower productivity than the Linga soil, which is cropped mainly in the rainy season, and both have lower productivity than the Sarol soil, which is cropped in both seasons (Fig. 3). These differences between yields obtained by better farmers have not been tested for statistical significance, but average yields by all farmers of the main crops grown on the soils are statistically different. The soils are all in different families. It will, indeed, be very useful if surveys of yields obtained by better farmers—i.e. Level-B management—can be used to discriminate between soil families or, alternatively, to help define soils that need to be separated to make meaningful family classifications.

What remains to be done in the project is the development of soil suitability maps for the use of the improved Vertisol technologies throughout the region. The basic data for these maps exist from the trials and demonstrations of the technologies that have been carried out on soils that have been surveyed very intensively (scale of 1:5000). This information, combined with what we are learning about the performance under better-farmer conditions of soils with significant areal extent in the region, should allow us to produce reliable suitability maps for intensively surveyed soils (scales of 1:20 000 or 1:63 000). This information can then be extrapolated, perhaps through one or two intermediate steps, to soil maps at a scale of 1:1 000 000, which already exist for the entire region. Such maps can show associations of soil families and are suitable for regional planning.

Soil suitability maps at this scale, showing what areas are well-suited, moderately well-suited, or unsuited to particular technologies, accompanied by tabular and textual information defining the returns to be expected from the use of the technologies at

Table 3. Some properties of the 10 Benchmark soils in Table 2.

Soil series	Solum depth (cm)	Clay (%)	CEC[1] (C mol kg^{-1})	MAST[2] °C
Inceptisols				
Kamliakheri	45	63.5	62.1	26.4
Sawargaon	60	49.6	47.2	27.4
Vertisols				
Nimone	107	57.6	49.1	26.4
Aroli	120	59.6	56.3	28.4
Kasireddipally	130	61.1	58.9	27.4
Linga	140	74.5	62.2	28.4
Barsi	147	69.0	62.6	28.4
Kheri	150	63.4	64.1	26.4
Sarol	160	57.3	51.7	25.5
Marha	180	47.3	50.9	26.4
For the 8 Vertisols:				
Mean	142	61.2	57.0	27.2
CV (%)	16.2	13.3	10.3	4.2
For the 10 soils:				
Mean	124	60.3	56.5	27.1
CV (%)	34.6	13.5	11.2	3.8

1. CEC = cation exchange capacity.
2. MAST = mean annual soil temperature.

Table 4. Cropping patterns on the Kamliakheri soil series.

	First year		Second year		Percent of farmers using the pattern
Pattern	Rainy season	Postrainy season	Rainy season	Postrainy season	(n = 104)
1	Sorghum or sorghum/pigeonpea	Fallow	Sorghum or sorghum/pigeonpea	Fallow	29.8
2	Sorghum or sorghum/pigeonpea	Fallow	Fallow	Wheat or chickpea	19.2
3	Fallow	Wheat or chickpea	Fallow	Wheat or chickpea	2.9
4	Sorghum or sorghum/pigeonpea	Fallow	Soybean	Wheat or chickpea	6.7
5	Soybean	Wheat or chickpea	Soybean	Wheat or chickpea	21.2
6	Soybean	Wheat or potatoes or vegetables	Soybean	Wheat or potatoes or vegetables	20.2

Table 5. Average cropping patterns on six soil series.

Soil series	First year Rainy season	First year Postrainy season	Second year Rainy season	Second year Postrainy season	Average percentage of fallow Rainy season (%)	Average percentage of fallow Postrainy season (%)
Inceptisols						
Sawargaon	33% fallow 67% pearl millet	33% sorghum or wheat 67% fallow	50% fallow 50% pearl millet	25% fallow 25% wheat 50% sorghum	42	46
Vertisols						
Nimone	33% pearl millet 67% fallow	33% wheat 67% sorghum	33% fallow 67% chickpea	33% fallow 67% chickpea	50	16
Kamliakheri	3% fallow 40% soybean 57% sorghum or sorghum/pigeonpea	45% wheat or wheat in combination 55% fallow	25% fallow 30% sorghum or sorghum/pigeonpea 45% soybean	30% fallow 70% wheat/chickpea	14	42
Sarol	6% fallow 47% soybean 47% sorghum or sorghum/pigeonpea	45% fallow 55% wheat	20% fallow 20% sorghum or sorghum/pigeonpea 60% soybean	20% fallow 80% wheat/chickpea	13	30
Linga	33% cotton 67% cotton/pigeonpea	100% fallow	100% sorghum	33% fallow 67% wheat	0	67
Kasireddipally	15% fallow 15% mungbean 30% chillies 40% sorghum/pigeonpea	33% sorghum 67% fallow	20% mungbean 80% fallow	100% sorghum	50	33

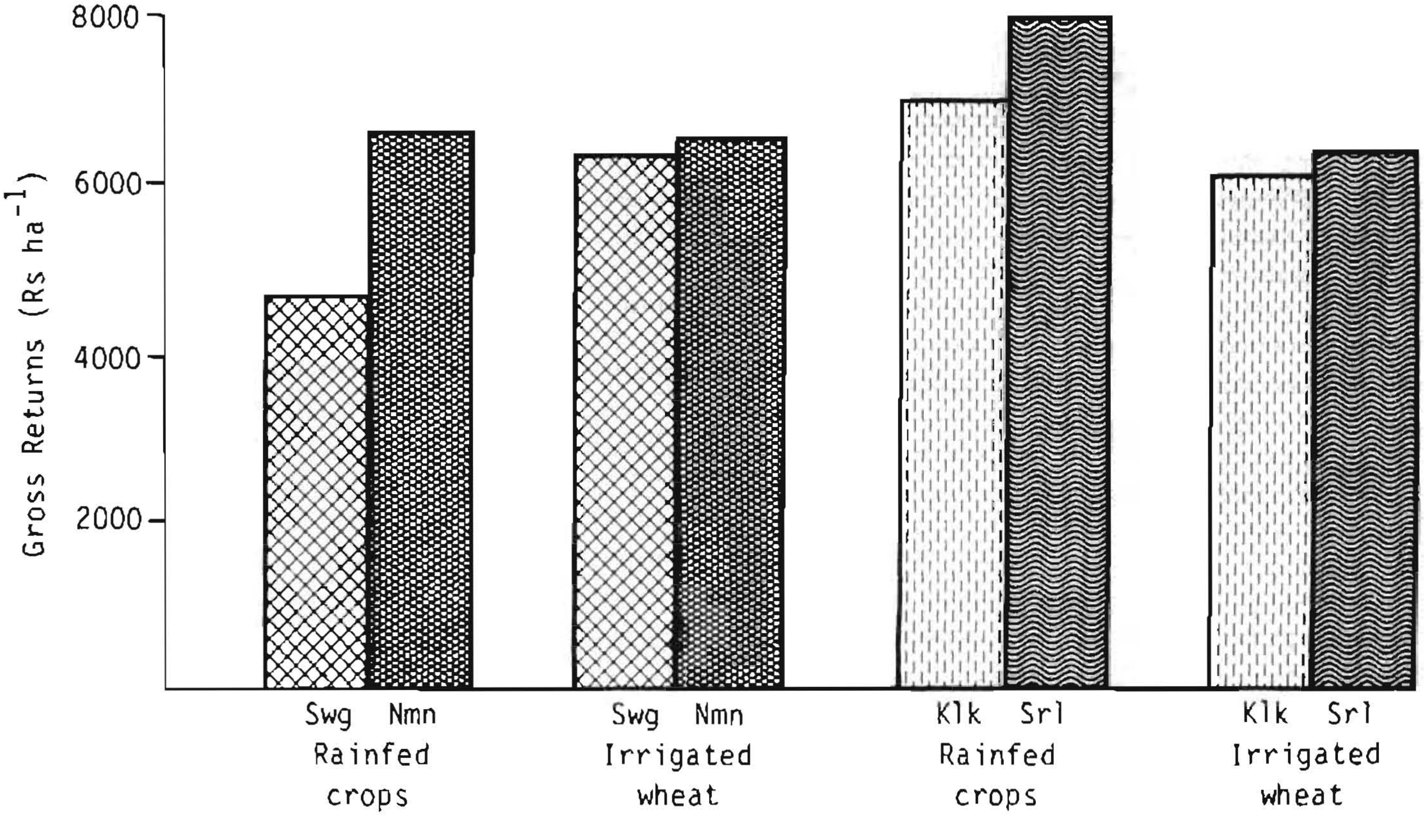

Figure 2. Rupee yields of associated Vertic soils in different orders (Vertisols: Swg-Sawagaon, Klk-Kanliakheri; Inceptisols: Nmn-Nimone, Srl-Sarol).

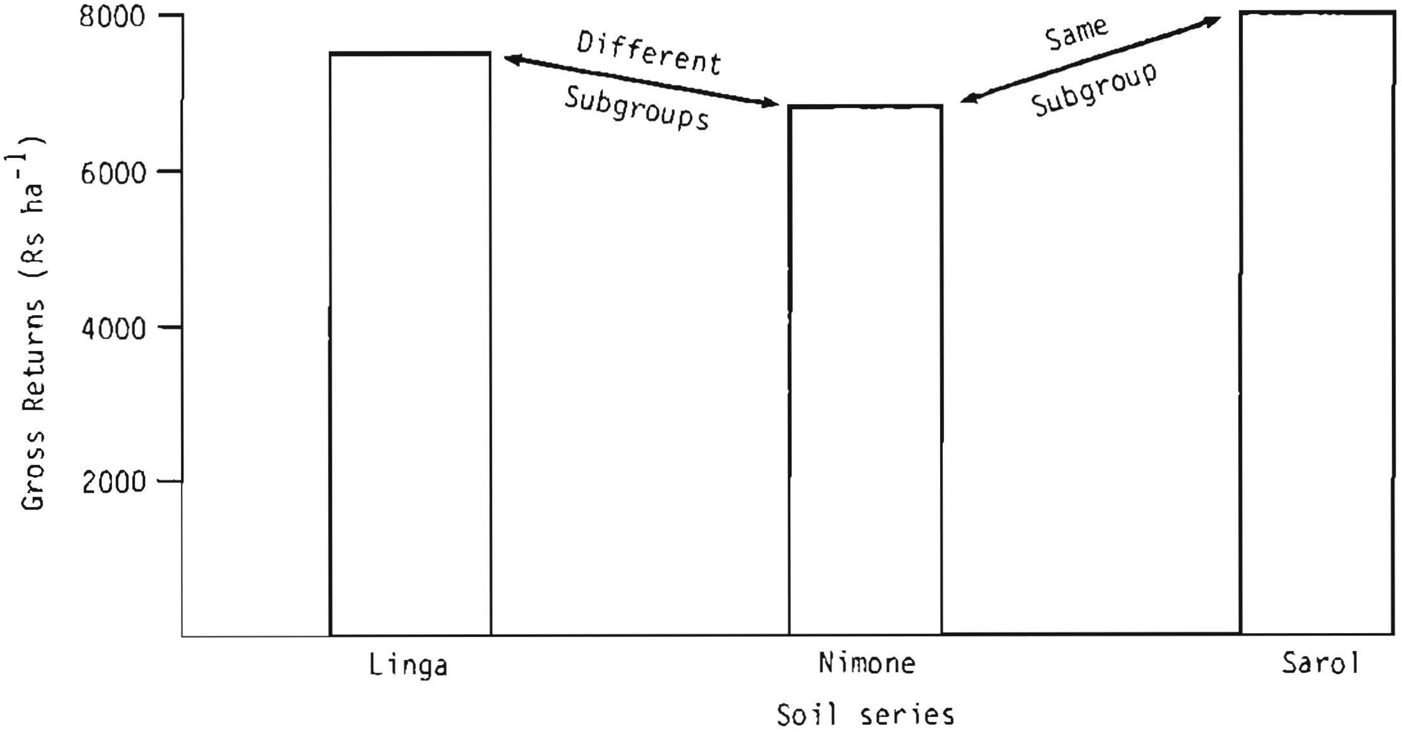

Figure 3. Rupee yields of Vertisols in different families.

various defined levels of management, will be the primary output of the project. The Union and State Governments in India consider the improvement of rainfed farming to be a major development priority. The maps and information from this joint ICRISAT/NBSS and LUP project will enable governments to encourage investment in those areas and in technologies that can be expected to profit farm families, provide good returns on investment, produce increased income streams and employment, and reduce soil and water losses. Increased rates of growth in agricultural production and improvements in the livelihood and welfare of the people will be the ultimate results.

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Discussion

Valverde: Dr Swindale, could you comment about the negative response of farmers to barley within the cropping systems developed by ICRISAT, and why you use barley as an example to demonstrate the productivity potential of both soils under irrigated conditions? Inceptisols and Vertisols are almost similar.

Swindale: In my last slide, I was referring solely to irrigated wheat and in this region a lot of the wheat is grown under irrigation. Though this is largely a dryland area, there is a limited amount of irrigation available and often this is used to grow wheat in winter. This reduces the water constraints. At Begumgunj we are talking about rainfed wheat, grown in this case in a remarkably wet year, but the difference is between irrigated and nonirrigated wheat.

Willey: Wheat does seem to show rather a special double-crop situation. What seems to happen is that, in the traditional system, the farmer is at least able to use the latter part of the rainy season to provide a good seedbed.

Hong: A big applause to the Benchmark Soils concept. Soil survey information should be 'utilized', not merely 'documented.' Unfortunately, however, today the dialogue between soil surveyers and agronomists is not as appropriate as it should be to make soil surveys useful and used. I had an opportunity some years back to accompany a colleague on his soil survey trip. I was deeply impressed with his profound knowledge in describing the soil profile. But I was deeply disappointed when I found he was rather reluctant to pay attention to the practical significance of the soil characteristics that he was describing. I think the movement to promote the dialogue between soil survey specialists and agronomists should be carried out in a big way!

Influence of Environment on the Management and Productivity of Cereals on a Vertisol at Jindiress, Syria

P.J.M. Cooper[1], **J.D.H. Keatinge**[2], **and S. Kukula**[3]

Abstract

There are 5.3 million ha of Vertisols in the Mediterranean region of West Asia and North Africa, of which 0.61 million ha are in Syria. These Vertisols occur in areas receiving more than 350 mm expected annual rainfall and thus represent high-potential agricultural production zones. In such zones, wheat is a dominant and important crop, but current national average wheat yields in Syria (1.34 t ha^{-1} *in 1982) are well below the environmental potential. Recent research at Jindiress (mean annual rainfall 475 mm) in northwest Syria, a typical Vertisol location, indicates the importance of single management improvements for increasing cereal yields.*

This paper describes the soil and climate at Jindiress, with emphasis on the great season-to-season and within-season variability of both rainfall and temperature. The main effects and interactions of time of sowing, seeding rate, variety, nitrogen fertilizer, phosphate fertilizer, and weed control are discussed, and it is concluded that in both West Asia and North Africa, early sowing, weed control, and optimal use of nitrogen and phosphorus fertilizer will have major effects on increasing yields on Vertisols. The implications of improved productivity through fertilizer use on crop water use and water patterns are discussed in detail, and it is concluded that substantial increases in productivity and water-use efficiency are possible without corresponding increases in evapotranspiration. This is largely due to the effect of increased crop cover on the ratio of moisture lost as soil evaporation under the crop to that actively used as crop transpiration. The effect of fertilizer on cereal root production and the implications for water-extraction patterns are presented, and the importance of climatic variability on fertilizer recommendations is discussed. Enough is known about relatively simple improvements in soil and crop management in Mediterranean Vertisols to allow the successful short-term transfer and extension of these results to farmers of the region, but further research is required in some areas and topics to optimize these recommendations over the longer term.

Résumé

Influence de l'environnement sur la gestion et la productivité de céréales sur un Vertisol à Jindiress, Syrie : *Il y a 5,3 millions d'hectares de Vertisols dans la région méditerranéenne de l'Asie occidentale et de l'Afrique du Nord, dont 0,61 million d'hectares se trouvent en Syrie. Ces Vertisols se trouvent dans des régions qui reçoivent plus de 350 mm de précipitations annuelles et, par conséquent, représentent des zones de production agricole à potentiel élevé. Dans ces régions, le blé est une culture dominante et importante, mais les rendements moyens nationaux pour la Syrie (1,34 t ha*$^{-1}$ *en 1982) sont bien en dessous du potentiel. De récentes recherches à Jindiress (pluviométrie annuelle moyenne de 475 mm) au nord ouest de la Syrie, emplacement typique d'un Vertisol, indiquent*

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ICRISAT (International Crops Research Institute for the Semi-Arid Tropics). 1989. Management of Vertisols for improved agricultural production: proceedings of an IBSRAM Inaugural Workshop, 18-22 February 1985, ICRISAT Center, India. Patancheru, A.P. 502 324, India: ICRISAT.

l'importance d'améliorations de gestion afin d'augmenter les rendements de céréales.

Cet article décrit le sol et le climat à Jindiress, tout en insistant sur la variabilité des précipitations et de la température de saison à saison et dans une même saison. Les principaux effets et interactions de la date des semis, du taux de l'ensemencement, de la variété, de l'engrais azoté, de l'engrais phosphaté et du contrôle des mauvaises herbes sont examinés et l'on conclut qu'en Asie occidentale et en Afrique du Nord, les semis précoces, le contrôle des mauvaises herbes et l'emploi maximum d'engrais azoté et phosphaté auront des effets importants sur l'accroissement des rendements sur les Vertisols. Une discussion détaillée sur la production améliorée grâce à l'apport d'engrais sur l'utilisation de l'eau par les cultures et sur les systèmes d'irrigation est présentée, et on conclut que des augmentations substantielles de la productivité et de l'efficacité de l'utilisation de l'eau sont possibles sans augmentations correspondantes de l'évapotranspiration. Cela est dû en grande partie à l'effet d'un couvert accru de la culture sur le rapport entre la perte d'humidité sous forme d'évaporation du sol sous culture et celle utilisée sous forme de transpiration de la culture. L'effet de la fertilisation sur la production des racines des céréales et sur les systèmes d'extraction d'eau sont présentés, ainsi que l'importance de la variabilité du climat sur les recommandations pour l'application des engrais. On a suffisament de connaissances sur les améliorations relativement simples de la gestion du sol et des récoltes sur Vertisols méditerranéens pour permettre le transfert valable et la vulgarisation à court terme de ces résultats aux agriculteurs de la région. Mais, de recherches plus approfondies sont nécessaires dans certains domaines et thèmes d'études afin d'utiliser au maximum ces recommandations à long terme.

Introduction

ICARDA's research responsibility for rainfed agricultural systems in regions of West Asia and North Africa (WANA) focuses on areas that receive 200–600 mm a^{-1} of expected winter rainfall, which roughly corresponds to a growing period range of 75–210 days (Kassam 1981). Within WANA a total of 125 million ha (North Africa, 34.7 million; West Asia, 89.8 million) fall within these boundaries, comprising 86% of the total area with an estimated growing period greater than 75 days (FAO 1978a, 1978b).

Of this total area, Vertisols occupy 5.3 million ha (North Africa, 1.2 million; West Asia, 4.1 million), or 4.2% of the rainfed agricultural area. Sudan has no areas in the subtropics that receive winter rainfall, but it is one of the countries in ICARDA's sphere of responsibility. Vertisols are widespread in Sudan, occupying 42.2 million ha, or 17% of its total agricultural area.

This paper discusses management of Vertisols in rainfed agricultural systems in WANA, which fall within the cool subtropics receiving winter rainfall, and draws examples from our research conducted within Syria, ICARDA's host country. In particular, the management of cereals at a typical location, Jindiress, highlights the problems associated with crop production on Vertisols. Syria has 18.3 million ha that fall within this climatic definition, of which 6.19 million are currently under cultivation (Statistical Abstracts 1983). Within this land area, 0.61 million ha are classified as Vertisols according to Soil Taxonomy (USDA 1975), but a larger area (2.22 million ha) are classified as Grumusols according to the older U.S. nomenclature (Fig. 1).

A large proportion of the area mapped as Grumusols exhibits many of the management-related properties associated with Vertisols—namely, high smectitic clay content, deep cracking, and self-mulching with substantial soil churning.

Farming Systems Associated with Vertisols in Syria

Figure 1 illustrates the distribution of Vertisols in areas that receive > 350 mm annual rainfall and thus represent the high-potential areas of agricultural production in Syria. Such areas are dominated by wheat-based farming systems, in which farmers grow winter wheat (both bread wheat and durum wheat) in rotation with winter food legumes (such as lentil, chickpea, and faba bean) and summer crops (such as watermelon, sesame, and cotton). Previous surveys showed the predominance of three-course rotations—wheat, followed by a food legume, followed by a summer crop—on the deeper soils (> 80 cm) in these farming systems (Watson 1979), but there is evidence that, owing to the increased labor costs associated with hand weeding and hand harvesting, many farmers are reducing their food-legume production and moving into two-course rotations of wheat followed by a summer crop.

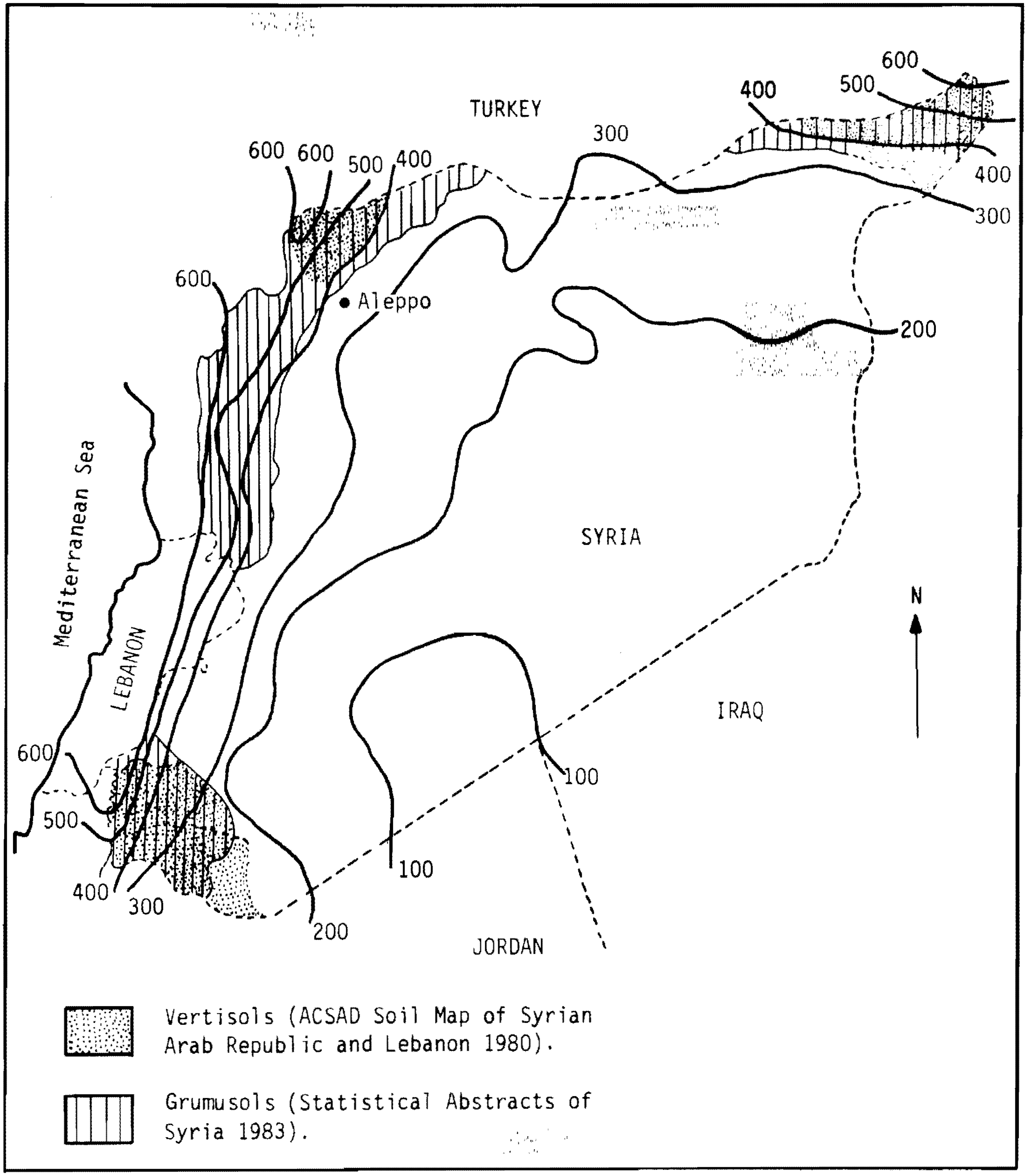

Figure 1. Rainfall isohyets and distribution of Vertisols in Syria.

The percentage of arable land used for the main crops is as follows:

- Legumes—lentil 18%, vetch 8%, chickpea 5%.
- Cereals—local wheat 15%, improved wheat 15%, barley 4%.
- Summer crops—watermelon 20%, sesame 5%, cotton 2%, and miscellaneous 8%.

Livestock, principally sheep, is an important aspect of these systems. Although some forage vetch is grown as feed, the sheep are largely fed on crop residues (lentil and wheat straw) during the summer months and use the natural pastures growing on nonarable grazing areas during the winter months. Such nonarable grazing areas occupy about 20% of the total area of these systems. Barley also constitutes an important source of feed (Watson 1979) and is grown on the shallower soils, where it is usually followed by fallow.

Fruit production is substantial on these rainfed farming systems, with a total area of 412 000 ha under production. Olives (342 000 ha) are usually grown on the deeper soils, and grapes (101 000 ha) on the shallower and poorer soils. Apples, almonds, pistachios, figs, apricots, and cherries are predominant on the remaining land (Statistical Abstracts 1983).

Farmers have a wide choice of agricultural and commercial crops in these high-potential areas, and thus a diverse range of farming systems and agricultural practices is found. In general, farming is a profitable proposition in these areas, which provide a major portion of Syria's local food supply.

Jindiress: Soil and Environmental Characterization

Soil Description

Jindiress (36° 23'N, 36° 41'E) is about 80 km northwest of Aleppo at an altitude of 230 m. The soil at our research location was classified as Chromic Vertisol (FAO), Palexerollic Chromoxerert (USDA), or *Smecti-Bisialsol, vertique* (ORSTOM). In older systems of soil classification, it would have been classified as Grumusol (USA), Vertisol (France), Cinnamonic-brown Earth, or Takyr (USSR).

A full description of this soil was previously reported (Cooper et al. 1981), and the details are presented in the Appendix. Analytical data on this Vertisol are presented in Table 1. Taxonomically, the soil is characterized by an ochric epipedon, the occurrence of deep cracks in polygonal patterns (Fig. 2), slickensides (Fig. 3), a prismatic structure, and wedge-shaped structural aggregates at depth. The substratum consists of weathered limestone and glauconitic minerals. There is no pronounced calcic horizon, probably because of the intensive churning of the soil. Clay minerals are mainly smectitic. The structure of the soil is coarse subangular blocky near the surface, and coarse to very coarse prismatic below. The structural aggregates contain few fine pores; roots, in particular in the B-horizon, follow the surfaces of the aggregates (see Fig. 3).

Early in the winter-rainfall season, the internal

Table 1. Selected analytic data on Palexerollic Chromoxererts, Jindiress, Syria[1].

Soil depth (cm)	Particle-size distribution (% w/w) 25 mm 50μ	50–2μ	< 2μ	CaC0$_3$ *equivalent* (% w/w)	pH	Organic *carbon* (% w/w)	Total *nitrogen* (ppm)	Available *phosphorus* (ppm)	Mineral nitrogen (ppm) NH$_4$-N	N0$_3$-N
0–20	4	32	61	20	8.0	0.65	601	3.4	4	5
20–40	4	32	61	21	8.0	0.49	515	1.6	4	3
40–60	4	33	61	21	8.0	0.43	451	1.0	3	2
60–90	4	33	62	22	8.0	0.37	395	1.0	4	2
90–120	4	32	62	22	8.1	0.33	290	0.9	4	1
120–150	8	33	60	n.d.	8.1	n.d.	234	0.8	3	1

1. Analyses were made by the following methods: mechanical analysis (hydrometer), lime equivalent (titration), pH (1:1 soil-water suspension), organic carbon (Walkley-Black), total nitrogen (Kjeldhal), available phosphorus (Olsen), and mineral nitrogen (Bremner).

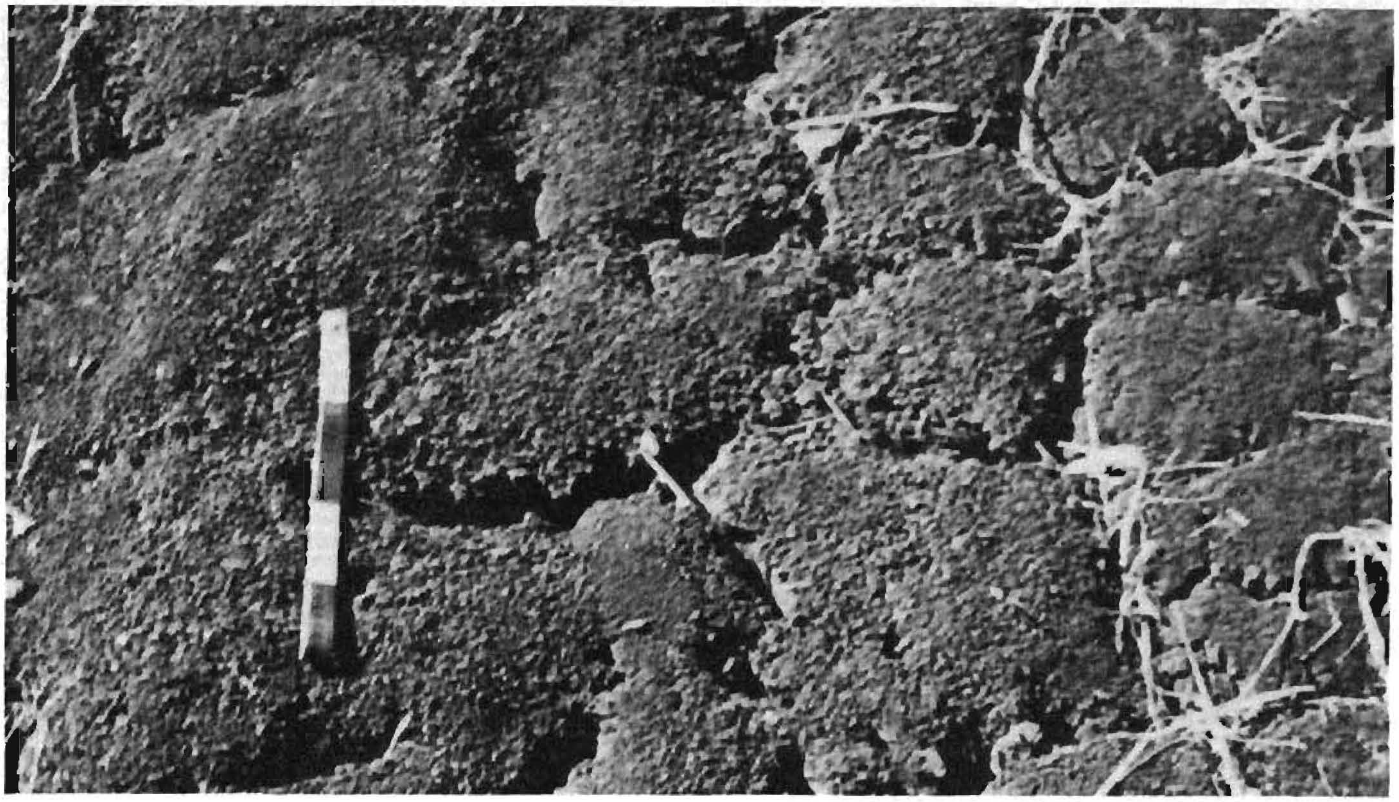

Figure 2. Deep cracks in polygonal pattern and surface mulching at Jindiress (see Appendix 1, soil 5). Typical also at Kafr Antoon and Tel Hadya, Syria.

drainage of the soil at Jindiress is usually good because of the deep cracks; however, some rainwater may be lost due to deep drainage. Infiltration of water from cracks into soil aggregates is slowed down by the slickensides on the aggregates, and, therefore, the distribution of soil moisture might be uneven. Soil moisture stored in the aggregates may only be slowly available to the crop, since the roots penetrate the aggregates to a limited extent. Also, part of the moisture absorbed by the soil aggregates is largely unavailable to the crop because the soil dries to less than the effective wilting point. In Vertisols, the self-mulching properties of the surface soils should prevent extensive losses of soil moisture in early spring, a favorable characteristic for agriculture. However, deep cracking in late spring could cause root damage and increased loss of soil moisture through soil evaporation.

Churning of the soil should result in a more even distribution of plant nutrients throughout the profile than in nonchurned soils. The relationship between total nutrient content and plant-available nutrient content in a soil is complicated, however, and the amount of nutrients available to plants generally depends more on physicochemical conditions in the soil than on total nutrient content.

The major factors affecting management strategies for the soil at Jindiress are the heavy clay texture, the high pH and calcareous nature, the low organic-matter content, and the low availablity of nitrogen and phosphorus, all of which reflect the relatively even distribution of plant nutrients in the soil, resulting from the churning associated with these dryland Vertisols.

Environmental Description

Jindiress has a highly variable climatic regime. In simple terms, it experiences Mediterranean environmental conditions with winter rainfall and hot, dry summers. However, within the crop-growing season (November–June), the orographic effects of the Antilebanon and Amanos mountains and the variable intensity of anticyclonic conditions in eastern Turkey combine to cause acute variability in precipitation and temperature. At Jindiress, over the period of 1960–1984, the long-term annual average precipi-

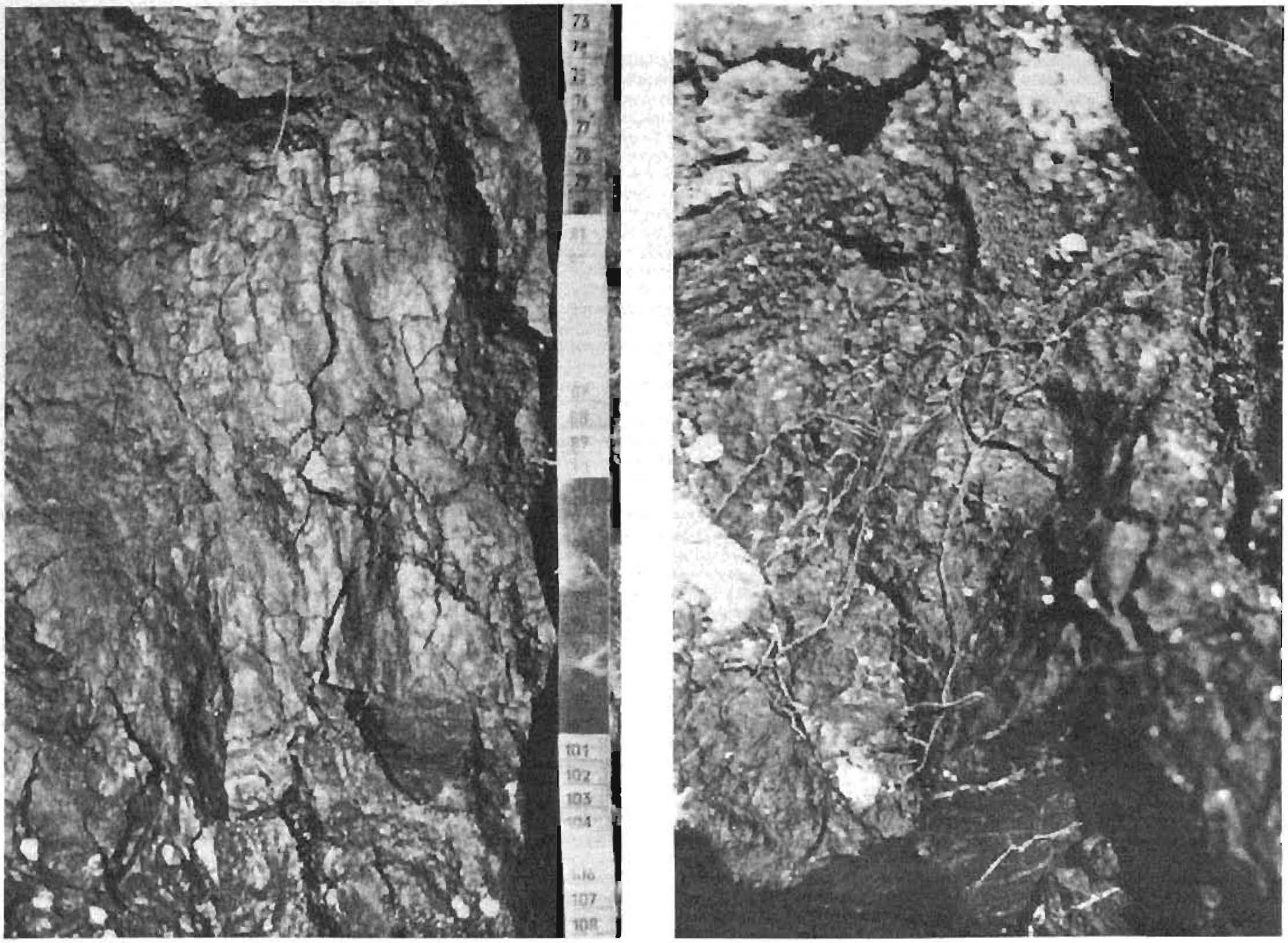

Figure 3. Slickenside at Kafr Antoon (left) and Jindiress (right). Note roots running across aggregate surfaces in the photo on the right.

tation was 479 mm (standard deviation 138 mm), with a low of 173 mm in 1972 to a high of 733 mm in 1968 (Figure 4 shows the probability distribution of rainfall). This gross variability in seasonal rainfall clearly influences crop productivity, but the within-season rainfall distribution may also be critical (Keatinge et al. 1985). (Mean monthly rainfall and temperature regimes are shown in Figure 5). For instance, the rapid increase in air temperature in April and May and the declining precipitation indicate that, during the grain-filling period for most winter-planted crops, growth will depend on stored soil moisture.

A typical example of the wetting and drying pattern of soil moisture under a fertilized barley crop was observed in 1982/83 (Fig. 6), a year with slightly lower precipitation than average. During such years, crops depend on stored soil moisture, especially in the latter portion of the growing season, and there is

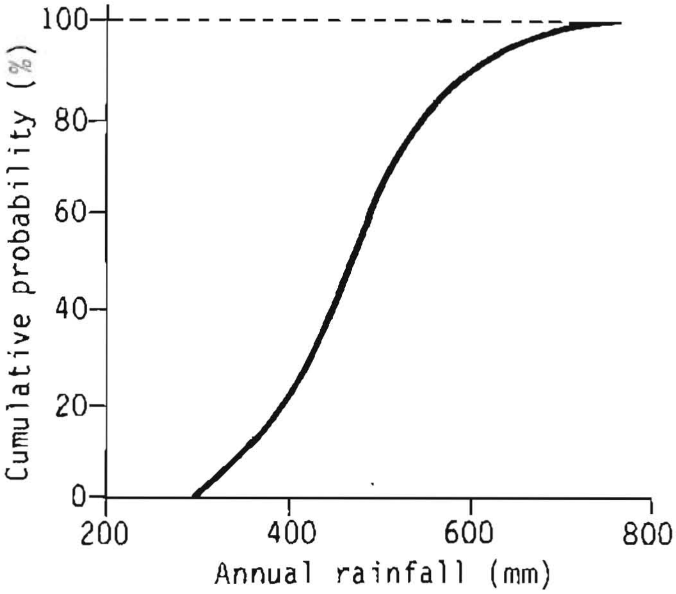

Figure 4. Cumulative probability distribution of annual (August-July year) rainfall totals at Jindiress (Dennet et al. 1984).

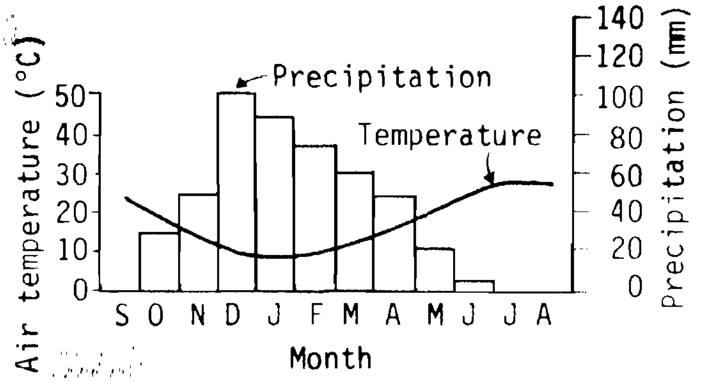

Figure 5. Mean monthly precipitation and mean monthly air temperature at Jindiress (1960–1984).

risk of the deep soil cracking associated with Vertisols. Cracking is usually observed to develop close to the period of crop anthesis.

Low air temperatures in winter, particularly in combination with conditions of inadequate phosphate availability, may also seriously influence crop development and productivity in cereals. In the period 1965–1983, the number of days per season with minimum shaded air temperature below 0 °C ranged from 1 to 46, with an average of 15. Crop maturity dates, as a result, can vary by up to 4 weeks, and this will have a substantial impact on the drought and heat stresses affecting the crop and will

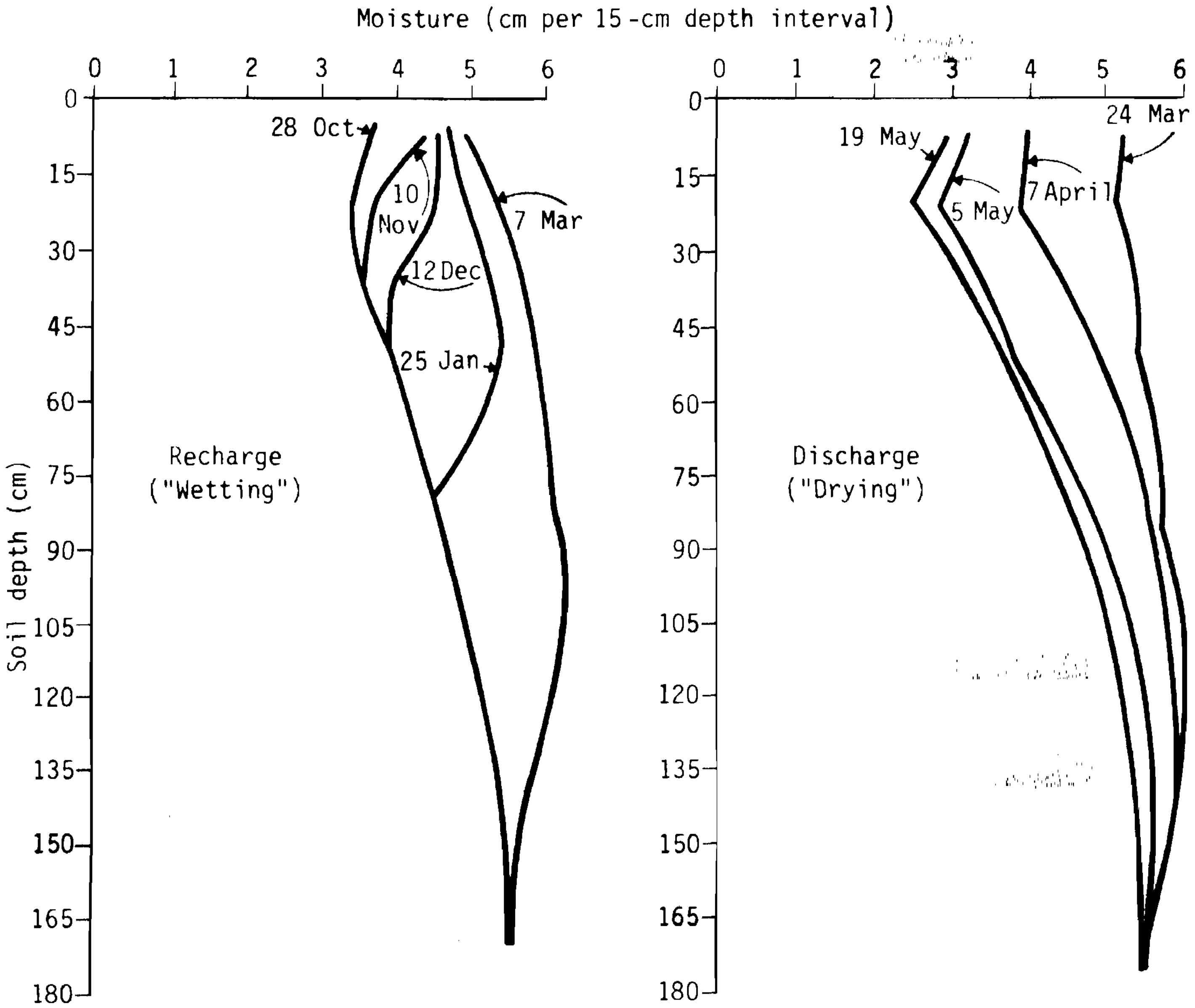

Figure 6. Pattern of wetting in autumn-winter and drying in spring of Vertisol soil profile under fertilized barley at Jindiress, 1982/83.

influence the likely choice of suitable crop cultivars. Stapper (1984) has demonstrated that medium-duration wheat cultivars, such as Mexipak, will be more productive than an early-maturing cultivar (Sonnalika) in the majority of years at Jindiress and that the opposite is the case at a drier site, such as Breda (278 mm mean annual precipitation).

Major Effects of Management on Cereal Production on Vertisols

Large areas of wheat are grown in Syria in areas in which Vertisols predominate. In 1982, 1.22 million ha of wheat produced, on average, 1.34 t ha^{-1} of grain (Statistical Abstracts 1983). Farmers currently sow their crops late to allow the early rains to germinate weed seeds, and the weeds are subsequently killed by cultivation prior to sowing. Phosphate fertilizer (triple superphosphate), when used, is applied to the soil surface before this preplanting tillage and is incorporated into the soil. Band placement of phosphate with the seed is seldom practiced. Cereals are largely hand broadcast over ridges at a seeding rate of 100–120 kg ha^{-1}, and the seed is covered by splitting the ridges. Nitrogen fertilizer (urea or calcium ammonium nitrate), if applied, is usually top dressed in early spring. Preliminary survey work indicates that in these areas, late sowing, poor weed control, and lack of or incorrect fertilizer use result in yields well below the environmental potential.

In the 1982/83 and 1983/84 cropping seasons, trials using a 2^5 factorial design were run at Jindiress to examine the main effects and interactions of some important management factors on wheat yields. In both years, the trial followed a summer crop of sesame. The treatments and the results are shown in Table 2.

In 1982/83, time of sowing was not examined, and the entire trial was sown early, on 10 November. Substantial responses to nitrogen fertilizer were found, but only in the presence of phosphate or weed control, and responses to phosphate also increased in the presence of added nitrogen. Reducing the seed rate resulted in a yield decrease; thus current farmer seeding rates seem satisfactory. These results suggest that nitrogen and phosphate fertilizer, with weed control (WC), would produce economic yield responses. To test this, partial budgeting was conducted using yield data from N^0 P^0 WC^0 and N P WC plots for Jindiress and for a similar trial at Kafr Antoon (35 km northwest of Aleppo), which was also located on a Vertisol (Table 3). Very attractive rates of return were obtained, indicating that such practices have a high likelihood of acceptance.

Table 2. Management practices in wheat agronomy trials on Vertisols in north Syria, 1982/83 and 1983/84.

Management/practice	Level
Nitrogen (Ammonium nitrate kg N ha^{-1})	0
	100[1]
Phosphate (TSP kg P_2O_5 ha^{-1})	0
	60
Weed control[2], + Bromoxynil + diclofop methyl[3]	0
	0.5+1.0
Seed rate (kg ha^{-1})	60
	100
Variety	Mexipak (Local)
	Norting (Improved)
Sowing	Late
	Early

1. 20 kg N ha^{-1} at planting, 80 kg ha^{-1} topdressed at start of stem extension.
2. Dominant weed species at Jindiress: *Scorpiorus subvilosus, Sinapis arvensis, Euphorbia* spp., *Phalaris brachystachys, Coronilla scorpioides.*
3. Applied at 0.5 at planting + 1.0 kg ai ha^{-1} at start of stem extension.
4. Rainfall in 1982/83 was 417 mm; in 1983/84, 392 mm.

In 1983/84, variety was not tested, but date of sowing was included. The similarity of yield responses for the 2 years reflect the similar rainfall totals (both below the long-term average). Apart from confirming the previous season's results, these data highlighted the important interaction between weed control and date of sowing. The farmer practice of late sowing is clearly an effective weed-control method, reflected by the lack of response to herbicide in late-sown wheat. However, early sowing plus herbicide use gives substantial yield gains (ICARDA 1983, 1984).

These results are from one location only, but they are similar to results obtained in other areas of Vertisols in the wheat-producing areas of West Asia and North Africa (FAO 1969). In general, these soils are characterized by low soil fertility and high weed-infestation levels, and it is clear that substantial

Table 3. Partial budget estimates[1] of local and recommended practices for bread wheat on two Vertisols in northern Syria.

	Jindiress	Kafr Antoon
Local practice		
Grain (t ha^{-1})	1.44	1.41
Straw (t ha^{-1})	2.35	2.16
Recommended practices		
Grain (t ha^{-1})	3.55	2.81
Straw (t ha^{-1})	5.33	3.55
Increased revenue (SL ha^{-1})[1]		
Grain	2532.0	1680.0
Straw	983.4	458.7
Total	3515.4	2138.7
Additional costs (SL ha^{-1})[2]		
Phosphorus fertilizer	163.0	163.0
Nitrogen fertilizer	261.0	261.0
Nitrogen application	30.0	30.0
Herbicide	75.0	75.0
Herbicide application	34.0	34.0
Threshing	307.7	204.2
Bagging	101.1	67.1
Transport (Rajad)	189.9	126.0
Total	1161.7	960.3
Net increases in revenue (SL ha^{-1})	2353.7	1178.4
Marginal rate of return (%)[3]	303.0	223.0

1. One US \$ = approx. 6 Syrian lire (SL) in 1982/83.
2. Estimates based on following prices (in SL per kg): Bread wheat, 1.20; Cereal straw, 0.33; Superphosphate (20% P), 1.25; Ammonium nitrate (33% N), 0.87; Nitrogen application cost, 0.04; Bags for produce, 0.05; Threshing cost, 0.15; Transport (Rajad) cost, 0.08.
   (Source: Market and farmer surveys by the Farming Systems Program, ICARDA.)
3. Increased revenues/additional costs.

increases in yield are possible through improved fertilizer and herbicide use.

Effects of Fertilizer on Barley Production and Moisture Dynamics of Vertisols

Yield and Water Use

Because the region that ICARDA serves is characterized by generally low and erratic rainfall, it is important to understand the implications of the effects of increased productivity through improved management on water use and water-use efficiency. If greater dry-matter production is associated with increased water use, risk of crop failure in dry years may be enhanced.

Detailed studies were conducted for 3 years at Jindiress to assess the effect of fertilizer on moisture balances in cereals, using barley as a test crop. Data on the yield, growth component, and water use in these trials are presented in Table 4. (Full management details of these trials were reported elsewhere [ICARDA 1981, 1982, and 1983]). A full description of monitoring of soil moisture, using the neutron back-scattering technique, was given by Cooper et al. (1981). Weeds were controlled to a uniformly low level of infestation.

The responses in total dry matter and seed yield to N and P fertilizer reflect those reported for wheat. In the 2 wetter years (1980/81, 1982/83), increased production was associated with an increase in evapotranspiration (ET), but in the drier year, substantial yield increases were obtained with no additional water use. This increase in ET in the 2 wetter years was accompanied by very large responses in production and, thus, dramatic increases in water-use efficiency (WUE) in all 3 years.

Similar trials were conducted at other drier locations on differing soil types, and the results support the evidence obtained at Jindiress that, even in dry years or dry locations, large increases in production are possible without changes in total ET. An example of this is given in Table 5 for Breda, in northern Syria (35° 55'N, 37° 10'E), which has a long-term average rainfall of 278 mm, on soils classified as Calcic Xerosols (FAO) or Typic Calciorthids (USDA 1975).

ET consists of two components, namely, crop transpiration (T) and evaporation from the soil under the crop (E-sc). It has been shown that:

$$\text{WUE} = \frac{\text{TE}}{1 + E_{sc}/T}$$

where TE is the transpiration efficiency of the crop, in units of kg ha^{-1} mm^{-1} (Cooper 1983), which is controlled by crop physiological interactions with atmospheric demand (Fisher 1981). In dry years, crop management will largely affect WUE through a change in the ratio of water lost through soil evaporation to that actively transpired by the crop. Soil-evaporation rates are largely determined by

Table 4. Effect of fertilizer[1] on components of growth, yield, water use, and water-use efficiency (WUE) of barley (cv Beecher) on a Vertisol in three successive years (1980/81–1982/83)[2] at Jindiress, northern Syria.

	1980/81		1981/82		1982/83	
	-F	+F	-F	+F	-F	+F
Crop duration (days from germination to maturity)	154	148	186	172	185	182
Maximum green area index (GAI)	1.8	4.3	1.8	3.7	2.6	3.7
Total dry matter (t ha^{-1})	5.43	12.48	4.32	8.68	6.92	10.24
Grain yield (t ha^{-1})	2.25	5.02	1.44	2.93	2.73	4.16
Harvest index	0.41	0.40	0.33	0.34	0.39	0.41
Evapotranspiration (mm)[3]	323	376	323	315	335	359
WUE (kg ha^{-1} mm^{-1})[4]	16.8	33.2	13.4	27.5	20.6	28.5
Increase in WUE (%)		98		105		38

1. Fertilizer applied: 90 kg N and 90 kg P_2O_5 per ha in 1980/81, 60 kg N and 70 kg P_2O_5 per ha in 1981/82, and 100 kg N and 60 kg P_2O_5 per ha in 1982/83.
2. Seasonal rainfall was 472 mm in 1980/81, 350 in 1981/82, and 417 in 1982/83.
3. ET between germination and maturity.
4. WUE of total biological yield.

frequency of wetting of the soil surface (common to all crops in a given area) and the amount of incident radiation reaching the soil surface. In this respect, the rate and extent of crop-canopy development will play a major role in determining the level of interception of radiant energy and, thus, the amount of soil evaporation occurring beneath the crop.

Based on this rationale, by splitting ET into its two components (Cooper et al. 1983), it was calculated (Cooper 1984) that in farmers' cereal crops that are poorly managed and thus have incomplete ground cover, as little as 20% of ET is actively used as crop transpiration, and the remaining 80% is lost by evaporation from the soil. Thus in dry years and locations, large increases in WUE are possible with no increase in water use, but in years of greater

Table 5. Effect of fertilizer[1] on yield, water use, and water-use efficiency (WUE) of barley (cv Beecher) on a Typic Calciorthid in four successive years (1980/81 to 1983/84)[2] at Breda, northern Syria.

	1980/81		1981/82		1982/83		1983/84	
	-F	+F	-F	+F	-F	+F	-F	+F
Total dry matter yield (t ha^{-1})	3.84	7.54	4.54	6.13	2.01	3.40	1.37	2.09
Grain yield (t ha^{-1})	1.52	2.58	1.32	2.22	0.90	1.49	0.74	1.16
Evapotranspiration (ET, mm)[3]	234	225	231	231	224	235	171	174
WUE (kg ha^{-1}mm^{-1})	16.4	33.5	19.7	26.5	9.0	14.5	7.8	12.0
Increase in WUE (%)		104		35		61		53

1. Fertilizer applied: 90 kg P_2O_5 and 90 kg N per ha in 1980/81; 60 kg P_2O_5 and 60 kg N per ha in 1981/82; 60 kg P_2O_5 and 30 kg N per ha in 1982/83 and 1983/84. Triple superphosphate and ammonium nitrate fertilizer were used.
2. Seasonal rainfall was 299 mm in 1980/81, 324 in 1981/82, 284 in 1982/83, and 207 in 1983/84.
3. ET between germination and maturity.
4. WUE of total biological yield.

moisture supply, improved crop growth will also result in greater ability of the crop to extract moisture. This is discussed further in subsequent sections.

Patterns of Water Use

Fertilizer additions may or may not affect the total water use of the crop, as indicated in Tables 4 and 5, depending on the amount of soil moisture available for uptake; however, in all years, there were marked effects on the pattern of seasonal water use. This is due to two reasons. First, the effect of fertilizer on crop-canopy development was reflected both in rates of ET (Fig. 7) and in the apportioning of ET into its two components (Fig. 8). Second, in phosphate-deficient soils, improved nutrition had a marked, though variable, effect on the rate of cereal-crop development. Two barley varieties, Beecher and Arabic White, when they received phosphorus fertilizer, had greater leaf emergence rates, earlier anthesis, and earlier maturity (see Fig. 8).

During the cold winter months, when the crop canopy was small, there were no differences in accumulated water use between cropped and fallow land. However, as the canopy developed and evaporative demand increased (days 89 to 115), both crop and fertilizer effects became apparent, and by day 132 there were appreciable differences between cropped land and fallow, and between fertilized and nonfertilized barley. Further differences due to variety also became apparent as the crops approached maturity, and these differences were largely due to contrasting rooting patterns. Arabic White develops a more extensive rooting system than Beecher (Brown 1984), and thus during the period of soil-moisture discharge in the soil, it is able to extract more water and maintain higher evapotranspiration rates.

Higher-order polynomial regression curves can be fitted to this accumulated water-use data and then differentiated to give seasonal changes in rate of evapotranspiration. This can also be done for accumulated pan evaporation data, and seasonal changes in ET/E_0 ratios can be calculated.

When ET is split into its two components, T and E-sc, it can be seen that fertilizer has pronounced effects on crop-canopy development. This is illus-

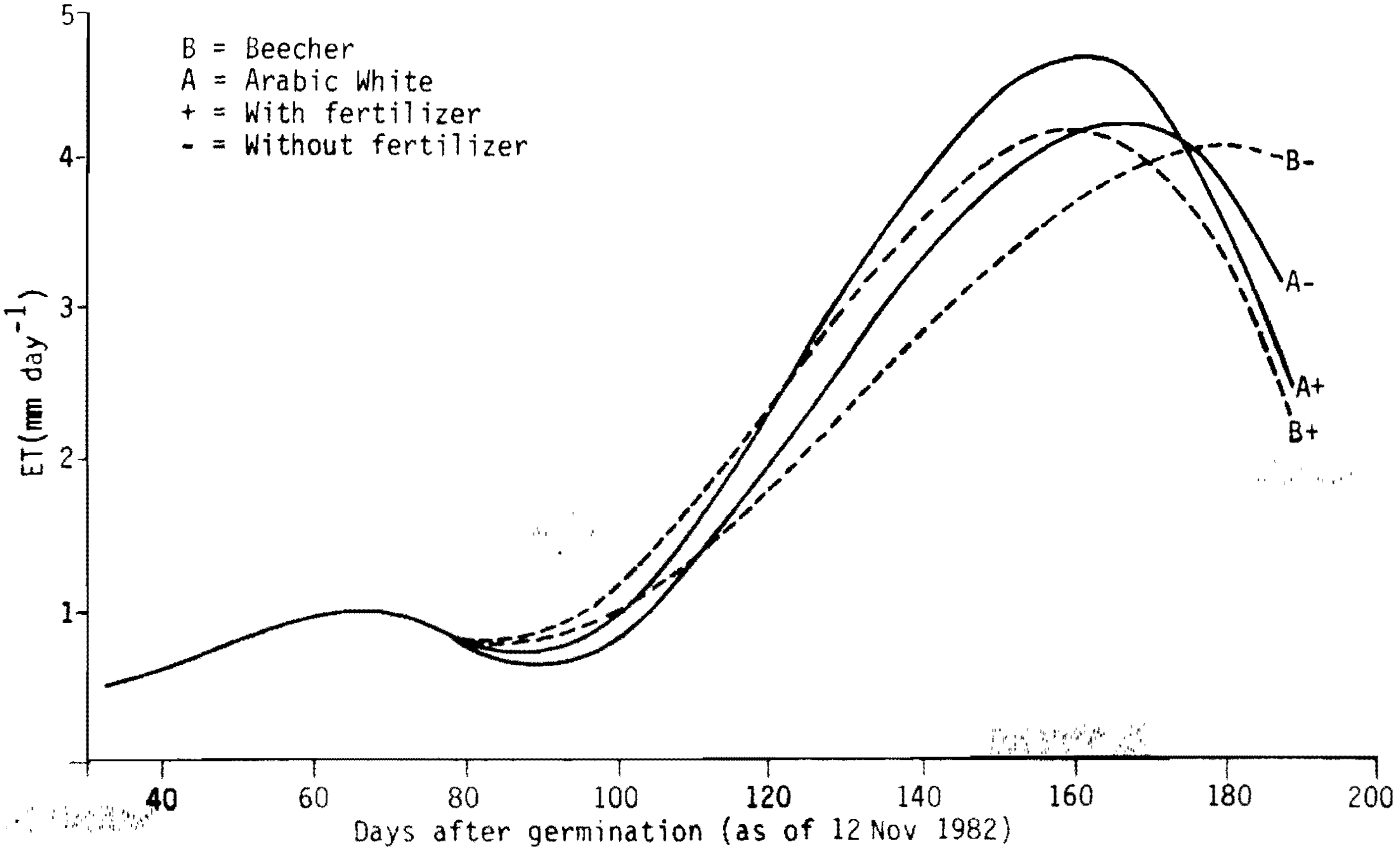

Figure 7. Rates of ET through the growing season for two barley varieties at Jindiress, northern Syria.

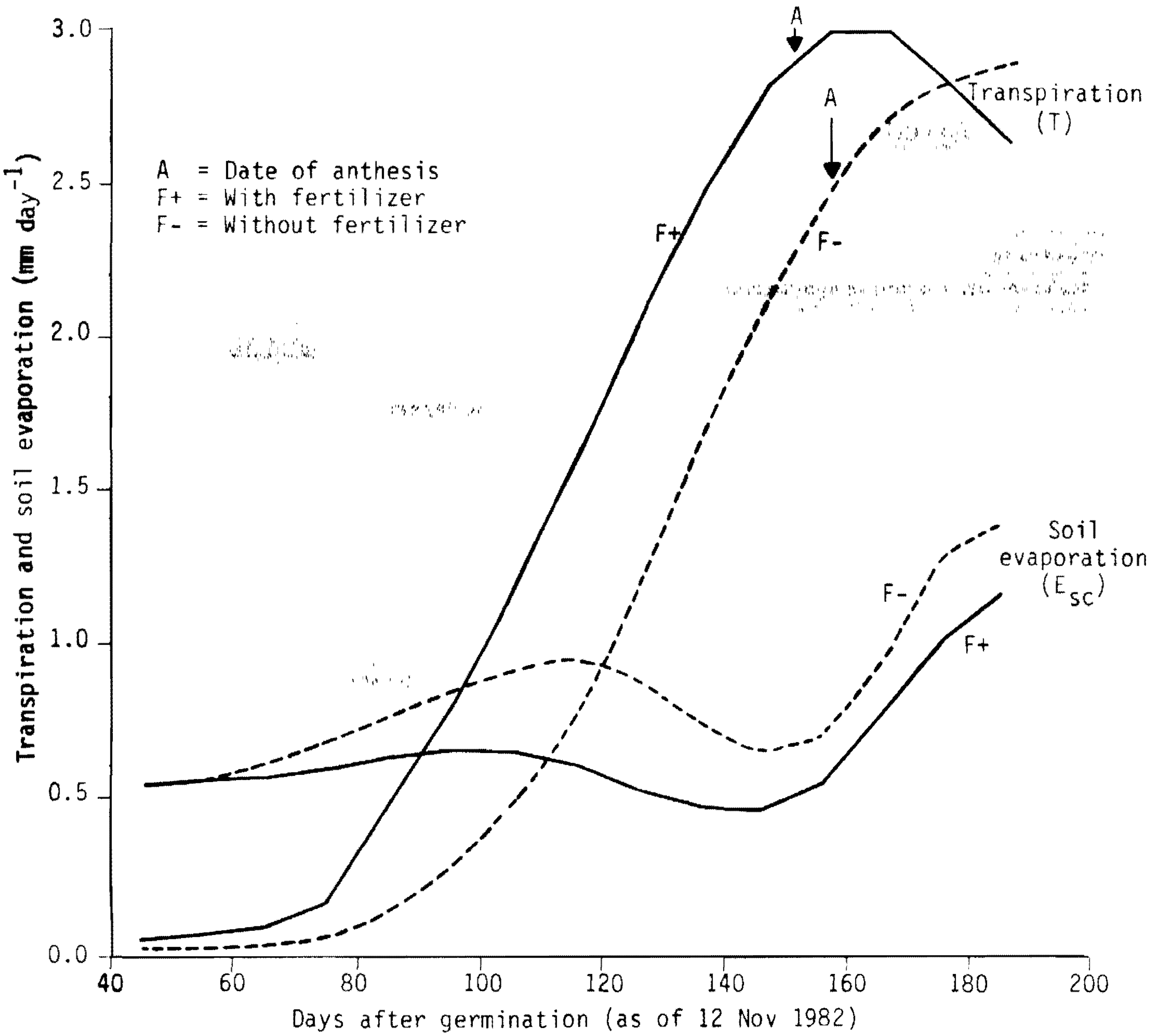

Figure 8. Effect of fertilizer addition on transpiration and soil evaporation rates of barley (var. Beecher) at Jindiress, northern Syria, 1982/83.

trated for a barley crop at Jindiress (see Fig. 8), but the same patterns are observed across location, soil type, and year. During the cool winter months, E-sc accounted for almost 100% of ET, but as the crop canopy developed, T became an increasingly larger component, and E-sc rates declined. The greater crop canopy of fertilized crops resulted in greater T and lower E-sc rates. After anthesis, as leaf senescence occurred and increased amounts of radiant energy reached the soil surface, T values fell and there was a corresponding increase in E-sc. (These effects have been described in more detail in Cooper et al. 1983). Fertilizer addition had a dramatic effect on the E-sc/T ratio and, hence, on the WUE of the crops; Cooper (1984) showed that, over a range of years, cereal crops, and locations, there were clear relationships between the percentage of ET used as T and the grain yield or maximum green area index (GAI) achieved by the crop (Fig. 9).

Root Production and Moisture Extraction

During the last 2 years of the study in Jindiress (see

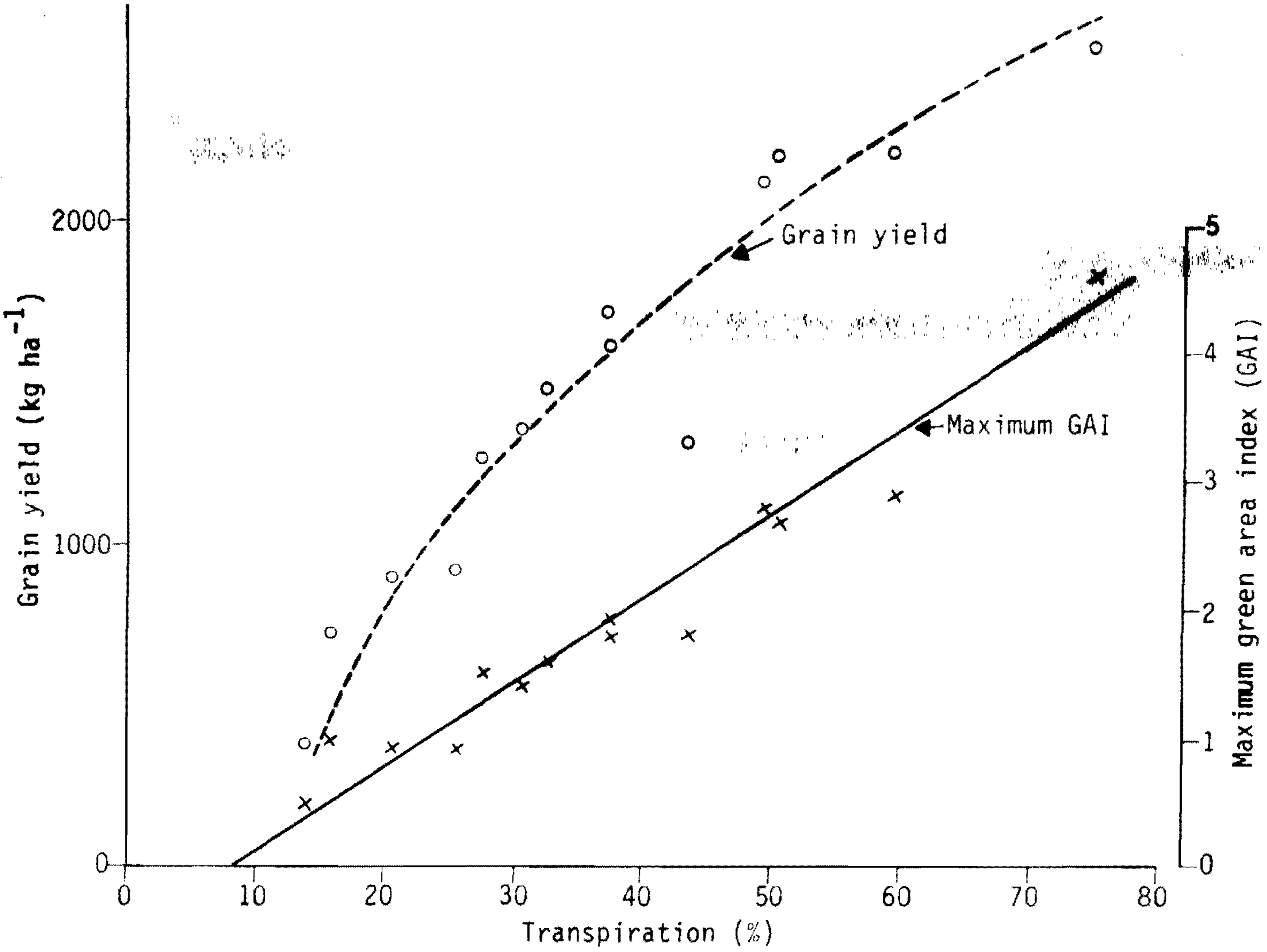

Figure 9. Effect of percentage of ET used as T on grain yield and maximum green area index of cereal crops.

Table 4), detailed root studies were conducted as part of a larger cooperative program of research with Reading University, UK, which is examining the effects of variety, management, soil type, and moisture supply on the root production of barley (Brown 1984, Gregory et al. 1984, Wehbe 1984). Important highlights are presented here, using the 1982/83-season data as examples.

Fertilizer additions not only resulted in increased shoot dry-matter production but also increased root production, which is reflected both in root dry weight and root length density (Table 6). These large increases in root production occurred in the 0-60 cm horizon; below this depth, no detectable effect was observed. This pronounced effect of fertilizer on root production was observed in three varieties and across two contrasting locations and years.

Such increased root proliferation is reflected in a greater ability of the crop to extract moisture from the soil. "Extractable moisture" can be defined as the difference between the maximum amount of moisture observed in any given depth interval and that recorded at crop maturity. This definition is in contrast to the traditional definition of available moisture (a soil characteristic) and allows for the interaction of root distribution with soil physical characteristics and for an assessment of management effects on a crop's ability to extract water. Figure 10 illustrates the clear relationship between the observed extractable moisture in specific soil layers and the measured root length density. It is of interest that these data were associated across location, soil type, year, and fertilizer treatment.

In addition to increasing a crop's ability to extract moisture (reflected in the greater moisture use in wet years), fertilizer application may well reduce soil evaporative losses from the surface horizons. In dry periods between rainfall, increased rooting density

Table 6. Effect of fertilizer (N,P) on root dry weight and root length density distribution of barley (cv Beecher) at maturity at Jindiress, northern Syria, 1982/83.

Soil depth interval (cm)	Root length density (cm cm^{-3}) - Fertilizer	+ Fertilizer
0–15	1.93 (38)[1]	3.78 (43)
15–30	1.19 (23)	2.03 (23)
30–45	0.52 (10)	1.33 (15)
45–60	0.44 (9)	0.85 (10)
60–75	0.32 (6)	0.42 (5)
75–90	0.26 (5)	0.23 (3)
90–105	0.24 (5)	0.13 (2)
105–120	0.20 (4)	0.08 (1)
Total root weight (R) (t ha^{-1})	0.51	0.83
Shoot weight (S) (t ha^{-1})	6.92	10.24
R/R+S	0.07	0.08

[1] Figures in parentheses indicate the percentage distribution in the horizon.

in surface layers will result in a greater proportion of ET being used as T than being lost as E-sc.

Nitrogen Application Strategy and Environment

Somel (1984) demonstrated that, in addition to the positive responses to N and P fertilizer in the presence of weed control observed for wheat at Jindiress (see Table 3), the magnitude of nitrogen response depends on both rate of fertilizer application and precipitation: response increases with increasing precipitation. Pooled analysis– of seed rate (S), nitrogen (N), and phosphate (P) trials (conducted over 3 years and five sites, including Jindiress and Kafr Antoon)—incorporated the environmental variables of total annual rainfall (R), available phosphorus (PA), and available (nitrate) nitrogen (NA) in the top 40 cm. For reasonable rates of seed and phosphate, the grain yield (Y) response for barley (cv Beecher) to nitrogen increased with rainfall, for example, for the seed rate of 100 kg ha^{-1}, and to phosphate at 90 kg P_20_5 ha^{-1}:

$$\frac{\delta Y}{\delta N k R}\ (\text{kg Y/kg N per mm}) = 0.0468\ 0.00029\ N$$

The response was positive up to N rates of 161 kg ha^{-1}.

For Jindiress, at these rates of S and P, and when PA was 4.97 ppm, NA was 8.6 ppm, and the long-term average rainfall was 479 mm, the response to nitrogen was positive:

$$\frac{\delta Y}{\delta N}\ (\text{kg Y/kg N}) = 21.13\ 0.14\ N$$

for N rates up to 154 kg ha^{-1}.

As a result of the influence of precipitation on nitrogen response, it is evident from the gross variability in seasonal total precipitation at Jindiress that the economic optimum amount of N to apply depends on the season's precipitation. A uniform nitrogen fertilizer application strategy will, therefore, be a suboptimal economic solution in the wheat-growing areas of northern Syria (Keatinge et al. 1985). In the particular case of Jindiress, the

Table 7. Probability of receiving more than the specified amount of rainfall between 1 October and the date shown, Jindiress (Keatinge et al. 1985).

Rainfall (mm)	1 Feb	14 Feb	1 Mar	15 Mar	1 Apr	Rainfall between 14 Feb and 31 May	Probability in % of years
200	0.70	0.84	0.93	0.97	0.99	**135**	**80**
225	0.56	0.73	0.86	0.94	0.97	**176**	**50**
250	0.43	0.61	0.77	0.89	0.94	**227**	**20**
275	0.30	0.48	0.67	0.83	0.89		
300	0.20	0.36	0.55	0.72	0.81		
350	0.08	0.18	0.32	0.50	0.62		
400	0.02	0.06	0.15	0.28	0.40		

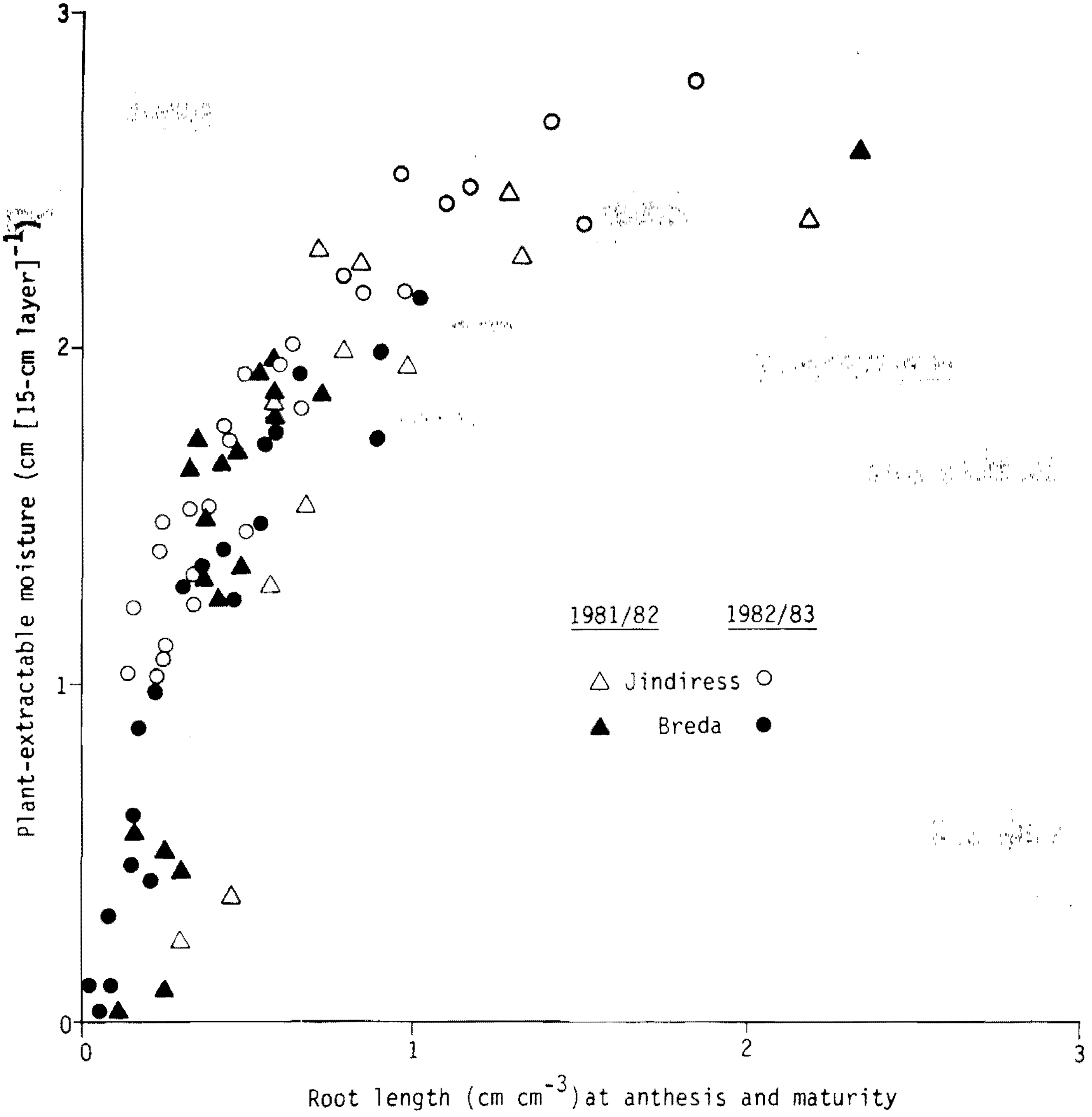

Figure 10. Effect of root length on water extracted for two sites and two years; points plotted are four fertilized-refertilized treatments on three different barley varieties.

probabilities presented in Table 7 indicate that a farmer who has decided to topdress with nitrogen on 14 February, will have to decide how much N to apply, with the knowledge that in 5 years out of 10 just less than 275 mm of precipitation will have been received by that date. Furthermore, there is the probability that in at least 8 years out of 10, he can expect a further 135 mm of rain before 31 May. He could additionally attempt to evaluate the possible benefit of a split application of N on, for example, February 1 and March 15, by monitoring his rainfall and evaluating a trade-off between his increased certainty of an economic response to the N he proposes to apply and the cost of broadcasting twice.

Conclusions

1. Cereal production on the Vertisol at Jindiress has been shown to be highly responsive to improved agronomic management, in particular to measures of weed control and fertilizer application.
2. The highly variable physical environment is characteristic of the area of Vertisols in Syria and has a substantial influence on crop productivity. There is a marked interaction between physical environmental factors and the economic effectiveness of measures of improved management.
3. Appropriate use of fertilizer application, cultivar selection, weed control, seed rate, and sowing date may considerably enhance the efficiency of soil water use and thus potential crop productivity. This is usually achieved by the early and superior development of the crop canopy, which permits a greater proportion of the seasonal moisture supply to be transpired rather than lost as soil evaporation.

Appendix

Profile Description of Vertisol at Jindiress, northern Syria

Ap 0-20 cm
Reddish brown (5YR 4/6) silty clay.
Strong, coarse subangular blocky structure.
Many deep cracks form polygonal patterns on the surface.
Cracks are generally 1 cm wide at 50-cm depth.
Consistency of dry soil is hard.
Few very fine pores, many fine roots.
About 1% small (1-5 cm) hard lime concretions (kankar).
Few limestones and flintstones (1-2 cm).
Gradual boundary.

B1 20-44 cm
Dull reddish brown (5YR 4/4) clay.
Strong, coarse subangular blocky structure, transition to platy structure.
Consistency of dry soil is hard.
Few very fine pores, many fine roots.
About 1% kankar, few larger stones.
Gradual boundary.

B21 44-88 cm
Dark reddish brown (5YR 3/4) clay.
Strong, coarse prismatic structure.
Slickensides present on surfaces with their long axes tilted from the horizontal.
Consistency of dry soil is hard.
Few very fine pores, few roots on ped surfaces.
About 1% kankar, locally some (1-3%) distinct soft lime spots (oblong and oval).
Gradual boundary.

B22 88-130 cm
Dull reddish brown (5YR 4/4) clay.
Strong, coarse prismatic structure.
Wedge-shaped structural aggregates.
Very pronounced slickensides on virtually all surfaces.
Consistency of dry soil is hard.
Very few fine pores, virtually all roots on ped surfaces.
About 1% kankar, locally some (1-2%) soft lime spots.
Irregular boundary.

B3 130-140 cm
Transitional layer, mixture of dull to dark reddish brown clay, soft white lime, greenish glauconitic material, and rounded-off white to grayish hard limestone.

R >140 cm
White to grayish limestone, and light olive-green to brown sandy material, which is heavily cemented below 150-160 cm depth.

Source: Described by P. Buringh and K. Harmsen, 21/10/80 (Cooper et al. 1981).

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New Approaches to Vertisol Classification and Their Influence on the Transfer of Technology

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Abstract

Based on an interchange of ideas and information with 140 soil scientists through four Circular Letters, and through field observations made on approximately 300 Vertisols primarily in Australia, the Sudan, the United States, and Venezuela, ICOMERT (International Committee on the Classification of Vertisols) has made the following proposals for modifications to the Vertisol description in Soil Taxonomy (USDA 1975):

- *It is necessary to quantify the amount of slickensides and tilted parallelepipeds in the control section of Vertisols; a minimum occurrence of 10% of either is suggested. The presence of gilgai as a prerequisite in the general definition of Vertisols is proposed to be waived.*
- *A new suborder, the Aquerts, is suggested; proposed are great groups based on acidity (Dystraquerts), duripan (Duraquerts), periodic ponding (Epiaquerts), and absence of any of these three criteria (Eutraquerts).*
- *The suborder Xererts should be subdivided into those with a duripan (Duri-) and those without (Haplo-).*
- *The suborder Torrerts should be subdivided into those with a salic horizon (Sali-) and those without (Haplo-).*
- *The suborders Uderts and Usterts should be subdivided into the acid (Dystr-) and nonacid (Eutr-).*
- *As new subgroups the following are proposed: chromic, leptic, sodic, mazic, and grumic. Redefinition of the following subgroups is proposed: aeric, aridic, udic, and xeric.*

Résumé

Nouvelles approches à la classification des Vertisols et leur influence sur le transfert de technologie : *Fondé sur un échange d'idées et d'information avec 140 pédologues par l'intermédiare de quatre circulaires et d'observations de terrains faites sur environ 300 Vertisols, principalement en Australie, au Soudan, aux Etats-Unis et au Vénézuela, le Comité international de la classification des Vertisols (ICOMERT) a fait les propositions suivantes en ce qui concerne les modifications de la description des Vertisols dans la "Soil Taxonomy" (USDA 1975) :*

- *Il est nécessaire de définir quantitativement le nombre des parallélépipèdes inclinés et faces de glissement dans la section de contrôle des Vertisols; une présence minimum de 10% des uns et des autres est envisagée. Il est suggéré de renoncer à la présence de gilgai comme critère dans la définition générale des Vertisols.*
- *Un nouveau sous-order, les Aquerts, est conseillé; les grands groupes proposés sont fondés sur*

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l'acidité (Dystraquerts), duripan (Duraquerts), inondation périodique (Epiaquerts), et l'absence de l'un de ces trois critères (Eutraquerts).

- *Le sous-ordre des Xererts devrait être subdivisé entre ceux qui ont un duripan (Duri-) et ceux qui n'en ont pas (Haplo-).*
- *Le sous-ordre des Torrerts devrait être subdivisé entre ceux qui ont un horizon salique (Sali-) et ceux qui n'en ont pas (Haplo-).*
- *Les sous-ordres des Uderts et des Usterts devraient être divisés en groupes acides (Dystr-) et non acide (Eutr-).*
- *Comme nouveaux sous-groupes, on propose les suivants : chromique, leptique, sodique, mazique et grumique. Une nouvelle définition des sous-groupes suivants est proposée : aérique, aridique, udique et xérique.*

Introduction

Clay soils, subjected to considerable changes in volume when wet and dry, cover around 260 million ha in the world (Blokhuis 1982). Most of those soils are grouped under the name of Vertisols in Soil Taxonomy (USDA 1975), as well as in the French System (Duchafour 1970) and in the Legend to the Soil Map of the World (FAO/UNESCO 1974). Especially in tropical and subtropical regions, these soils represent important current and potential soil resources, mainly due to their natural fertility and high water-holding capacity.

Little information was received from soil scientists in the tropical and subtropical latitudes during development of the Soil Taxonomy. Presently, however, soils in most of these areas are being classified according to Soil Taxonomy, and it has become evident that the Soil Taxonomy must be made more adequate and representative for its use in tropical and subtropical regions. It is in this respect that the Soil Conservation Service of the USDA has created several International Committees to coordinate the proposals that soil scientists throughout the world may have on possible modifications to Soil Taxonomy. In 1981, an International Committee on the Classification of Vertisols (ICOMERT) was established.

This paper presents a review of the most important items discussed and agreed through four Circular Letters of ICOMERT and includes the last proposed key for the order Vertisols.

The Circular Letters

ICOMERT has been working primarily by using a system of Circular Letters. As Chairman of the Committee, I developed the first Letter from my own observations and studies of the soils under question; I then sent the letter to a large number of scientists interested in the specific problem. From the answers received, plus any other information gathered, the next Letters, in turn, tried to present a balance of the different points of view. Following is a summary of the discussions that took place in the ICOMERT Circulars.

First Circular

The First Circular was prepared and sent during 1981. The main problems presented were (1) the poor relationship between field drainage and taxonomic class and (2) the need to include acidity and calcareous nature as criteria at the family level.

The problems and suggestions related to the way field drainage is considered by Soil Taxonomy were derived from research done in Venezuela (Comerma et al. 1978), where the new suborder, Aquerts, was introduced. The suggestions related to acidity and calcareous nature were derived from Trinidad (Smith 1975) and Venezuela (FNIA 1976), where new families were proposed.

Second Circular

The second circular, in 1982, presented as main items of discussion the objections and some proposals in relation to the new suborder, Aquerts, and a new definition of an aquic moisture regime for these soils. Stagnant water on the soil surface for about 3 months, as the core of the definition, raised several doubts. A shorter time of water stagnation, or even areas without any water on the soil surface, were proposed by some to be included in the new definition of an aquic regime.

In relation to calcareous families, there were no objections; but acidity as a criterion for family was controversial. Many scientists thought that, due to the stability of this characteristic in this kind of soil, it might be worth considering acidity at a higher taxonomic level, such as the subgroup or even great group level.

Finally, several new potential problems in the classification of Vertisols were presented. These included: whether sodium should be used as a criterion to establish a separate soil taxon; whether to separate the different kinds of soil structure and consistence of the surface horizons into mazic and grumic; whether Vertisols should be separated by depth (shallow and deep), by argillic horizons (with and without), and by gilgai (with and without). All these points, together with the rationale for their consideration, were included in the Third Circular Letter.

Third Circular

In 1983, the Third Circular Letter summarized the various opinions received and presented the following tentative conclusions:

1. To eliminate gilgai as a typical characteristic that, along with the amount of clay, cracks, and depth, defines Vertisol at the order level.
2. To test decreasing the required depth of 50 cm to 30 cm, whenever there is evidence of intersecting slickensides or of tilted parallelepipeds.
3. To discuss whether slickensides should be diagnostic for Vertisols if they occur at depths deeper than 1 m.
4. To tentatively subdivide the suborder Aquerts into Dystr-, Eutr-, and Plan-, according to their base saturation in the upper meter and to whether they flood.
5. To divide the Usterts into Dystr-, Orth-, and Eutr-, again based on the base saturation and the presence of gilgai.
6. To divide the Torrets with the same criteria as the Orthids (Sali-, Pale-, Duri-, Calci-, and Haplo-).

Fourth Circular

In 1984, with the Fourth Circular letter, and after several tours and discussions (Comerma 1985a,b), the following tentative agreements were reached:

General definition of Vertisols. It was agreed that (1) gilgai should not be retained in the general definition; (2) the depth of occurrence of slickensides and the minimum depth established in Soil Taxonomy should stay as it is; and (3) a quantification of the minimum amount of slickensides and/or tilted parallelepipeds in the control section should be added.

New suborders. For the Aquerts, a special aquic moisture regime applied to this kind of soil was developed. Instead of the auger-hole method to detect a water table, it was suggested that piezometers, tensiometers, or dyes should be used to detect iron or manganese in the reduced stage.

A new suborder, the Monerts, was suggested (Ali et al. 1982) to be applied to areas subjected to a monsoonal climate. Monerts would have their cracks opening and closing only once during the year. Several objections were raised about the exclusiveness of this behavior to only monsoon climates, and consequently this suggestion was not accepted for inclusion in the key.

Changes in great groups. As the main separation relating to drainage was now considered at the suborder level with the proposed inclusion of Aquerts, the criterion suggested was to separate the acid and nonacid Vertisols (Dystr- and Eutr-) in the Aquerts, Uderts, and Usterts. The use of pH instead of aluminium or base saturation is dubious, as available data are inadequate; the same is the case for the exclusion from acid Vertisols of those with a pH less than 5 but with salts higher than 0.4 S m^{-1}.

The great group Planaquerts was seriously objected to, because of the similarity of its name to Planosols, and was replaced by Epiaquerts; this name, however, also requires modification in its present use in Soil Taxonomy.

After several discussions on the convenience and practicality of identifying features in the field, the great groups of the Torrerts were divided into those with a salic horizon or with a temporary saturation with water, and those without those features; the ones that, in addition, were rich in sodium were left for the subgroup level, because they are difficult to identify in the field.

In the Aquerts as well as in the Xererts, cases with a duripan were seen in the field, a great group was created for those and included.

Changes at subgroup level. Several new names for subgroups, as well as modifications of those already in use, were considered necessary. The new names include:

- Chromic, to separate the light-colored ones from the ones considered typic;
- Leptic, to include those with features of Vertisols within 50 cm, but not within 1 m or more;
- Sodic, for those with an exchangeable sodium percentage (ESP) of 15 or a sodium absorption ratio (SAR) of > 13 within 1 meter;
- Mazic and grumic for the type of structural condition at the surface horizons.

The redefined names include those related to divisions within the prevailing moisture regime that are known to affect the use of the soils in a definite manner; so aridic, ustic, udic, and xeric were redefined, based on the length of time the cracks remain open during the year.

Changes at family level. In addition to the use of fine and very fine textures and of mineralogy for classifying families, the proposal is to include calcareous and noncalcareous families, defined on the basis of reaction or not in the field, to HCl in the upper 50 cm.

According to the rationale and tentative solutions that have been given above, ICOMERT presented in the Fourth Circular Letter the Proposed Key (see Appendix) for the consideration of anyone interested in the classification of Vertisols. The Committee is still functioning, and comments may be sent to me for inclusion in the next Circular Letter.

Appendix

ICOMERT: Proposed Key to the Order of Vertisols

D. (Vertisols are) other soils that

1. Do not have a lithic or paralithic contact, petrocalcic horizon, or duripan within 50 cm of the surface; and
2. After the soil to a depth of 18 cm has been mixed, as by plowing, have 30% or more clay in all subhorizons to a depth of 50 cm or more; and
3. Have at some time in most years, unless irrigated or cultivated, open cracks[1] at a depth of 50 cm that are at least 1 cm wide and extend upward to the surface or to the base of the plow layer or surface crust; and
4. Between a depth of 25 cm and 1 m or to a lithic or paralithic contact, a petrocalcic horizon, or a duripan, have 10% or more (as a weighted average) of the aggregates or of the major ped surfaces constituted by either:
   a. wedge-shaped aggregates, or
   b. slickensides close enough to intersect,
   In both cases they should have their long axis tilted 10 to 60° from the horizontal, to be accountable.

Suborders

Vertisols that lack a salic horizon whose upper boundary is within 75 cm of the surface, and have an aquic moisture regime or are artificially drained and have within 50 cm of the surface, in more than half of each pedon, dominant color[2] (moist) on ped faces, or in the matrix if peds are absent, as follows:

1. If there is mottling, chroma is 2 or less; or
1. If there is no mottling, chroma is 1 or less.

Aquerts

DB. Other Vertisols that have a thermic, mesic, or frigid soil temperature regime and, unless irrigated, have cracks that open and close once each year and remain open for 60 consecutive days or more in the 90 days following the summer solstice in more than 7 out of 10 years, but that are closed for 60 consecutive days or more during the 90 days following the winter solstice.

Xererts

DC. Other Vertisols that have, in most years, cracks that either remain open throughout the year or are closed for less than 60 consecutive days at a period when the soil temperature at a depth of 50 cm is continuously higher than 8°C, or are saturated within 1 m of the surface for 1 month or more in some years and have a salic horizon whose upper boundary is within 75 cm of the surface.

Torrerts

DD. Other Vertisols that have cracks that open and close one or more times during the year in most years, but do not remain open for as many as 90 cumulative days in most years.

Uderts

DE. Other Vertisols

Usterts

Great Groups

Aquerts

DAA. Aquerts that, having an EC of the saturation extract less than 4 mmhos/cm (0.4 S m^{-1}) at 25°C, have a pH of 5.0 or less in 1:1 water or 4.5 in 0.01 M $CaCl_2$ in the major part of the upper 50 cm in more than half of each pedon.

Dystraquerts

DAB. Other Aquerts that have a duripan with its upper boundary within 1 m of the surface.

Duraquerts

DAC. Other Aquerts that are subject to at least a few continuous days of ponding each year in more than 7 out of 10 years.

Epiaquerts

DAD. Other Aquerts

Eutraquerts

Xererts

DBA. Xererts that have a duripan with its upper boundary within 1 m of the surface.

Durixererts

DBB. Other Xererts.

Haploxererts

Torrerts

DCA. Torrerts that have a salic horizon whose upper boundary is within 75 cm of the surface and are saturated with water within a depth of 1 m for 1 month or more in some years or are artificially drained.

Salitorrerts

DCB. Other Torrerts.

Haplotorrerts

Uderts

DDA. Uderts that, having an EC of the saturation extract less than 4 mmhos/cm (0.4 S m^{-1}) at 25°C, have a pH 5.0 or less in 1:1 water or 4.5 in 0.01 M $CaCl_2$ in the major part of the upper 50 cm in more than half of each pedon.

Dystruderts

DDB. Other Uderts

Eutruderts

Usterts

DEA. Usterts that, having an EC of the saturation extract less than 4 mmhos/cm (0.4 S m^{-1}) at 25°C, have a pH 5.0 or less in 1:1 water or 4.5 in 0.01 M $CaCl_2$ in the major part of the upper 50 cm in more than half of each pedon.

Dystrusterts

DEB. Other Usterts.

Eutrusterts

Subgroups

Dystraquerts. Typic Dystraquerts are the Dystraquerts that

a. Have in 60 percent or more of the matrix in all subhorizons down to a depth of 75 cm one or more of the following:
   1. If mottled and if hue is 2.5Y or redder and the value, moist, is >5, the chroma, moist, is 2 or less; if the value, moist, is 5 or less, the chroma, moist, is 1 or less;
   2. If mottled and the hue is yellower than 2.5Y, the chroma, moist, is 2 or less;
   3. The chroma, moist, is 1 or less whether mottled or not.

b. Do not have within a depth of 1 m from the soil surface, any layer, horizon, or contact, except a duripan, that interrupts the presence of slickensides and/or wedge-shaped aggregates.

c. Do not have either of the following:
   1. Jarosite mottles and a pH between 3.5 and 4.0 (1:1 water, air-dried slowly in shade) in some subhorizon within 50 cm of the soil surface; or
   2. Jarosite mottles and a pH <4 (1:1 water, air-dried slowly in shade) in some subhorizon between depths of 50 and 100 cm from the soil surface.

d. Have both of the following:
   1. cracks that open and close one or more times during the year in most years, and remain open for 150 or more cumulative days; and
   2. cracks that are closed for 60 consecutive days or more in most years at a time when the soil temperature at a depth of 50 cm is continuously above 8°C.

Aeric Dystraquerts are like the Typic Dystraquerts except for a.

Leptic Dystraquerts are like the Typic Dystraquerts except for b.

Sulfic Dystraquerts are like the Typic Dystraquerts except for c.

Udic Dystraquerts are like the Typic Dystraquerts except for d(1).

Xeric Dystraquerts are like the Typic Dystraquerts except for d(2).

Duraquerts. Typic Duraquerts are the Duraquerts that

a. Have in 60 percent or more of the matrix in all subhorizons down to a depth of 75 cm one or more of the following:
   1. If mottled and if hue is 2.5Y or redder and the value, moist, is >5, the chroma, moist, is 2 or less; if the value, moist, is 5 or less, the chroma, moist, is 1 or less;
   2. If mottled and the hue is yellower than 2.5Y, the chroma, moist, is 2 or less;
   3. The chroma, moist, is 1 or less whether mottled or not.

b. Have cracks that open once a year for 60 consecutive days or more in the 90 days following the summer solstice, and have a thermic, mesic, or frigid soil temperature regime.

Aeric Duraquerts are like the Typic Duraquerts except for a.

Ustic Duraquerts are like the Typic Duraquerts except for b.

Epiaquerts. Typic Epiaquerts are the Epiaquerts that

a. Have in 60 percent or more of the matrix in all subhorizons down to a depth of 75 cm one or more of the following:
   1. If mottled and if hue is 2.5Y or redder and the value, moist, is >5, the chroma, moist, is 2 or less; if the value, moist, is 5 or less, the chroma, moist, is 1 or less;
   2. If mottled and the hue is yellower than 2.5Y, the chroma, moist, is 2 or less;
   3. The chroma, moist, is 1 or less whether mottled or not.

b. Do not have within a depth of 1 m of the soil surface, any layer, horizon, or contact that interrupts the presence of slickensides and/or wedge-shaped aggregates.

c. Do not have within a depth of 1 m any subhorizon with a value of 15 exchangeable sodium percentage (ESP) or 13 sodium absorption ratio (SAR) or more.

d. Have both of the following:
   1. cracks that open and close one or more times during the year in most years, and remain open for 150 or more cumulative days; and
   2. cracks that are closed for 60 consecutive days or more in most years at a time when the soil temperature at a depth of 50 cm is continuously above 8°C.

Aeric Epiaquerts are like the Typic Epiaquerts except for a.

Leptic Epiaquerts are like the Typic Epiaquerts except for b.

Sodic Epiaquerts are like the Typic Epiaquerts except for c.

Udic Epiaquerts are like the Typic Epiaquerts except for d(1).

Xeric Epiaquerts are like the Typic Epiaquerts except for d(2).

Eutraquerts. Typic Eutraquerts are the Eutraquerts that

a. Have in 60 percent or more of the matrix in all subhorizons down to a depth of 75 cm, one or more of the following:
   1. If mottled and if hue is 2.5Y or redder and the value, moist, is >5, the chroma, moist, is 2 or less; if the value, moist, is 5 or less, the chroma, moist, is 1 or less;
   2. If mottled and the hue is yellower than 2.5Y, the chroma, moist, is 2 or less;
   3. The chroma, moist, is 1 or less whether mottled or not.

b. Do not have within a depth of 1 m from the soil surface, any layer, horizon, or contact that interrupts the presence of slickensides and/or wedge-shaped aggregates.

c. Do not have within a depth of 1 m any subhorizon with a value of 15 ESP or 13 SAR or more.

d. Have both of the following:
   1. cracks that open and close one or more times during the year in most years, but do not remain open for as many as 90 cumulative days; and
   2. cracks that are closed for 60 consecutive days or more in most years at a time when the soil temperature at a depth of 50 cm is continuously above 8°C.

Aeric Eutraquerts are like the Typic Eutraquerts except for a.

Leptic Eutraquerts are like the Typic Eutraquerts except for b.

Sodic Eutraquerts are like the Typic Eutraquerts

except for c.
Ustic Eutraquerts are like the Typic Eutraquerts except for d(1).
Xeric Eutraquerts are like the Typic Eutraquerts except for d(2).

Durixererts. The Typic Durixererts are the Durixererts that

a. Have chromas, moist, of 1 or less throughout the upper 30 cm in more than half of each pedon.
b. Have a platy or massive duripan that is indurated in some subhorizon.
c. Have cracks that open once a year for 90 to 180 consecutive days.

Aridic Durixererts are like the Typic Durixererts except for c and the cracks are open once a year for more than 180 consecutive days.
Chromic Durixererts are like the Typic Durixererts except for a.
Haplic Durixererts are like the Typic Durixererts except for b.
Udic Durixererts are like the Typic Durixererts except for c and the cracks are open once a year for less than 90 consecutive days.

Haploxererts. The Typic Haploxererts are the Haploxererts that

a. Have chromas, moist, of 1 or less throughout the upper 30 cm in more than half of each pedon.
b. Do not have within a depth of 1 m from the soil surface, any layer, horizon, or contact that interrupts the presence of slickensides and/or wedge-shaped aggregates.
c. Have cracks that open once a year for 90 to 180 consecutive days.

Aridic Haploxererts are like the Typic Haploxererts except for c and the cracks are open once a year for more than 180 consecutive days.
Chromic Haploxererts are like the Typic Haploxererts except for a.
Leptic Haploxererts are like the Typic Haploxererts except for b.
Udic Haploxererts are like the the Typic Haploxererts except for c and the cracks are open once a year for less than 90 consecutive days.

Salitorrerts. The Typic Salitorrerts are the Salitorrerts that

1. Have a salic horizon with its upper boundary within 75 cm from the surface and are either saturated within 1 m of the surface for 1 month or more in some years or are artificially drained.

Haplotorrerts. The Typic Haplotorrerts are the Haplotorrerts that

a. Do not have within a depth of 1 m from the soil surface, any layer, horizon, or contact that interrupts the presence of slickensides and/or wedge-shaped aggregates.

Leptic Haplotorrerts are like the Typic Haplotorrerts except for a.

Dystruderts. The Typic Dystruderts are the Dystruderts that

a. Have chromas, moist, of 1 or less throughout the upper 30 cm in more than half of each pedon.
b. Do not have within a depth of 1 m from the soil surface, any layer, horizon, or contact that interrupts the presence of slickensides and/or wedge-shaped aggregates.

Chromic Dystruderts are like the Typic Dystruderts except for a.
Leptic Dystruderts are like the typic Dystruderts except for b.

Eutruderts. The Typic Eutruderts are the Eutruderts that

a. Have chromas, moist, of 1 or less throughout the upper 30 cm in more than half of each pedon.
b. Do not have within a depth of 1 m from the soil surface, any layer, horizon, or contact that interrupts the presence of slickensides and/or wedge-shaped aggregates.

Chromic Eutruderts are like the Typic Eutruderts except for a.
Leptic Eutruderts are like the Typic Eutruderts except for b.

Dystrusterts. The Typic Dystrusterts are the Dystrusterts that

a. Have chromas, moist, of 1 or less throughout the upper 30 cm in more than half of each pedon.
b. Do not have within a depth of 1 m from the soil surface, any layer, horizon, or contact that interrupts the presence of slickensides and/or wedge-shaped aggregates.
c. Have cracks that are open one or more times during the year in most years and remain open for 150 to 210 cumulative days.

Aridic Dystrusterts are like the Typic Dystrusterts except for c and their cracks remain open for more than 210 cumulative days.
Chromic Dystrusterts are like the Typic Dystrusterts except for a.
Leptic Dystrusterts are like the Typic Dystrusterts

except for b.

Udic Dystrusterts are like the Typic Drystrusterts except for c and their cracks remain open for less than 150 cumulative days.

Eutrusterts. The Typic Eutrusterts are the Eutrusterts that

a. Have chromas, moist, of 1 or less throughout the upper 30 cm in more than half of each pedon.
b. Do not have within a depth of 1 m from the soil surface, any layer, horizon, or contact that interrupts the presence of slickensides and/or wedge-shaped aggregates.
c. Do not have within a depth of 1 m any subhorizon with a value of 15 ESP or 13 SAR or more.
d. Have cracks that are open one or more times during the year in most years and remain open for 150 to 210 cummulative days.

Aridic Eutrusterts are like Typic Eutrusterts except for d and their cracks remain open for more than 210 cumulative days.

Chromic Eutrusterts are like Typic Eutrusterts except for a.

Leptic Eutrusterts are like Typic Eutrusterts except for b.

Sodic Eutrusterts are like Typic Eutrusterts except for c.

Udic Eutrusterts are like Typic Eutrusterts except for d and their cracks remain open for less than 150 cumulative days.

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Using Soil Survey Interpretations for Vertisols in Land-Use Planning

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Abstract

Vertisols cover about 9 million ha in the continental United States. All seven great groups in the Vertisol order and 23 of the 25 subgroups are represented. Soil temperature regimes range from hyperthermic to frigid; soil moisture regimes range from udic to aridic.

This paper presents the kinds of soil survey interpretations applied in the United States; for this, the soil series Houston Black clay and Lake Charles Mapping Unit (both Vertisols) are used to provide examples. In addition, there is information on where the interpretations can be found and how they are used; most of the interpretations used in soil surveys in the United States are discussed.

Résumé

Utilisation des interprétations de cartes pédologiques pour les Vertisols pour la planification de l'utilisation des terres : *Les Vertisols comprennent environ 9 millions d'hectares sur le continent des Etats-Unis. Les sept grands groupes dans l'ordre Vertisol et 23 des 25 sous-groupes sont représentés. Les régimes de température du sol varient d'hyperthermique à frigide; les régimes d'humidité du sol varient d'udique à aridique.*

Cet article présente les différentes interprétations utilisées pour les Vertisols aux Etats-Unis. Les séries du sol "Houston Black Clay" et "Lake Charles Mapping Unit" (toutes les deux Vertisols) sont fournies comme exemples. En plus, on fournit des informations sur l'endroit où les interprétations peuvent être trouvées et comment elles sont utilisées. La plupart des interprétations utilisées dans les cartes pédologiques aux Etats-Unis sont données.

Introduction

Vertisols cover about 9 million ha in the continental United States (Fig. 1); over one-half this area is in the State of Texas. Vertisols are important for agriculture because of their generally smooth topography and their occurrence in areas that already have farming and cattle-raising operations. Although rainfall is somewhat limited in most areas, crops can be grown on Vertisols that occur in the udic and ustic moisture regimes. Interpretations for these soils are also important for nonagricultural purposes, because their high shrink-swell potential and clayey textures complicate their use for houses, streets, roads, and any excavations.

The U.S. Department of Agriculture's (USDA) Soil Conservation Service (SCS) has classified soils in the United States into all seven great groups in the Vertisol order and 23 of the 25 subgroups. Soil temperature regimes range from hyperthermic to frigid, soil moisture regimes from udic to aridic. Soil Taxonomy (USDA 1975) provides information on texture, moisture and temperature regimes, and clay mineralogy inherent in this system of soil classifica-

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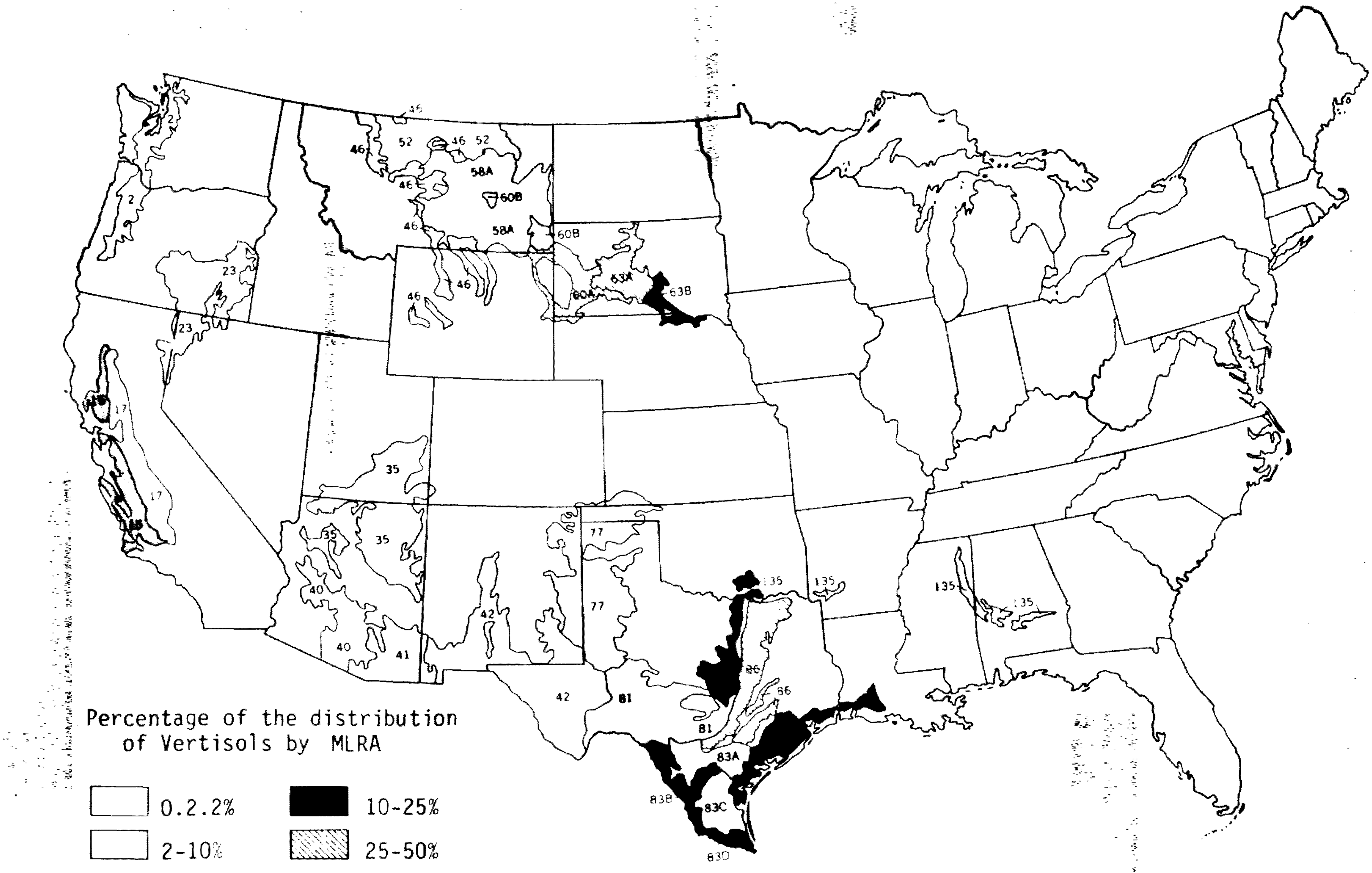

SOURCE: Map of Major Land Resource Areas (MLRA) of the United States, January 1984

Figure 1. Distribution of Vertisols in the United States of America as percentage in Major Land Resource Areas.

tion. Interpretative information in the National Cooperative Soil Survey program in the United States is mainly transferred at the soil series level.

Soil Survey Interpretations and Their Use

Soil survey interpretations are predictions of soil behavior for specified land uses and specified management practices. They are based on the soil properties that directly influence the specified use of the soil.

Soil surveys in the United States include both detailed and general soil maps, and interpretations are made for both taxonomic and mapping units. Coordinated soil survey interpretations, by taxonomic units, are compiled from a soil interpretations record, Form SCS-SOI-5. The data on this record are also stored in a database at the University of Iowa, Ames, Iowa, which enables cross-checking and checking for compatibility with established guidelines, and printing of the data in various formats. These soil surveys and the resulting data, then, form the basic data for soil survey interpretations. These basic data plus data from the SCS field office technical guides are included in soil survey publications, which describe soil mapping units. The Appendix provides an example of a description of a mapping unit of Houston Black clay, 1 to 3% slopes, from the Soil Survey of Tarrant County, Texas (USDA 1981).

The technical guide in each SCS field office contains the soil survey interpretations that are a part of soil survey publications. In addition, these guides detail procedures for various projects, which enable SCS employees to give direct assistance to those who use the land. Some of this specific information includes how to drain fields and how to design and construct field terraces, diversions, and waterways. Other available local information includes material gained from experience, including how to implement no-till, stubble mulch, stripcropping, and other conservation practices. Detailed information on various types of irrigation is available in areas where land is irrigated. Information is also available to assist the conservationist in using the Universal Soil Loss Equation (USDA 1978).

Information for using the unique properties of Vertisols is introduced at the local level rather than at the level of soil survey interpretations. Three primary uses of soil interpretations include rating soil potential, providing evaluations for land and assessments of sites for various purposes, and identifying soil moisture needs.

Soil Potential Ratings

Soil potential ratings indicate the relative quality of a soil for a particular use, compared with other soils in a given area (USDA 1983). Yield or performance level, the relative cost of applying modern technology to minimize the effects of any soil limitations, and the adverse effects of continuing limitations, if any, on social, economic, or environmental values are considered. The criteria for developing soil potential ratings for a particular use are established specifically for the area for which the ratings are made.

Soil potential ratings are developed primarily for planning purposes and are not intended as recommendations for soil use. They help decisionmakers determine the relative suitability of soils for a given use and, along with other resource information, provide a guide for land-use decisions. Soil potential ratings supplement the land capability classes, woodland suitability groups, range sites, soil limitation ratings, and other soil interpretations in soil handbooks and technical guides.

Several papers on developing soil potential ratings have been published (McCormack 1974, Guthrie and Latshaw 1980, Brasfield 1984).

Land Evaluation and Site Assessment (LESA)

In agricultural land evaluation, soils of a given area are rated and placed into groups ranging from the best to the most suitable for a stated agricultural use, such as cropland, forest land, or rangeland. The best group is assigned a value of 100, and all other groups are assigned lower values. The site assessment identifies important factors other than soils, which contribute to the quality of a site for agricultural use. Each factor selected is stratified into a range of possible values in accordance with local needs and objectives.

Thus, LESA scores combine a value for land evaluation with a value for site assessment to determine the total value for agriculture. The higher the total value of a site, the higher the economic viability of the site for agriculture. Information on LESA is contained in the National Agricultural Land Evaluation and Site Assessment Handbook (USDA 1979); explanations of the system are also available (Dunford et al. 1983, Wright et al. 1983).

Soil Moisture Information

Information on soil moisture is a part of the soil classification system; however, information on available water capacity and permeability is also given in soil survey interpretations. A model for generating data on soil-moisture regime for soil classification (USDA 1975) can be used on days the soil-control sections are either dry or moist.

Models that give more precise information on soil moisture for specific crops are currently being developed and tested. One such model uses data on soil, plant consumptive use, and climate to predict how much and when soil moisture will be available for plant growth. This information has been developed for use with no special equipment (personal correspondence, Robert Grossman, National Soil Survey Laboratory, SCS, MNTC, Lincoln, Nebraska). Other, more sophisticated computerized models are also under development.

Examples of Interpretations

Using the soil series Houston Black clay, mapping unit 34, described in the Appendix, and Lake Charles, mapping unit LcA, we can provide examples of soil survey interpretations that have been done on Vertisols in the United States. This exercise may provide an example of a methodology useful for storing information for transfer in a Vertisol network. All examples are from USDA 1981.

Some ratings are shown as limitations. The limitations are considered "slight" if soil properties and site features are generally favorable for the indicated use and if limitations are minor and easily overcome; "moderate" if soil properties or site features are not favorable for the indicated use and if special planning, design, or maintenance is needed to overcome or minimize the limitations; and "severe" if soil properties or site features are so unfavorable or difficult to overcome that special design, significant increase in construction costs, and possibly increased maintenance, intensive maintenance, limited use, or a combination of these are required.

A rating of "good" usually indicates that the soil is suitable for use without many problems. Soil that has a rating of "fair" is usually suitable for use with some problems or modifications needed. A soil rated "poor" is not suitable for the use or is suitable only with major modifications.

Yields per Hectare

Estimates are made of average yields (per ha) that can be expected of the principal crops under a high level of management (Table 1). In any given year, yields may be higher or lower than those indicated in the Table because of variations in rainfall and other climatic factors. Yield estimates are based mainly on the experience and records of farmers, conservationists, and extension agents. Available data from nearby counties and results of field trials and demonstrations are also considered.

Land Capability Classification

In a general way, the suitability of soils for use as cropland is shown by land capability classification. Crops that require special management are excluded. The soils are grouped according to their limitations for field crops, the risk of damage if they

Table 1. Average expected yields per hectare of crops and pasture, under high level of management (USDA 1981).

Map symbol and soil name	Grain sorghum (kg ha^{-1})	Wheat (kg ha^{-1})	Oats (kg ha^{-1})	Cotton lint (kg ha^{-1})	Improved bermudagrass (AUM)[1]
34-Houston Black	5400	2300	3400	610	9.5

[1] AUM = Animal units, modified.

Table 2. Average expected rangeland productivity (USDA 1981).

Map symbol and soil name	Range site name	Estimated productivity (kg ha^{-1}) Favorable year	Average year	Unfavorable year
34 Houston Black	Blackland	7750	6750	4000

are used for crops, and the way they respond to management. Not included in this grouping of soils are those that require major, and generally expensive, landforming that would change slope, depth, or other characteristics of the soils; soils that require possible but unlikely major reclamation projects are also excluded.

Prime Farmland Soils

Prime farmland is one of several kinds of important farmland defined by the USDA. It is of major importance in meeting the nation's short- and long-range needs for food and fiber. The extent of high-quality farmland is limited, and the USDA recognizes that government at local, state, and federal levels, as well as individuals, must encourage and facilitate the wise use of the nation's prime farmland.

Prime farmland soils, as defined, are soils that are best suited to producing food, feed, forage, fiber, and oilseed crops. Prime farmland soils produce the highest yields with minimal inputs of energy and economic resources. Farming these soils results in the least damage to the environment.

Rangeland

In areas that have similar climate and topography, differences in the kind and amount of vegetation produced on rangeland are closely related to the soil. Effective management is based on the relationship between the soils and vegetation and water.

For example, the total annual production of vegetation in favorable, normal, and unfavorable years is estimated (Table 2); the characteristic vegetation is described; and the average percentage of each species is determined. Only those soils that are used as rangeland or are suited to use as rangeland are listed in this interpretation.

A National Range Handbook by the USDA Soil Conservation Service is available.

Woodland Management and Productivity

Woodland interpretations can be used by woodland owners or forest managers to plan the use of soils for wood crops (Table 3). Only those soils suitable for wood crops are listed. The ordination symbol (woodland suitability) for each soil is included in the Table; soils assigned the same ordination symbol

Table 3. Suitable woodland management and expected productivity (USDA 1981).

Map symbol and soil name	Ordination symbol	Management concerns: Equipment limitations	Seeding mortality	Plant competition	Potential productivity: Important trees	Site index (m)	Trees to plant
LcA Lake Charles	2w9	Severe	Severe	Severe	Loblolly pine Southern red oak	27 24	Loblolly pine Slash pine

Table 4. Potential woodland understory vegetation (USDA 1981).

Map symbol and soil name	Potential production: Kind of year	Potential production: Dry weight (kg ha⁻¹)	Common plant name	Composition
LcA–Lake Charles	Favorable	3350	Little bluestem	15
	Normal	2250	Virginia wildrye	10
	Unfavorable	1650	Indiangrass	7

require the same general management and have about the same potential productivity.

A National Woodland Handbook by the USDA Soil Conservation Service is available. Woodland interpretations are coordinated by soil and data stored in the Soil Interpretations Record (SCS-SOI-5).

Woodland Understory Vegetation

For each soil suitable for woodland use, the potential for producing understory vegetation, which consists of grasses, forbs, shrubs, and other plants, is indicated (Table 4). Some woodland, if well managed, can produce enough understory vegetation to support grazing by livestock or wildlife, or both, without damage to the trees.

Windbreaks and Environmental Plantings

Windbreaks protect livestock, buildings, and yards from wind and snow. They also protect fruit trees and gardens, and they furnish habitat for wildlife. Several rows of low-growing and high-growing broadleaf and coniferous trees and shrubs provide the most protection.

Field windbreaks are narrow plantings made at right angles to the prevailing wind and at specific intervals across the field. The interval depends on the erodibility of the soil. Field windbreaks protect cropland and crops from wind, help keep snow on the fields, and provide food and cover for wildlife. Environmental plantings help to beautify and screen houses and other buildings and to abate noise. The plants, mostly evergreen shrubs and trees, are closely spaced. The height that locally grown trees and shrubs are expected to reach in 20 years on each soil can be indicated (Table 5) to assist decisions on choice of species.

Climate

Climatic information in soil surveys includes data on temperature and precipitation for the survey area, as recorded at a station in the site or nearby. Other data include probable dates of the first freeze in fall and the last freeze in spring, length of the growing season, average temperatures and precipitation for winter and summer, and highest and lowest recorded temperatures. Information on wind and humidity can also be given.

Recreation

Soils are also rated according to the limitations that affect their suitability for recreation (Table 6). The ratings are based on such restrictive soil features as wetness, slope, and texture of the surface layer. Susceptibility to flooding is considered.

Table 5. Suitable windbreaks and environmental plantings (USDA 1981).

Map symbol and soil name	Expected height (m) of 20-year-old trees: Eastern red cedar	Eastern cottonwood	Green ash	Osage orgnage
20-Lela	8	18	12	6

Table 6. Suitability for recreational development (USDA 1981).

Map symbol and soil name	Camp areas	Picnic areas	Playgrounds	Paths and trails
34-Houston Black	Moderate: Percolates slowly, too clayey.	Moderate: Too clayey, percolates slowly.	Moderate: Slopes, too clayey.	Moderate: Too clayey

Wildlife Habitat

Soils affect the kind and amount of vegetation that is available to wildlife as food and cover. They also affect the construction of water impoundments. The kind and abundance of wildlife depend largely on the amount and distribution of food, cover, and water. Wildlife habitat can be created or improved by planting appropriate vegetation, by maintaining the existing plant cover, or by promoting the natural establishment of desirable plants. Thus, soils in the survey area are rated according to their potential for providing habitats for various kinds of wildlife.

Engineering

The engineering section of the interpretation provides information for planning land uses related to urban development and water management. Soils are rated for various uses, and the most limiting features are identified. Ratings are given for building site development, sanitary facilities, construction materials, and water management; they are based on observed performance of the soils and on the estimated data and test data in the "Soil Properties" section.

Engineering information is intended for land-use planning, evaluating land-use alternatives, and planning site investigations before design and construction.

Building Site Development

The degree and kind of soil limitations that affect shallow excavations, dwellings with and without basements, small commercial buildings, and local roads and streets are rated (Table 7). Special feasibility studies may be required where the soil limitations are severe.

Dwellings without Basements

The rating criteria for dwellings without basements show how soil characteristics are applied to interpretations (Table 8). This table is shown as an example of the criteria used in tables. The ratings criteria are in the National Soil Handbook (USDA 1983).

Sanitary Facilities

Information on sanitary facilities shows the degree and kind of soil limitations that affect septic tank absorption fields, sewage lagoons, and sanitary landfills, as well as suitability of the soil for use as a daily cover for landfills.

Construction Materials

Information about soils as a source of roadfill, sand,

Table 7. Suitability for building site development (USDA 1981).

Map symbol and soil name	Shallow excavation	Dwellings without basements	Dwellings with basements	Small commercial buildings	Local roads and streets
34-Houston Black	Severe: cutbanks cave.	Severe: shrink-swell.	Severe: shrink-swell.	Severe: shrink-swell.	Severe: low strength, shrink-swell.

Table 8. Rating criteria for use for dwellings without basements (USDA 1981).

Property	Limitation			Restrictive feature
	Slight	Moderate	Severe	
1. USDA Texture	—	—	ice	Permafrost
2. Total subsidence in (cm)	—	—	30	Subsides
3. Flooding	none	—	rare, common	Flooding
4. Depth to high water table (cm)			+	Ponding
	75	45–75	45	wetness
5. Shrink-swell[1]	low	moderate	high, very high	Shrink-swell
6. Unified[1]	—	—	OL,OH,PT	Low strength
7. Slope (%)	8	8-15	15	Slope
8. Depth to bedrock (cm)				
hard	100	50–100	50	Depth to bedrock
soft	50	50	-	
9. Depth to cemented pan (cm)				
thick	100	50-100	50	Cemented pan
thin	50	50	-	
10. Fraction 75 mm (wt pct)[2]	75	25-50	50	Large stones
11. Downslope movement	—	—	-[3]	Slippage
12. Formation of pits	—	—	-[4]	Pitting
13. Differential settling	—	—	-[5]	Unstable fill

1. In the thickest layer between 25 and 100 cm depth.
2. Weighted average to 100 cm.
3. If the soil is susceptible to movement downslope when loaded, excavated, or wet, rate "severe slippage."
4. If the soil is susceptible to the formation of pits caused by the melting of ice when the ground cover is removed, rate "severe pitting."
5. If the soil is susceptible to differential settling, rate "severe unstable fill."

gravel, and topsoil is provided for construction purposes. The soils are rated good, fair, or poor as a source of roadfill and topsoil; they are rated as a probable or an improbable source of sand and gravel. The ratings are based on soil properties and site features that affect the removal of the soil and its use as construction material. Each soil is evaluated to a depth of 150 or 180 cm.

Water Management

The soil properties and site features that affect water management are delineated (Table 9). The degree and kind of soil limitations are given for pond reservoir areas; and embankments, dikes, and levees. Restrictive features that affect each soil for drainage, irrigation, terraces and diversions, and grassed waterways are also given. These are explained below.

Pond reservoir areas hold water behind a dam or embankment. Soils best suited to this use have low seepage potential in the upper 150 cm. The seepage potential is determined by the permeability of the soil and the depth to fractured bedrock or other permeable material.

Embankments, dikes, and levees are raised structures of soil material, generally less than 6 m high, constructed to impound water or to protect land against overflow. Soils are rated as a source of materials for embankment fill.

Drainage is the removal of excess surface and subsurface water from the soil. How easily and effectively the soil is drained depends on the depth to bedrock, to a cemented pan, or to other layers that affect the rate of water movement; permeability; depth to a high water table or depth of standing water if the soil is subject to ponding; slope; susceptibility to flooding; subsidence or organic layers; and potential frost action.

Irrigation is the controlled application of water to supplement rainfall and support plant growth. The design and management of an irrigation system are affected by depth to the water table, the need for

Table 9. Effect on water management (USDA 1981).

Map symbol and soil name	Limitations for		Features affecting			
	Pond reservoir areas	Embankments, dikes, and levees	Drainage	Irrigation	Terraces and Diversion	Grassed waterways
34 Houston Black	Slight	Severe: hard to pack.	Deep to water	Slow intake	Percolates slowly	Percolates slowly

drainage, flooding, available water capacity, intake rate, permeability, erosion hazard, and slope. The construction of a system is affected by large stones and depth to bedrock or to a cemented pan. The performance of a system is affected by the depth of the root zone, the amount of salts or sodium, and soil reaction.

Terraces and diversions are embankments or a combination or channels and ridges constructed across a slope to reduce erosion and conserve moisture by intercepting runoff. Slopes, wetness, large stones, and depth to bedrock or to a cemented pan affect the construction of terraces and diversions. A restricted rooting depth, a severe hazard of wind or water erosion, an excessively coarse texture, and restricted permeability adversely affect maintenance.

Grassed waterways are natural or constructed channels, generally broad and shallow, that conduct surface water to outlets at a nonerosive velocity.

Engineering Index Properties

Estimates of the engineering classification and of the range of index properties for the major layers of each soil in the survey area are provided (Table 10). Most soils have layers of contrasting properties within the upper 150 to 180 cm. Depth to the upper and lower boundaries of each layer is indicated.

Texture is given in the standard terms used by the USDA, defined according to percentages of sand, silt, and clay in the fraction of the soil that is <2 mm in diameter.

Classification of the soils is determined according to the Unified Soil Classification System and the system adopted by the American Association of State Highway and Transportation Officials (AASHTO 1970). The Unified system classifies soils according to properties that affect their use as construction material (ASTM 1974). The AASHTO system classifies soils according to those properties that affect roadway construction and maintenance.

Physical and Chemical Properties

Estimates of how some physical and chemical characteristics and features affect soil behavior, are developed (Table 11). These estimates are given for the major layers of each soil in the survey area. The estimates are based on field observations and test data for these and similar soils.

Clay as a soil component consists of mineral soil particles that are <0.002 mm in diameter. In this table, the estimated clay content of each major soil layer is given as a percentage, by weight, of the soil material that is <2 mm in diameter.

Moist bulk density is the weight of soil (oven dry) per unit volume. Volume is measured when the soil is at field moisture capacity, that is, the moisture content at 1/3 bar moisture tension. Weight is determined after drying the soil at 105°C.

Permeability refers to the ability of a soil to transmit water or air. The estimates indicate the rate of downward movement of water when the soil is saturated.

Available water capacity refers to the quantity of water that the soil is capable of storing for use by plants. The capacity for water storage in each major soil layer is stated in cm of water per cm of soil. The capacity varies, depending on soil properties that affect the retention of water and the depth of the root zone. The most important properties are the content of organic matter, soil texture, bulk density, and soil structure.

Soil reaction is a measure of acidity or alkalinity and is expressed as a range in pH values. The range in pH of each major horizon is based on many field tests. For many soils, values have been verified by laboratory analyses. Soil reaction is important in selecting crops and other plants, in evaluating soil

Table 10. Engineering index properties (USDA 1981).

Map symbol and soil name	Depth (cm)	USDA texture	Classification		Fragments 75 mm (%)	Percentage passing sieve number				Liquid limit (%)	Plasticity index
			Unified[1]	AASHTO[2]		4	10	40	200		
34-Houston Black	0-105	Clay	CH	A-7-6	0	95-100	95-100	95-100	85-100	58-98	34-72
	105-203	Clay, Silty clay	CH	A-7-6	0	95-100	95-100	95-100	85-100	51-00	34-75

1. American Society for Testing and Materials (1974).
2. American Association of State Highway and Transportation Officials (1970).

Table 11. Physical and chemical properties of soils (USDA 1981).

Map symbol and soil name	Depth (cm)	Clay (%)	Permeability	Available water (cm water [cm soil]$^{-1}$)	Soil reaction (pH)	Shrink-swell potential	Erosion factors		Wind erodibility group	Organic matter (%)
							K[1]	T[1]		
34-Houston Black	0-105	40-60	0.4×10^{-4}	0.20	7.4-8.4	Very high	0.42	11.2	4	1-4
	105-202	40-60	0.4×10^{-4}	0.20	7.4-8.4	Very high	0.42			

1. See text for explanation of K and T.

amendments for fertility and stabilization, and in determining the risk of corrosion.

Salinity is a measure of soluble salts in the soil at saturation. It is experessed as the electrical conductivity of the saturation extract. Estimates are based on field and laboratory measurements at representative sites of nonirrigated soils.

Shrink-swell potential is the potential for volume change in a soil with a loss or gain in moisture. Volume change occurs mainly because of the interaction of clay materials with water and varies with the amount and type of clay minerals in the soil.

Erosion factor K indicates the susceptibility of a soil to sheet and rill erosion by water. Factor K is one of six factors used in the Universal Soil Loss Equation (USLE) to predict the average annual rate of soil loss by sheet and rill erosion. Losses are expressed in $\mathrm{t\ ha^{-1}\ a^{-1}}$. Erosion factor T is an estimate of the maximum average annual rate of soil erosion by wind or water that can occur over a sustained period without affecting crop productivity. This rate is also expressed in $\mathrm{t\ ha^{-1}\ a^{-1}}$.

Wind erodibility groups are made up of soils that have similar properties affecting their resistance to wind erosion in cultivated areas. The groups indicate the susceptibility of soil to wind erosion and the amount of soil lost.

Organic matter is the plant and animal residue in the soil at various stages of decomposition. The estimated content of organic matter is expressed as a percentage, by weight, of the soil material that is <2 mm in diameter.

Soil and Water Features

Estimates of the importance of various soil and water features are also provided (see Table 12 for some examples). The estimates are used in land-use planning that involves engineering considerations.

Hydrologic soil groups are used to estimate runoff from precipitation. Soils are assigned to one of four groups. They are grouped according to the intake of water when the soils are thoroughly wet and receive precipitation from long-duration storms. Runoff increases from group A to group D.

Flooding, the temporary inundation of an area, is caused by overflowing streams, runoff from adjacent slopes, or tides. Water standing for short periods after rainfall or snowmelt is not considered flooding, nor is water in swamps and marshes. The frequency and duration of flooding and the time of year when flooding is most likely to occur are given.

High water table (seasonal) is the highest level of a saturated zone in the soil in most years. The depth to a seasonal high water table applies to undrained soils. The estimates are based mainly on the evidence of a saturated zone, namely, grayish colors or mottles in the soil. Indicated in Table 12 is the depth to the seasonal high water table, and provision is made for statements on the kind of water table (perched, artesian, or apparent) and the months of the year that the water table commonly is high. A water table that is seasonally high for <1 month is not indicated.

Depth to bedrock is given if bedrock is within a depth of 150 cm. The depth is based on many soil borings and on observations during soil mapping. The rock is usually specified as either soft or hard.

Cemented pans are cemented or indurated subsurface layers within a depth of 150 cm. Such pans cause difficulty in excavation. Pans are classified as thin or thick. A thin pan is less than 7.5 cm thick if continously indurated, or less than 45 cm thick if discontinuous or fractured.

Subsidence is the settlement of organic soils or of saturated mineral soils of very low density. Subsidence results from either desiccation and shrinkage or oxidation of organic material, or both, following drainage. Subsidence takes place gradually, usually over a period of several years.

Potential frost action is the likelihood of upward or lateral expansion of the soil caused by the formation of segregated ice lenses (frost heave) and the subsequent collapse of the soil and loss of strength

Table 12. Soil and water features (USDA 1981).

Map symbol and soil name	Hydrologic group	Flooding			High water table			Bedrock		Risk of corrosion	
		Frequency	Duration	Months	Depth (m)	Kind	Months	Depth (cm)	Hardness	Uncoated steel	Concrete
34–Houston Black	D	None	–	–	1.5	–	–	150	–	High	Low

on thawing. This interpretation is normally given for soils in colder climates.

Risk of corrosion pertains to potential soil-induced electrochemical or chemical action that dissolves or weakens uncoated steel or concrete.

Appendix

Description of Soil Mapping Unit

34–Houston Black clay, 1 to 3% slopes. This deep, gently sloping soil is on broad, smooth uplands. Areas follow the contour of the slope and are longer than they are wide. They range from 4 to about 60 ha.

Typically, this soil is moderately alkaline clay to a depth of about 200 cm. It is very dark gray in the upper part, grayish brown in the middle, and light yellowish brown in the lower part.

This soil is moderately well drained. Permeability is very slow, and available water capacity is high. Runoff is medium, and the hazard of erosion is moderate. The soil is difficult to work during extremes in moisture conditions. Plowpans form if the soil is tilled when it is wet. The root zone is deep, but plant roots penetrate slowly.

Included with this soil in mapping are small areas of the closely similar Heiden and Leson soils. These inclusions make up as much as 25% of some mapped areas.

This Houston Black soil is mainly used as cropland, and is well suited to this use. Cotton and grain sorghum are the main crops, but corn (maize) and small grains are also grown. The main objectives of management are controlling erosion and maintaining tilth. Terracing and contour farming help to slow runoff and control erosion. Growing crops that produce large amounts of residue or growing deep-rooted legumes helps to control erosion, maintain tilth, and aerate the soil.

This soil is well suited to use as pastureland. Improved bermudagrass, tall fescue, kleingrass, indiangrass, johnsongrass, and vetch are well suited to the soil. Some areas are seasonally wet, and seedbeds are difficult to prepare. Proper pasture management includes fertilization, weed control, and controlled grazing.

This soil is moderately suited to most urban uses. The main limitations are shrinking and swelling with changes in moisture, corrosivity to uncoated steel, and low strength affecting streets and roads. The soil is poorly suited for use as septic tank absorption fields because of its very low permeability.

This Houston Black soil is poorly suited to recreation use. The limitations are the very slow permeability and the clayey texture throughout the soil that causes deep, wide cracks when the soil is dry and stickiness when the soil is wet.

Areas of this map unit are regularly inhabited by doves and quail. Grain crops grown on this soil provide food.

This soil is in capability class IIe at the Blackland range site.
(Source: USDA 1981.)

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Socioeconomic Aspects of Transfer of Vertisol Technology

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Abstract

Recent research has confirmed the viability of a new technology for improved management of Vertisols. The management system, developed over a 5-year period of on-station research at ICRISAT Center, has produced higher and more stable yields at moderate additional costs. Three years ago this technology was taken into farmers' fields, where it produced good results with management support and inputs supplied, provided other constraints do not interfere. Both the continuing need for management support and input supplies and the emergence of further constraints, however, seem to impose much narrower limits for the application of the technology than had earlier been anticipated. This experience with technology transfer into farmers' fields indicates many of the regional or location-specific constraints that remain to be overcome for a wider adoption of improved Vertisol management systems.

The questions that we scientists who work on this technology have to ask ourselves are:

- *How should we go about overcoming these constraints?*
- *What should the research priorities be and how should the task be divided between national institutions and ICRISAT?*
- *What kind of lessons can be learned from this experience for linking station research and on-farm research?*

This paper reviews the performance of an improved Vertisol technology at the research station and in farmers' fields. As on-farm application shows, numerous constraints emerge that require attention by researchers and policymakers; some of the important issues in transfer of the technology are discussed. The implications for research are also drawn.

Résumé

Aspects socio-économiques du transfert de la technologie relatif aux Vertisols : *Des recherches pendant les trois dernières années ont confirmé qu'il y a une technologie viable pour une gestion améliorée des Vertisols. Des observations démontrent qu'un système complet de gestion (développé pendant une période de cinq ans en station expérimentale) a produit des rendements plus élevés et plus stables à peu de frais supplémentaires. Il y a trois ans, cette technologie fut appliquée en champs paysans où elle a donné de bons résultats, tant qu'un soutien à la gestion et à l'application des intrants a été maintenu et que d'autres contraintes n'ont pas interféré. Néanmoins, le besoin continu de soutien à la gestion et d'approvisionnement en intrants, et l'apparition d'autres contraintes, semblent imposer à cette technologie des limites plus étroites que l'on avait pu anticiper. Cette expérience avec le transfert de technologie aux champs des agriculteurs indique que plusieurs des contraintes*

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régionales ou spécifiques restent à surmonter afin d'assurer une adoption plus large des systèmes d'aménagement améliorés des Vertisols.

Les questions que nous, les chercheurs, devons nous poser sur cette technologie sont :

- *Quels sont les moyens par lesquels nous pouvons surmonter ces contraintes?*
- *Quelles devront être les priorités de recherche et comment faut-il partager les responsabilités entre l'ICRISAT et les instituts nationaux?*
- *Que faut-il apprendre de cette expérience pour établir des liens entre la recherche conduite en milieu contrôlé et celle en milieu réel?*

Cet article passe en revue les résultats d'une technologie améliorée pour les Vertisols à la station expérimentale et en champs paysans. Les essais en champs mettent en évidence plusieurs problèmes qui méritent attention par les chercheurs et les décideurs. Sont examinés également certains points importants du transfert de la technologie et les conséquences pour la recherche.

Improved Vertisol Technology

The improved Vertisol management system to which this paper refers can be described as follows: land is developed into watersheds of up to about 25 ha to enable farmers within the watershed to improve their management of soil, water, and crops. On the watershed, broadbeds and furrows are established, across the natural slope, with a constant grade of 0.4 to 0.6% (ICRISAT 1981). These furrows retain the rainwater. Excess runoff, which may be generated during high-intensity storms or after several days of less intensive but continuous rain, is guided by the furrows to run slowly across the natural slope of the field into a waterway, which is covered with grass to avoid erosion. In areas of sufficient rainfall, small reservoirs can be established to store runoff water for supplementary irrigation of the second crop; to generate runoff in reliable quantities under Indian conditions, Pandey (1985) suggests that total rainfall should probably be >1000 mm a^{-1}.

In this system, soil and water are managed to achieve maximal infiltration of rainfall into the soil, and to thus minimize erosion. Crops are sown on the broadbeds. Most of the cultivation operations are carried out with an oxen-drawn wheeled tool carrier. In areas of dependable rainfall (> 750 mm a^{-1}), this form of land management allows farmers to produce crops during the rainy season as well as the following postrainy season. Thus, farmers can increase their cropping intensity from one to two crops annually, using either sequential cropping or intercropping of markedly different growth durations (e.g., sorghum or maize/pigeonpea).

The individual technology components include:

- cultivating the land immediately after the previous postrainy-season crop, before the soil hardens;
- improving drainage by smoothing land, and installing graded broadbeds and furrows, as well as field and community drainage channels;
- applying appropriate sequential or intercropping systems with correct row arrangements;
- dry seeding crops before the monsoon;
- using improved seeds and adequate amounts of fertilizer;
- precision placement of seeds and fertilizers; and
- improved plant protection.

Optimal combinations of these components can generate a synergistic effect on productivity in Vertisol areas with dependable rainfall.

Performance of the Technology at ICRISAT Center

This technology for Vertisols was tested at ICRISAT Center for 8 years (1976/77 to 1983/84). The economic performance of the new technology, using improved cropping systems, is compared to traditional practices and cropping systems in Table 1. The improved cropping systems include a maize/pigeonpea intercrop, a maize-chickpea sequential crop, and a sorghum/pigeonpea intercrop. Rainy-season fallow followed by a postrainy-season crop of sorghum or chickpea form the traditional cropping system.

The long-term (8-year) results are quite consistent over time (Virmani et al. 1989); the last 3 years of experimentation confirm the findings published earlier (Ryan et al. 1982) on the first 5 years. The improved cropping systems yielded 3800-4400 kg

Table 1. Economic performance of Vertisol technology at ICRISAT Center: averages of annual performances over 8 years (1976/77 to 1983/84).

Technology/cropping system	Mean yield (kg ha^{-1})	Gross returns[1] (Rs ha^{-1})	Operational Costs[2] (Rs ha^{-1})	Gross Profit[3] (Rs ha^{-1})	CV of gross profits (%)	Marginal rate of retun (%)
Improved management and improved cropping systems						
Maize/pigeonpea intercrop		6765	2060	4705	28	272
Maize	2712					
Pigeonpea	1121					
Maize-chickpea sequence		7021	2757	4264	43	159
Maize	3205					
Chickpea	1164					
Sorghum/pigeonpea intercrop[4]		8875	2471	6404	26	304
Sorghum	2887					
Pigeonpea	1088					
Traditional management and common cropping systems						
Rainy-season fallow followed by postrainy-season sorghum or chickpea[5]		1643	682	961	43	
Sorghum	567					
Chickpea	718					

Source: Ryan et al. (1982) for results of 1976/77 to 1980/81; and Srivastava et al. (1985) for 1981/82 to 1983/84.

1. Includes value of grain, fodder, and other byproduction. Indian Rs 13 = US$ 1.00.
2. Costs include all material, human and animal labor, and annual costs of implements. ICRISAT wage rates were used to value human labor.
3. Gross profit is calculated as gross returns minus operational costs. Overhead costs such as land revenue, depreciation on buildings, etc., have not been deducted; hence the use of the term "gross profits".
4. Averaged over 3 years, 1981/82 to 1983/84.
5. Averaged from results for separate crops of sorghum or chickpea.

ha^{-1} against 500–700 kg ha^{-1} with the traditional cropping systems. On average, the improved technology gave about 2900 kg ha^{-1} of cereals and 1100 kg ha^{-1} of pulses. The average gross returns of the improved options were more than 4-5 times those of the traditional systems. Although the improved technology required additional operating costs, which ranged between Rs 1400-2100 ha^{-1} above the operating costs for the traditional system, the additional gross profits generated by the improved technology were Rs 3300-5400 ha^{-1}, offering marginal rates of return of 160 to 300%.

In these experiments, we found that the cereal/pigeonpea intercrops performed better than the maize-chickpea sequential crop. In addition, the maize-chickpea sequential system was less stable than the cereal/pigeonpea intercrops, with a coefficient of variation of the same order of magnitude as that of the traditional fallow-sorghum or chickpea cropping system. These experiments show that the improved technology promises to decrease risk, at least with the cereal/pigeonpea intercrops, compared to the traditional cropping system of a single postrainy-season crop.

Economic Results from On-farm Verification Trials

To test the performance of the technology away from ICRISAT Center, on-farm trials were carried out during 3 years (1981/82 through 1983/84) at different locations in dependable-rainfall, Vertisol areas in India. These trials were conducted collaboratively by ICRISAT and the departments of agriculture and other institutions in the states of Andhra Pradesh, Karnataka, and Madhya Pradesh. After initial trials in 1981/82 at Taddanpally village in Andhra Pradesh, the state departments of agriculture in Andhra Pradesh, Karnataka, and Maharashtra initiated their own tests. In 1982/83 these covered 116 ha and involved 40 farmers; in 1983/84 the tests were expanded to cover 2122 ha and involved 1406 farmers.

An economic evaluation of these on-farm trials was conducted, based on data collected from seven experiments in which ICRISAT collaborated: one in 1981/82 at Taddanpally, four in 1982/83 at Taddanpally, Sultanpur, Farhatabad, and Begumgunj; and two in 1983/84 at Farhatabad and Begumgunj. Table 2 shows the performance of the improved technology in comparison with existing farmer technology. The marginal rate of return was used as a suitable criterion to evaluate profitability and viability of the improved technology; it shows the additional returns resulting from the additional operational costs.

The improved technology performed best in Taddanpally and Sultanpur, in Andhra Pradesh. An additional investment in operating cost of about Rs 600 ha^{-1} generated incremental returns between Rs 1400 and 2200 ha^{-1} during 1981/82 and 1982/83. In Farhatabad, differences between the operational costs of traditional and improved technologies were too small to allow computation of meaningful marginal rates of return; but results for both years (1982/83 and 1983/84) show that gross profits under the improved technology were about 1 1/2-2 times the profits under the traditional system.

Profitability of the improved technology was lower in 1982/83 and 1983/84 in the Begumgunj watersheds in Madhya Pradesh than in the other regions. This was partly because of adverse climatic conditions at Begumgunj. In 1982, an early-season drought in late June and early July was followed by uninterrupted rain in mid-to-late July and August; this led to poor stand establishment and ineffective weed control. But overall profitability was also low because some farmers had chosen less profitable cropping systems. Some important results emerged

Table 2. Economic performance of Vertisol technology at ICRISAT collaborative on-farm test sites, 1981/82 to 1983/84.

	Improved technology		Traditional technology		
Test site and year	Operational costs (Rs ha^{-1})	Gross profits (Rs ha^{-1})	Operational costs (Rs ha^{-1})	Gross profits (Rs ha^{-1})	Marginal rate of return (%)
Taddanpally, Andhra Pradesh					
1981/82	1181	3055	595	1625	234
1982/83	1035	3957	448	1722	381
CV of gross profits (%)		42		50	
Sultanpur, Andhra Pradesh					
1982/83	1062	3576	448	1722	302
CV of gross profits (%)		37		50	
Farhatabad, Karnataka					
1982/83	1194	3323	1142	2186	-[1]
1983/84	1226	4494	1188	2207	-[1]
CV of gross profits (%)		23		31	
Begumgunj, Madhya Pradesh					
1982/83	2348	1172	866	786	26
1983/84	2321	2743	1250	1611	106
CV of gross profits (%)		76		89	

Source: Walker, Ryan et al. (1984) for results of 1981/82 and 1982/83 and Ghodake (1984) for results of 1983/84.

1. The difference in operational cost are too small to get a meaningful value for marginal rate of return.

from the Madhya Pradesh experience in 1982/83. For instance, a few selected improved cropping systems (not shown in Table 2), particularly the soybean/pigeonpea intercrop, performed well with profits over Rs 3300 ha^{-1}, while traditional cropping systems netted farmer profits of only about Rs 800 ha^{-1}. On the other hand, farmers trying to grow chickpea and/or wheat as second crops without irrigation found it difficult to get the crops established. Crop establishment is a critical factor for success of the postrainy-season crops.

Profits from the use of traditional practices in the watersheds in Andhra Pradesh and Karnataka were about twice as high or even higher than those in Madhya Pradesh in 1982/83. In 1983/84, however, the profits from traditional technology in Begumgunj increased considerably over those for 1982/83 and so did profits of the improved technology. With an additional operating cost of about Rs 1070 ha^{-1} for the improved technology, farmers in 1983/84 got an additional profit of about Rs 1130, or a marginal rate of return of 106%. Thus the improved technology appears to vary in its performance under extreme conditions. However, there may be ways to overcome this problem. For instance, it should be possible to reduce the relatively high operational costs of the improved technology in the wet, deep black soils of Madhya Pradesh and to bring them closer to those for similar agroclimatic and soil areas in Andhra Pradesh and Karnataka. Also, in Madhya Pradesh, the higher rainfall makes water harvesting in small farm ponds feasible, which would enable farmers to irrigate their postrainy-season crop of wheat or chickpea at least once before planting and, thereby, considerably improve plant establishment and stabilize yields (Kanwar 1983).

All sites consistently showed a lower coefficient of variation of gross profits for the improved technology than for the traditional technology. This indicates reduced risk with the improved technology.

Issues in the Transfer of the Technology

Although higher rates of return, better physical yields, attractive gross profitability, and lower risk are important economic indicators for the potential transfer of a technology, other factors also affect technology adoption. Important among these are input supply, quality of inputs, and timeliness of input availability. Examination of these factors can help highlight their influence in technology transfer. Special surveys have been undertaken in the on-farm research sites to investigate mean input use for traditional and improved technologies; these data present a picture of the comparative input requirements of these technologies (Table 3).

Human Labor

Employment of farm laborers was found to increase with the improved technology at all locations; in absolute terms, employment went up by 300–400 person hours ha^{-1}. Thus, improved technology employed about twice as many laborers as did traditional practices. The lowest increase in employment was 85% at Taddanpally/Sultanpur, and the highest was 260% at Begumgunj, while the Farhatabad site registered a 95% increase. (Ryan and Sarin [1981] observed a 250% increase in human labor use with the improved technology over traditional technology at ICRISAT Center). Indirect effects through backward and forward linkages arising from increased demand for inputs and higher levels of output are not reflected in these data.

A higher rate of productive employment through the improved technology would certainly be desirable for achieving overall growth of incomes in economically disadvantaged regions of dryland areas. Poverty and underemployment are positively related (Dantwala 1979), and more employment would therefore benefit the poor. Moreover, the improved technology has the potential to provide more stable employment than the traditional technology, as indicated by the lower coefficients of variation in labor use in Taddanpally and Begumgunj. Such increased stability of employment would help reduce the seasonal underemployment prevalent in dryland areas. Ryan and Ghodake (1984), for instance, found unemployment rates to be 39–50% during the slack season in dryland areas.

Even though the higher labor requirements of a new agricultural technology must be regarded as a positive attribute in a surplus labor economy such as India, the technology may face temporary labor bottlenecks, which may restrict its adoption. Our analysis of labor demand showed several periods during the cropping seasons when labor availability in dryland areas was not sufficient to meet the demand created by this labor-intensive, improved technology (Ghodake 1983). In order to better understand the effect of labor constraints on adoption of the

Table 3. Mean levels of important inputs for improved Vertisol technology and traditional technology at on-farm research sites.

Site and year	Input	Traditional technology	Improved technology[1]	Percent change[1]
Taddanpally/ Sultanpur 1981/82 and 1982/83	Human labor (person h ha^{-1})	345	638	85
	CV of employment (%)	170	110	-35
	Bullock labor (pair h ha^{-1})	95	72	-25
			(96)	(1)
	Short-term cash (Rs ha^{-1})	497	1098	121
	Seed (Rs ha^{-1})	33	130	294
	Fertilizer/manure (Rs ha^{-1})	117	479	309
	Plant protection (Rs ha^{-1})	-	53	-[2]
	Weed control (Rs ha^{-1})	70	84	20
Farhatabad 1982/83 and 1983/84	Human labor (person h ha^{-1})	427	832	95
	CV of employment (%)	142	217	53
	Bullock labor (pair h ha^{-1})	56	36	-36
			(69)	(123)
	Short-term cash (Rs ha^{-1})	1165	1210	4
	Seed (Rs ha^{-1})	124	90	-27
	Fertilizer/manure (Rs ha^{-1})	237	267	13
	Plant protection (Rs ha^{-1})	206	200	-3
	Weed control (Rs ha^{-1})	106	109	3
Begumgunj 1982/83 and 1983/84	Human labor (person h ha^{-1})	157	565	260
	CV of employment (%)	187	126	-33
	Bullock labor (pair h ha^{-1})	85	31	-64
			(108)	(127)
	Short-term cash (Rs ha^{-1})	1044	2369	127
	Seed (Rs ha^{-1})	306	534	74
	Fertilizer/manure (Rs ha^{-1})	24	687	2762
	Plant protection (Rs ha^{-1})	-	58	-[2]
	Weed control (Rs ha^{-1})	-	65	-[2]

1. Values in parentheses are bullock labor figures for the first year of watershed development. Therefore, include bullock labor utilization for initial land development.
2. Because the values are negligible under the traditional technology, no meaningful percentage change can be obtained.

improved technology, whole-farm models were developed for representative farms at Taddanpally. Using the quadratic programming technique, two farm types were modeled: one with only rainfed land and another with an average amount of irrigated land (16% of farmers' land). The model produces optimal solutions for resource allocation, taking into consideration the farmer's objective of maximizing expected income within limiting constraints (Ghodake 1985).

The results demonstrate the relative importance of labor availability under different technologies through shadow wages during different constraining periods (Table 4). Shadow prices or wages are obtained by programming models for scarce resources, and they measure the marginal productivity of each resource. The degree to which the marginal product of an input exceeds its price is an indicator of its scarcity. Aggregate shadow wages, as well as number of constraining periods, were considerably higher for the improved technology than for the traditional technology in both farm types—rainfed and partly irrigated. Marginal productivity of labor, as reflected by shadow wage, was also higher for the improved technology when it had to compete with irrigation. Interestingly, the model predicted that available irrigation water should always be used for paddy irrigation; but, alternatively, the irrigation of

Table 4. Shadow price of labor[1] under improved and traditional technologies (results from whole-farm modeling, Taddanpally, 1981/82).

Item	Only rainfed land		With access to average level of irrigation (16%)	
	With improved technology	Only traditional technology	With improved technology	Only traditional technology
Aggregate shallow wage	38.6	14.9	109.0	23.7
No. of constraining fortnights	9	4	13	10
Shadow wage	4.3	3.7	8.4	2.4

Source: Ghodake and Kshirsagar (1983)

1. In Rs (person h)$^{-1}$. Actual wage rate prevailing in 1981/82 in Taddanpally was Rs 0.42 (person h)$^{-1}$. Shadow price (on wage) is calculated for each scarce resource by measuring the marginal productivity of each. The degree to which the marginal product of an input exceeds its price is an indicator of its scarcity.

dryland crops was never predicted. Under irrigated conditions, shadow wages were much higher than average wages.

The whole-farm analysis at Taddanpally indicates that traditional technology required more human labor (especially female) during the second week in July, primarily for preparatory tillage, weeding in mung bean, and transplanting of paddy. Other constraining periods were the 2nd and 3rd weeks of September, when land preparation for postrainy crops, weeding of chilies, and intercultivation and weeding in paddy took place. This period was followed by another longer period, beginning the 2nd week of October until the middle of November, when farmers needed labor for harvesting and threshing of paddy, sowing of postrainy-season crops, weeding, and intercultivation in already emerged postrainy-season crops.

The improved technology thus tends to cause peak labor demand periods to widen; these peak periods of labor demand exist under the traditional technology, but with the introduction of the improved technology they begin earlier and last longer. The first constraining period starts in the 1st week of June and continues up to the end of July when important operations with the improved technology are sowing and gap filling, land preparation, weeding and fertilizer application, spraying, and thinning. Transplanting of paddy in irrigated land is another important activity. This period is followed by a peak period from the 2nd week of September to mid-November, during which labor demand is high for both traditional and improved technology. For the improved technology, during this period farmers have to complete operations such as land preparation for postrainy-season crops, harvesting and threshing of rainy-season crops (high-yielding varieties of sorghum, mung bean, and maize), and sowing of postrainy-season crops (sorghum, safflower, and chickpea). The labor demand is further aggravated by harvesting and threshing of paddy rice. This peak period extends through the end of December, owing to the need for intercultivation operations in postrainy-season crops.

Access to Irrigation

The model predicts that the improved technology would be adopted on 84% of cropped land of the purely rainfed farms but only on 64% of farms with access to irrigation (Table 5). The technology in our model produces attractive increases in gross income—143% for the rainfed and 77% for the irrigated farms. Irrigation obviously provides higher labor employment than the rainfed situation—about 94% higher with the traditional technology and about 40% higher when the improved technology is introduced. Introduction of the improved technology increases labor employment in both situations, but both absolute and relative increases are much higher under the purely rainfed situation than under the irrigated situation. This indicates a higher potential for generation of employment by the improved technology under the purely rainfed situation than under irrigation.

Table 5. Irrigation and performance of Vertisol technology on an average farm of 3.34 ha (evaluation results from whole-farm modeling, Taddanpally, 1981/1982).

Item	Only rainfed land			With access to average level of irrigation (16%)		
	With improved technology	Only traditional technology	Percentage change	With improved technology	Only traditional technology	Percentage change
Land under improved technology (%)[1]	84	-	-	64	-	
Land-use intensity (%)[2]	76	56	36	76	63	21
Gross income (Rs)[3]	14 360	5 900	143	14 460	8 160	80
Male labor (h)	1 294	733	77	1 657	1 383	20
Female labor (h)	1 303	902	44	1 992	1 786	12
Total persons (h)	2 597	1 635	59	3 649	3 169	15
Returns to labor[4]	8 250	2 320	256	7 170	2 670	168

Source: Ghodake and **Kshirsagar** (1983)

1. Land allocation is computed by using operated land as the base.
2. Land-use intensity has been obtained by adding monthly cropping intensities over 12 months and dividing the total by aggregate of land available for cultivation over 12 months.
3. Indian Rs 13 = US $ 1.00.
4. Returns to labor are gross income minus all costs (fixed and variable) other than labor cost.

From those results, we infer that the Vertisol technology exhibits its full economic and social impact under solely rainfed agriculture. To some extent, availability of irrigation may impede the adoption of this technology because of competition for major resources between irrigated agriculture and the rainfed technology. On the other hand, in certain situations, such as at Begumgunj in Madhya Pradesh where rainy-season cropping may reduce the soil moisture for postrainy-season crops, water availability could enhance adoption of this technology if supplementary irrigation could be applied to establish a postrainy-season crop. Farm models to quantify the profitability of this particular type of supplementary irrigation in the Begumganj region have been developed by Pandey (1985). Experimental research is now under way to verify the potential.

Bullock Labor

Bullock labor requirements for crop cultivation only—i.e., disregarding requirements for initial land development—are about 20–60% less for the improved technology than for the traditional technology, or 20–50 pair hours less ha^{-1} (see Table 3). This is partly because the wheeled tool carrier is used as a component of the improved technology, and this increases bullock labor efficiency by a factor of about 2.15 over the traditional implements (Bansal and Srivastava 1981); in addition, watershed farmers at the Begumgunj site use tractors. Also, the seasonal pattern of bullock power utilization is substantially altered when intercropping and double-cropping systems are adopted. Seventy to 80% of the bullock labor use occurs between February and May with the improved technology, whereas 85% of it occurs after June with the traditional systems (Ryan and Sarin 1981). It is likely that the availability of draft power, and also of fodder for animals, may impose a more serious constraint for the improved systems, particularly during the hot season (from March to May). A major fodder problem is expected to arise in the initial year of adoption when watersheds are being developed, using bullock power, before additional fodder is produced by the system.

Cash and Credit Requirements

Cash on hand to meet variable crop expenses is another very important factor limiting the extent of transfer of the technology, particularly in a credit-starved economy such as the dryland regions in India. Our surveys at the Taddanpally and Begumgunj sites showed that short-term cash requirements for the improved technology were more than double those for the traditional technology. The additional requirement was Rs 600–1300 ha^{-1} (see Table 3). Only at Farhatabad were cash requirements of the improved technologies similar to traditional systems; this was because there were no major changes in cropping systems and cropping intensity. Additional cash requirements are likely to impose serious constraints to adoption of the technology if they are not met by adequate credit supply (ICRISAT 1982, 1984a).

To cover the full cash expenses through short-term crop loans in the Taddanpally/Sultanpur area, the crop loan should be around Rs 1000 ha^{-1} a^{-1}, with a range from Rs 400 for postrainy-season sorghum to Rs 1550 for a maize-chickpea sequence in the rainy season. In the Farhatabad area of Karnataka, the loan amount of an average should be Rs 1050 ha^{-1} a^{-1}, with a range from Rs 600 for postrainy-season sorghum to Rs 1450 for a groundnut/pigeonpea intercrop. These credit requirements would be much higher in the Begumgunj area. Here an average amount of Rs 2050 ha^{-1} a^{-1} is required; the lowest figure would be Rs 1200 for a sorghum-/pigeonpea intercrop, while the highest would be Rs 3000 for soybean-wheat and soybean-chickpea sequential systems. These figures, however, are highly sensitive to changes in input prices and, therefore, any scale of finance has to be sufficiently flexible so that it can be adapted to the local conditions of the farmer. We estimate that Rs 1000 ha^{-1} for a cropping year should be the minimum scale of finance for this technology, while the maximum scale depends on the cropping system and the area (ICRISAT 1984b).

In order to get further insight into the implications and role of credit in transfer of the technology at the farm level, we again employed the whole-farm modeling approach. This analysis was performed on experimental results of the 1981/82 trial at Taddanpally (Ghodake 1983).

Results at various levels of credit are presented in Table 6. The results show that with the traditional technology, credit up to Rs 300 ha^{-1} on small farms results in infeasible solutions, which means credit is insufficient to meet current expenses of the farm. Obviously, the repayment capacity is zero. With the improved technology, even a credit of Rs 150 ha^{-1} is sufficient to keep the farmer viable; the improved technology increases the feasibility of credit use to such an extent that the farmer is enabled to repay 20% of his loan. However, still higher amounts of credit are needed to reap the full potential benefit of this technology.

With the improved technology, credit needed from institutional sources is Rs 1200 ha^{-1} on small farms, Rs 940 ha^{-1} on medium farms, and Rs 980 ha^{-1} on large farms. This potential demand for credit is considerably higher than the present levels of credit available, which for India is, on the average, Rs 325 ha^{-1} (Bhende 1983). Even the figure of Rs 700 ha^{-1} adopted by the Andhra Pradesh Department of Agriculture for financing Taddanpally watershed farmers is less than the optimum credit needed. The variation in credit needs across farm sizes is rational in that a part of the credit is used for consumption purposes on small farms, while some part is used in supporting complementary activities, such as livestock. The whole-farm models account for such requirements.

Other Inputs

Other constraints were found to be imposed by rural infrastructural facilities in dryland areas for supplying important inputs such as improved cultivars, fertilizers, and plant protection. The levels of these inputs required for the improved technology, compared to traditional technology, indicate the need for additional facilities. For instance, investment in seeds of improved cultivars at the Taddanpally and Begumgunj sites indicates that the demand for better infrastructural facilities in terms of both quantity and quality of seed will substantially increase (see Table 3).

There will be a severalfold increase (3 and 30 times at Taddanpally and Begumgunj) in fertilizer consumption with the improved technology over the traditional technology; this implies the need for considerable improvement of infrastructure to ensure supply of the additional fertilizer.

Using traditional technology, farmers spend an almost negligible amount on plant protection, but with the improved technology there will be a substantial increase. At Begumgunj, for instance, farmers do not experience any significant weed problem under the traditional technology. But with the improved technology, weeds become increas-

Table 6. Potential demand for and repayment of institutional credit with improved and traditional technologies (Taddanpally 1981/82)[1].

	Improved technology						Traditional technology			
Farm size	Max. credit level allowed by the program (Rs ha^{-1})	Improved technology adoption (%)	Credit utilized[2] (Rs farm^{-1})	Shadow price of credit (Rs)	Marginal rate of net revenue increase (%)	Repayment potential[3] (%)	Credit utilized (Rs ha^{-1})	Shadow price of credit (Rs)	Marginal rate of net revenue increase (%)	Repayment potential[3] (%)
Small	0	**	**	**	**	-	**	**	**	-
	150	30	200	3.42	-	20	**	**	**	0
	300	59	500	2.53	1.93	100	**	**	**	0
	700	90	1100	0.97	2.41	100	1100	0.23	-	20
	No limit	91	1840 (1200)	0	0.27	100	1360 (890)	0	0.12	33
Medium	0	17	0	4.26	-	-	0	4.69	-	-
	150	33	500	3.82	3.75	100	500	0.87	1.71	100
	300	54	1000	2.55	3.54	100	1000	0.26	0.46	100
	700	75	2300	0.65	1.78	100	1780	0	0.21	100
	No limit	77	3130 (940)	0	0.21	100	1780 (530)	0	0.21	100
Large	0	16	0	4.14	-	-	0	2.97	-	-
	150	38	1000	3.59	3.70	100	1000	1.17	1.73	100
	300	55	2100	2.83	3.00	100	2100	0.64	0.93	100
	700	81	4800	0.71	2.00	100	3940	0	0.35	100
	No limit	80	6760 (980)	0	0.34	100	3940 (570)	0	0.35	100

Source: Ghodake (1983).

1. Asterisks indicate infeasible programming solution and hence infeasible farm business. Figures in parentheses are credit levels (Rs ha^{-1}) as actually available from formal sources.
2. Institutional credit to be taken by the farm as indicated by optimal programming solution.
3. Computed by subtracting variable expenses and minimum consumption expenses from total income.

ingly more difficult to control because of the buildup in the rainy-season crop. Weed management may not only be impeded by shortage of labor but may also require significantly more time and higher skills on the part of the farmer.

Other Considerations

The purchase of a wheeled tool carrier costing Rs 8000–10000 is beyond the reach of individual small farmers, whose average income per family may be around Rs 3400–5000 a $^{-1}$ (Kshirsagar et al. 1984). An alternative may be implements owned by a contractor or cooperative, hired out to farmers on a daily basis, but this option poses other problems of timely access. Moreover, farmers do not seem to believe that a wheeled tool carrier is indispensable to the package. This thinking is also reflected in the farmers' offer of not more than Rs 13 per day for custom hiring of the machine and their willingness to invest no more than Rs 3300, on average, for purchase of the tool carrier. Moreover, there are some technical problems for farmers to manage this machine in rural areas where sufficient support facilities for welding, repair of tires, and maintenance are not always assured (Ghodake and Mayande 1984).

The experience of managing this technology has underscored the importance of management and skills to which the technology is highly responsive and has, therefore, emphasized the necessity of extension and other development agencies in improving farmers' entrepreneurial and managerial capabilities. This points to the need for practical training for farmers, surveyors, blacksmiths, extension workers, and bankers (Ryan and von Oppen 1983).

In view of the much higher output of coarse cereals and pulses that can be realized through use of this technology, a better output marketing system is needed to ensure stable prices. Most of the additional output may find its way into the market as soon as it is harvested; therefore, the marketing and trading sector should be well-equipped with storage, transport, and other marketing facilities.

Watershed development requires grid surveying, land leveling/shaping, and main and field drain construction. These developments have different benefits to farmers as individuals and to watershed participants as a group. As it is difficult to apportion costs to the individual beneficiaries, either a full subsidy or group financing through a new line of medium- to long-term credit would be required.

The watershed approach also implies some complications that arise for individuals out of loans overdue and lack of land titles for individual farms or plots of land. Technically, it is desirable—and in many cases it is essential—that all farmers participate in the development of the watershed in the 1st year, when the main and field drains are constructed. State Departments of Agriculture may have to consider providing credit to watershed farmers who are defaulters, or to those who do not have clear titles to land and are, therefore, not serviced by banks. Lending procedures may have to be designed to improve loan recovery among farmers who are high credit risks (ICRISAT 1984a).

Implications for Research

On-farm trials with the improved Vertisol technology have helped identify a number of technical and other constraints. Some of these can possibly be removed with the help of technical improvements and through alternative components to overcome a particular drawback; other constraints require intervention from outside through a public authority. These cases will be discussed below, including the question of further research required on alternative components, as well as the type and level of intervention required. ICRISAT can contribute only partly to this research, and national research organizations will have to be involved to a large extent.

The implications of the experience with the Vertisol technology need to be considered in planning and coordinating research activities, integrating work on station and in farmers' fields. These are discussed hereunder, after consideration of research on alternative components.

Research on Alternative Components

1. An important area of research is the development of less costly versions of the wheeled tool carrier. This may best be done within the national system, by testing alternative versions for attributes such as low cost, technical simplicity, and work efficiency.
2. Weed control imposes several problems, requiring research on alternative methods (including hand weeding, mechanical methods, and chemical control) in different cropping systems.

Research on mechanical methods might best be conducted where the work on alternative wheeled tool carriers is also being carried out. ICRISAT's comparative advantage as an interdisciplinary research institute would probably imply work on cropping systems and herbicides.

3. In areas of 1000-mm rainfall and above, water for supplementary irrigation to establish the second season crop can come from runoff water harvested in small ponds. Preliminary research, based on model calculations, has shown high payoffs from water harvesting in Vertisol regions with high rainfall. Experiments in farmers' fields will be required to verify these model results and to gain experience in organization and planning of water harvesting in farmers' fields. Such experimentation would have to be done in collaboration with the respective state departments of agriculture and regional universities.
4. The costs for land development in the Begumgunj watersheds of over Rs 1000 ha^{-1} are high when compared to less than Rs 200 elsewhere (Virmani et al. 1989); this is partly explained by the more difficult topography and higher rainfall in Begumganj. However, there is need for a better understanding of how to execute land development at minimum cost; research work at national institutions can probably establish suitable principles and guidelines for optimum land development practices. Related to this is the need to train personnel to assist in land development.
5. Dry seeding is not a constraint in economic terms, but farmers resent dry seeding. They are averse to the risk of losing their seed, and they obviously assess this risk higher than agroclimatologists would expect, based on probability analysis (Virmani et al. 1981). Further research is needed on dry seeding and its alternatives (Walker, Singh et al. 1983).
6. Credit is a severe constraint to adoption, and more information is required about the minimum and maximum amounts of credit required at regional levels. National Universities could carry out such research; modeling approaches as developed by ICRISAT can be of help in such research.
7. Supply systems are notoriously weak in areas of dryland agriculture. Research is required on the costs and returns from making inputs more readily available to dryland farmers. Experiments could be conducted on effects of timely availability of fertilizers, pesticides, and seeds; the costs of such a supply system should be measured, as should the social and economic returns of higher input use (through farmers' responses). Such research could be carried out initially by ICRISAT in our study villages, but it might require collaboration of other institutions and possibly of the respective input industries.
8. The impact of improved technology on the output marketing system and consumer prices should be studied, to anticipate any adverse price effects and to improve marketing facilities.
9. In any watershed, not all farmers are willing or able to collaborate; reasons may range from lack of confidence to credit constraints or land title complications. Government policies should be designed to cope with such problems, and research in the field of policy and public administration is called for.
10. Apart from financial benefits of the improved Vertisol technology, which accrue directly to the farmers, the technology does have social benefits, through reducing the loss of topsoil, for instance, and through deep infiltration of water and recharge of groundwater. Measurement and quantification of the social benefits from soil and water conservation would be important, as this could help justify an amount of subsidy for enhancing the introduction of the new technology. Again, research by national institutions, in collaboration with ICRISAT, is called for.

Integration between On-Station and On-farm Research

ICRISAT's improved Vertisol technology was developed from component research stage to package-and-system design stage within the research station at ICRISAT Center, Patancheru, and then introduced into farmers' fields. Consequently a number of constraints were understood only at the stage when farmers were confronted with the technology, i.e., after about 13 years. With hindsight one could ask if other approaches might have given the same (or better) results faster.

An alternative research plan would integrate station research with experiments in farmers' fields at the component stage itself. The advantage of this plan would be the recognition of farmers' constraints before the design of packages and systems; morevoer, the time required to produce packages and systems is likely to be about 3 years shorter than the first approach. On the other hand, the efforts required to conduct on-farm trials with effective retrieval of data for scientific analysis are considerably greater, and even if these efforts were spent, the data might still be inferior in precision to those of the first approach, but possibly more relevant.

Another alternative (followed by IRRI) involves researcher-managed trials in farmers' fields of small technology packages. Such packages—if found acceptable—can later be fitted into a system and tried directly in farmer-managed trials. This alternative also would be faster, and it would generate field-level feedback into the technology design process, without undue cost for experimentation and data retrieval.

Any of these approaches, involving on-farm experimentation at an early stage rather than transferring entire systems to farmers' fields, requires that researchers adhere rigorously to principles of scientific testing and data analysis. For instance, a set of well-described representative locations would be required for on-farm research, as would a sufficient number of tests for making statistically qualified inferences. If the principles are spelled out clearly and the guidelines are followed, such strategies should result in a speedy process of technology design and, probably, substantial results in the long run.

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Discussion

Stewart: I do not have a clear picture of the supply-demand relationships. Is there a chance of the new technology being adopted so fast as to drive down the price and make the farmer not capable of paying for the equipment?

von Oppen: We do not think so because it will take 20 years to extend the technology to 5 million ha at a growth rate of 42% per year, or doubling the area every 2 years. There is a danger, of course, of local fluctuations, and the government must be able to offer some protection against this happening. This has been done, for example, for soybeans in Madhya Pradesh where they are being adopted rapidly. There, soybeans are an important component of the deep Vertisol technology.

Rasheed: Actually the point raised by Dr. Stewart is correct concerning Egypt. In upper Egypt, we are recommending UC 87 tomato to be grown by farmers, which did increase the production tremendously, and prices went down. Therefore, farmers now are refusing to grow this tomato recommended to them.

von Oppen: I agree that a perishable crop such as tomatoes may face a limited market and rapidly falling prices, if production exceeds demand only by a small amount. Marketing facilities, such as canning and preserving, would help to stabilize the price.

Cooper: Six new components are a large number to introduce into a simple farming system, as you have indicated that the 'complete package' has identified various costs and labor constraints. Have you tested the impact of individual components of this package in farmers' fields to identify acceptability, rates of return, or constraints? Some individual components may be much more readily accepted than the complete package.

von Oppen: We have not tested the impact of individual components of the package in farmers' fields. Had we done so early on, we might have been a little more knowledgeable to do what you suggest, i.e., to be able to put more weight on the more acceptable of these components as definite parts of the package and have the remaining ones, which are more difficult to accept, as optional additions to the package.

Sagua: (1) The time taken (10 years) before transfer of the improved technology to the farmer's field is too long. An intermediate stage—i.e., state-owned farms—can be used to demonstrate and prove new technology and to go from there to farmers' fields. This takes away the risk of failure for the farmer. (2) ICRISAT must expect higher yields and, therefore, a need for improved processing, storage, and marketing to take up the increased harvests arising from application of the new technologies. What is ICRISAT doing about these? Are you also organizing the farmers into cooperatives to improve their creditworthiness and purchasing power, which are constraints to obtaining inputs?

von Oppen: (1) Perhaps the trials on state farms are an alternative, but also farmers can be guaranteed freedom from risks if the researcher pays all costs. (2) ICRISAT envisages that increased yields will arise from application of its improved technology, but does not consider processing, storage, etc., as their priority at the moment. Maybe the national or state research programs can do these better.

Jutzi: What are the reasons for the relative failure of water harvesting and reuse of water at ICRISAT?

von Oppen: Unreliability for tank-filling in black soils with rainfall below about 1000 mm a^{-1}. The cost:output ratio is positive only in high-rainfall areas, such as central Madhya Pradesh.

Valverde: Your presentation clearly pointed out the socioeconomic constraints encountered within India to adoption of the ICRISAT technology. I believe that any kind of technological innovation within any country will require a complex process before it is adopted. The socioeconomic conditions will vary from country to country. What is important is that a firm commitment by and the political will of the country have to exist, as well as the minimum institutional and capital mass, to implement such technological innovation. You have mentioned a large list of needed research before the technology could be adopted—some to be done by ICRISAT and some by the national institutes according to their comparative advantage. In this respect I agree with you completely, but perhaps what is important for this workshop is to examine how and what role IBSRAM should play within the countries that want to introduce the technology innovation.

Research Networks: Some IDRC Experiences

A.D.R. Ker[1]

Abstract

This paper describes the involvement of the International Development Research Centre (IDRC) with research networks in developing countries[2]. IDRC policy has emphasized assistance to developing-country scientists and institutions to conduct research on their own problems. Over 100 research networks have been supported as part of this assistance.

Although networks take many forms in response to the needs of participating scientists, key organizational components for any one network include:

1. *Common objectives, agreed to by all network participants.*
2. *Willingness of all participants to adjust research programs and to invest resources in network activities.*
3. *An appropriate level of coordination by a coordinator possessing unusual qualities.*
4. *A level of interaction among participants appropriate to the complexity of the research being undertaken and the needs of the participants.*
5. *Linkage mechanisms, which may include workshops, advisory committees, consultants, training programs, and publications.*

Résumé

Réseaux de recherche—quelques expériences du CRDI : *Cet article décrit l'engagement du Centre de recherches de développement international (CRDI) dans les réseaux de recherche des pays en voie de développement. Le CRDI a mis l'accent sur l'aide aux scientifiques et institutions de pays en développement afin d'entreprendre des recherches sur leurs propres problèmes. Plus de 100 réseaux de recherche ont été appuyés comme partie intégrante de cette aide.*

Quoique les réseaux prennent plusieurs formes en réponse aux besoins des scientifiques qui y participent, les éléments clefs de chaque réseau comportent :

1. *Des objectifs communs, acceptés par tous les participants au réseau.*
2. *Volonté de tous les participants d'orienter les programmes de recherche et d'investir les ressources dans les activités du réseau.*
3. *Un niveau approprié de coordination par un coordinateur qui possède des qualités exceptionnelles.*
4. *Un niveau d'interaction parmi les participants, adapté à la complexité de la recherche entreprise et aux besoins des participants.*
5. *Des mécanismes des liens qui peuvent inclure des colloques, des comités de conseil, des experts, des programmes de formation et des publications.*

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[2] The views expressed or implied within this paper are those of the author and not necessarily those held by the International Development Research Centre.

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Introduction

Substantial advances have been made in recent years in agricultural production in many countries. For example, during the 20 years from 1950 to 1970, the world output of grain nearly doubled. In the developing countries, this increase was due almost equally to an increase in the area planted and to yield improvement (Wortman and Cummings 1978). Although it is difficult to quantify the relative contributions of different factors to these increases, it is generally accepted that scientific research has made substantial contributions to yield improvement in many crops. For example, the large increases in wheat and rice yields in the developing countries in the 1960s were largely due to the high-yielding varieties bred at the International Maize and Wheat Improvement Center (CIMMYT) in Mexico and the International Rice Research Institute (IRRI) in the Philippines, combined with improved management practices, including irrigation, fertilizer application, and others.

Although these high-yielding varieties were bred by scientists in the International Agricultural Research Centers (IARCs), the essential adaptation and selection for local conditions was performed by scientists working in national agricultural research centers. It is these national agricultural research systems that appear to hold the key to a major part of the further improvement of agriculture in the developing countries. They and only they, together with the national extension services, are in the position to maintain sufficiently close contact with the enormous numbers of small farmers and livestock producers who are the only people who can increase agricultural production in those countries. Although international organizations, such as the IARCs, can provide valuable support and backup for these national research systems, there is no way in which they can be a substitute for their activities, except perhaps on a very limited scale.

Scientists in national agricultural research organizations have many difficulties to contend with; these commonly include limited resources in terms of equipment, staffing levels, operating funds, and information availability. There is also the problem of relative isolation—being located far from other scientists working on similar problems.

Scientists worldwide have generally found it essential to discuss their problems and compare notes with other scientists working on similar problems. This is often done on an informal basis at scientific meetings, or by informal contacts, but one of the reasons for the enormous acceleration in the rate of scientific progress in recent years appears to have been the formation of more formal types of networks of cooperating scientists.

In the developing countries, these formal networks appear to be even more important than in the developed countries, because of the limited opportunities for many developing-country scientists to interact with their colleagues, to obtain access to the latest scientific information, and to update their own skills. Also, although in the larger countries internal networks may supply most of the scientists' needs, in the smaller countries only one or two scientists may be working on a particular problem or in a certain discipline, so that interaction with other scientists working on similar problems has to be international. These appear to be some of the reasons for the considerable growth in international agricultural research networks among developing-country scientists in recent years. Following are some examples of such networks and their impact.

International Nurseries

IDRC prefers the definition of G. Banta (unpublished paper, IDRC 1982) that a network is "A voluntary association of research organizations with sufficient common objectives to be willing to adjust current research programs and invest resources in network activities in the belief that they will meet their objectives more efficiently than conducting all research alone."

Although networks can take many forms, depending on the needs of the scientists involved, a number of the larger international nurseries in the developing world have been organized by the IARCs. For example, both CIMMYT and IRRI organized testing of their improved wheat and rice varieties in over 75 countries. Such international nursery programs allow scientists in these countries to compare improved varieties from the IARCs and from other countries with their own varieties, and to contribute their own best varieties to the testing programs. They form an important part of the exchange of germplasm and information, which is an essential component of modern crop-breeding programs. Many similar networks have been established by the other IARCs, and sometimes by national scientists themselves.

Plucknett and Smith (1984) have indicated the problems that can arise with networks of this type. For instance, national programs sometimes find they are expected to test enormous numbers of varieties, many of which do not contribute much to their own programs, so that they end up primarily serving the interests of the international centers. They point out that these kinds of networks can be counterproductive, and national scientists may complain about and even withdraw from them.

Although these germplasm testing programs are obviously important and should be organized so that all participants benefit mutually, the better types of networks appear to be those in which scientists from national programs fulfill important roles in establishing, organizing, and guiding the network. For example, seven countries in Latin America collaborated in the PRACIPA (Regional Cooperative Program for Potato) network to undertake research on potatoes, led by the International Potato Center (CIP) in Peru. Nine major potato-growing problems in the region were identified, and each country took responsibility for research on a different set of problems. This type of collaborative approach allows a more efficient use of resources than if each national program tries to undertake research on all the problems. The friendly collaboration of all scientists involved at regular workshops allows interchange of ideas, research results, and plans for the future, which has the effect of improving all the research programs.

IDRC-Supported Networks

A few words of explanation on IDRC may be appropriate here. The International Development Research Centre (IDRC) was created by an Act of the Parliament of Canada in 1970, largely as a result of Lester Pearson's leadership of the Commission on International Development, which was the predecessor to the Brandt Commission. The Act established the Centre under the control of a Board of Governors, six of whom come from developing countries, and Lester Pearson was the first Chairman of the Board.

The purposes of the Centre were set out in the Act, as "To initiate, encourage, support, and conduct research into the problems of the developing regions of the world and into the means of applying and adapting scientific, technical, and other knowledge to the economic and social advancement of those regions." (Revised Statutes of Canada 1970).

Since IDRC is a comparatively small funding agency, it is not able to support large, comprehensive research programs such as those funded by the larger donors, including the World Bank and several others. Therefore, the Board's policy has been to concentrate its support for research in certain broad subject areas, which have been identified as high priority for the developing countries, and where the Centre has sufficient expertise in its four program divisions of Agriculture, Food and Nutrition Sciences; Social Sciences; Health Sciences; and Information Sciences. Within its limited resources, it attempts to respond to requests from developing-country institutions for support of research in these areas.

A particular feature of IDRC support—which was unusual among government-supported funding agencies in its early days, but which has since become more widely accepted—is that the great majority of its grants have been provided for developing-country scientists to carry out their own research programs, without large teams of expatriates to manage and perform the research for them. This approach appears to have given encouraging results and has certainly been greatly appreciated by the developing-country scientists involved in the projects. Almost invariably, these projects have strongly emphasized building the capability of national research institutions to conduct their own applied research, focused particularly on solving the pressing problems of the great mass of small farmers and other poor people. This emphasis on institution-building has not been in the sense of providing bricks and mortar, but of supporting applied research and training for scientists and technicians, at all levels, and, where appropriate, training for research administrators.

Mainly at the request of the developing-country scientists themselves, an increasing emphasis has been placed on scientific linkages and information exchanges among scientists in several countries working on similar problems, and in this way research networks have grown. These networks take a great variety of forms, as they basically respond to the needs of the participating scientists themselves; they vary from large networks, with many projects and scientists in a number of countries, to small networks, with only three or four cooperating scientists (IDRC 1980). Some of these networks have proved effective for locating and channelling information and technical support to the participating institutions.

IDRC's Information Sciences Division has assisted in strengthening some of these networks, particularly in the Agriculture, Food and Nutrition Sciences Division, by establishing specialized information centers, which provide bibliographic services, reprints, and, in some cases, specialized monographs and reviews of the scientific literature in the subject areas covered, to all members of the network and other interested scientists.

Up to 1980, IDRC was involved in some 72 networks, which included 288 different projects (IDRC 1980). Since 1980, support has been provided for at least 30 additional networks, making over 100 in all. Although the IDRC mandate, as outlined in the Act, encourages the development of cooperation among scientists involved in networks, IDRC itself did not always deliberately create the networks. In some cases, the networks already existed, and IDRC provided funds to strengthen them. In others, when more than one project was developed in a particular area of research, the network developed naturally. In all cases, IDRC attempted to provide flexible and appropriate support to meet the needs of network participants.

In the early 1970s, IDRC supported a number of networks that provided collaboration between developed- and developing-country scientists. Although some of these networks gave fruitful results, a number of problems emerged. It was found that at workshops and other network activities, the developed-country participants, with their greater experience of these types of networks and backed by vastly greater resources, tended to dominate the discussions. Also some of them failed to understand the context within which developing-country scientists were working, so they seemed to be talking over the heads of their developing-country colleagues.

Therefore, for several years, IDRC concentrated on supporting networks of developing-country scientists only, with input from scientists working in developed countries limited to a few exceptional individuals. A requirement for developed-country participation was long experience in developing-country situations and the ability to relate closely with developing-country colleagues. Recently, IDRC started the Cooperative Program, which encourages cooperation between Canadian institutions and developing-country institutions, and a number of networks are developing. These are discussed below.

The Cassava Network

One of the largest networks supported by the Agriculture Division is that developed in close collaboration with CIAT (International Center for Tropical Agriculture), which has world responsibility among the IARCs for cassava research, and later with IITA (International Institute for Tropical Agriculture). This network at one time contained over 50 projects worldwide (Nestel and Cock 1976).

Most of the projects in this network were developed by the responsible IDRC program officer, but technical coordination and support were provided by CIAT and, in the case of the projects in Africa, by IITA. An advisory committee, which met regularly, assisted in planning. In the early days, the IDRC program officer coordinated the network, but later CIAT employed two coordinators with IDRC funding, one for Latin America and one for Asia. Consultants from both developed and developing countries also assisted in coordination.

A series of workshops on specific cassava research topics have been held, with proceedings published by IDRC or CIAT. CIAT also developed a comprehensive cassava information service, with support from IDRC's Information Sciences Division.

A global network such as this logically divides itself into a number of subnetworks, usually covering more limited geographical areas, such as Latin America, West and East Africa, or Asia. This saves travel costs and enables projects at similar levels of development to be linked more easily. However, most of the regional workshops have had one or two participants from the other regions in order to share experience and information. Also, more specialized workshops on particular technical problems, such as germplasm exchange, are held with selected participants from around the world, in order to get a wide spread of experience and feedback.

The Oilseeds Network

At present, the oilseeds network includes some eight different oilseeds in about 11 projects in eastern and southern Africa and South Asia. We can use it as an example of a network in which only one crop is the responsibility of an IARC; groundnut is the responsibility of ICRISAT, but the other seven oilseeds are not within an IARC mandate. IDRC has found it more difficult to plan and assist this network, due to the absence of an IARC with responsibilities for most of the crops involved.

The oilseeds network has the following features:

1. The network coordinator is particularly important. He is based with the national research program in Ethiopia, where he can interact with the national program scientists, help them when possible, and draw their support for other projects in the network.
2. The coordinator provides photocopies of relevant information and computer printouts of references and abstracts of the various oilseeds to any network scientist who requests them. The coordinator also produces an annual oilseeds newsletter for all participating scientists.
3. The network holds an annual or biennial workshop, with the site rotating among the various national research programs.
4. Now that individual national programs have begun to concentrate their research on specific oilseeds, we expect the network to be able to plan its activities so that particular national programs can confront particular problems as they arise. This will enable them to complement each other and implement a comprehensive research program.

Although it is expected that various problems will arise in the coordination of activities, it appears probable that the national programs may develop more rapidly this way than if they were compelled to depend on an IARC.

If the national programs request a consultant with a special knowledge of a particular crop, every effort is made to arrange a visit. Training programs of varying lengths at appropriate institutions are also built into each of the projects.

The Asian Rice Farming Systems Network

The Asian Rice Farming Systems Network, previously called the Asian Cropping Systems Network (ACSN), is one of the most highly developed networks with which IDRC has been involved. This network was based on research done at IRRI in the early 1970s, when it became apparent that the further spread of the high-yielding rice varieties developed there would depend on a more detailed understanding of the constraints and requirements of farmers working in the various rice-based farming systems in Asia (Banta 1982).

Although farming-systems research was not new when the ACSN began in 1975, the major achievement of the network was to develop and test a research methodology adapted to the needs of the national research programs and the small farmers of Asia (Zandstra et al. 1981). The ACSN is now recognized as one of the developing world's most successful agricultural research networks (CGIAR 1978). Banta (1982) suggests the following reasons for its success:

1. All the scientists involved had worked in standard agricultural research programs, mainly based on research stations, and all were dissatisfied with the effectiveness of their research results in improving the well-being of farmers.
2. IRRI made a definite commitment to support the national research programs wherever possible. IRRI's staff chose to be partners with scientists in the national programs rather than adopt a patron-client relationship.
3. Only those directly involved in the field research in the national programs and at IRRI were invited to take part in the various meetings and workshops. Thus there was a definite reward for those who worked, regardless of their position, and the discussions dealt with real problems and research results.
4. IDRC made a special effort to organize support for the national research programs and for the scientists and technicians doing the cropping systems research in the field, as well as support for a high level of interaction among the scientists in the network. This funding model has been followed by other agencies who have contributed to cropping systems research in Asia.
5. The real responsibility for organizing and managing the network lies with the Asian Cropping Systems Working Group. This is a small group of scientists from each national research program who are directly involved in cropping systems research and who normally meet twice a year.
6. The reports from the Working Group meetings and other relevant written information, whether it is of publishable quality or not, is rapidly photocopied and circulated to all research sites in the network. This ensures a rapid interchange of information and that all researchers, however isolated, are kept up-to-date.
7. Each year a monitoring tour to two countries is held, to allow young scientists who are actually working on research sites in the national programs to visit other countries and discuss research methods and results with scientists at their own levels.

8. The network coordinator, who is an IRRI scientist with an excellent rapport with the young scientists working in the national programs, visits the national research sites with the national leaders of cropping systems research, reviewing the ongoing work and discussing technical, methodological, and operational problems. This is perhaps one of the most important and valuable features of the network.
9. The Working Group and IRRI have made a particular effort to provide appropriate training for all who become involved in this type of research, including policymakers, administrators, coordinators, and all levels of researchers. All training was done locally in Asia, and there was no training in, and no visits to, developed countries.

Perhaps one should add that although this network has been outstandingly successful in developing an agreed and workable methodology for farming systems research, it has been a relatively expensive undertaking because it involves so much traveling for interpersonal interaction.

Also, although the national research programs have considered it sufficiently valuable to have adopted it in virtually all the Asian countries, the location-specific nature of farming systems research makes it relatively expensive, and a balance needs to be found between replicating research teams in every possible farming system and limiting activities to one or two of the more important systems.

Conclusions

To sum up, networks, like farming systems, must be adapted to the needs of the participants and, therefore, they take many forms. Some networks may be planned to last only for a limited period of time, and may then dissolve once their objectives are accomplished. However, most agricultural research networks can be expected to last for a substantial, if varying, period, and these are the ones discussed here.

For networks to be successful, certain principles appear to be important.

1. Objectives. All participants in the network need to discuss thoroughly and agree fully on common objectives and set priorities for the network.

2. Resource allocations. Researchable problems should be divided among participants in the network according to their research resources and interests.

3. Coordination. Although some form of part-time coordination may be successful in some very small networks, IDRC's experience is that in networks of any size, coordination will require a coordinator working somewhere near full-time. (It may be beneficial to him to maintain a small research program, so he does not lose touch with research.)

Good coordinators have unusual combinations of gifts, including excellent scientific capability and the ability to form close and friendly relations with colleagues of all ages and levels. They also need good organizing ability and communication skills.

4. Level of interaction. It appears that a network dealing with a new and complicated methodology, such as farming systems research, needs more intense interaction among its members than a network dealing, for example, with a commodity that already has a well-defined research methodology. This is the reason for the high level of interaction built into the Asian Rice Farming Systems Network.

5. Linkage mechanism. In addition to the coordinator, other linkage mechanisms used extensively are workshops, advisory committees, consultants, training programs, and publications. Each of these has a role in supporting linkages in the network, and all were found in the successful networks that IDRC has sponsored (IDRC 1980).

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Discussion

Bentley: Where do the funds to enable network activities such as publications, monitoring tours, coordinator, and so forth come from, and how much do they amount to in total?

Ker: Funds to a network come from many donors, and perhaps some even come from network units. For one network, the initial start-up fund from one donor was $700 000 for the first 3 years.

Group Discussions and Conclusions

After the formal presentations of papers, and a midweek field trip to the ICRISAT Center's Vertisol soil profile and a village using ICRISAT-improved technology for Vertisols, four Working Groups were formed, with the following topics for discussion:

1. Evaluation of the properties, survey, and classification of Vertisols,
2. Management of Vertisols under rainfed conditions,
3. Management of Vertisols under irrigated conditions, and
4. Validation of technologies.

Group discussions were lively, evincing much interest in the formation of networks and priorities for research to improve Vertisol management and increase agricultural production. Each working group presented a verbal and a written report to the entire body, and this was followed by a discussion period, which included reactions to group reports and suggestions for the kind of arrangements and the procedures to be followed in establishing a network. Network formation was clearly the desire of the participants.

Among the items considered in these sessions were:

1. Possibility of a limited number of Network Cooperators;
2. Possibility of four or five mini-networks, based upon climatic groupings;
3. Problems of developing proposals that would be realistic and attractive to donors.

It was agreed that the mini-networks on a climatic basis might be the most appropriate. A tentative proposal for a Mediterranean Region Vertisol Network was submitted. It was recommended that IBSRAM use the "Network Cooperator" for members. A brief consensus statement was read.

After the concluding session of the workshop, many participants remained on-site. They then developed these concepts into an outline for preparation of an IBSRAM-sponsored project proposal by a Network Cooperator.

Working Group No. 1

Research Priorities for Evaluation of the Properties, Survey, and Classification of Vertisols

Chairman: J.A. Comerma (Venezuela)
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Mhiri Ali (Tunisia)
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Kamron Saifuk (Thailand)
D. Tessier (France)

General Purpose: Provide guidelines and recommend lines of research that will produce better and more transferable results in Vertisols.

Objectives:

1. To recommend some guidelines for the selection of representative soils and the characterization of sites for experimental purposes within Vertisols.
2. To recommend research priorities in the area of properties of Vertisols considered important for determining various management systems and/or variations in their components for their extrapolation.

Statement:

Vertisols are among the soils that present a large spatial variability. This is, in principle, a consequence of their genesis, which produces a mixing of their horizons, and sometimes, as in the case of gilgai, marked differences within short distances. If the variability of physical soil properties over time is added, Vertisols are seen to be quite variable. Changes engendered by variations in moisture content clearly affect the properties of structure, consistence, voids, water and oxygen availability, and so on. To date, approaches and methods of characterization of Vertisols have not paid enough attention to these variabilities, and, consequently, Vertisol classification is deficient.

In accordance with these points, besides the conventional characteristics and qualities described in land surveys, there is a need to:

1. Emphasize a more detailed description of such features as structure;
2. Add and/or develop new parameters for field and laboratory analyses.

In all cases, it is considered that the dynamic study of certain physical properties in Vertisols, through periodic measurements, is essential for a better understanding and successful management of all kinds of Vertisols.

Research Needs:

1. Guidelines for the selection of representative soils and of convenient sites for experimental purposes.

As a first step, it will be necessary to have information on soils, climate, topography, cropping systems, and previous research results of the area under question. In case there is no previous adequate information on the area, at least a reconnaissance soil map at 1:250 000 should be made. Landsat imagery is suggested for assisting in the preparation of a base map. A description of natural vegetation and its distribution in the area can help to indicate climatic and moisture regimes.

With this information and after its analysis, we should aim to:

a. Know the extent of the primary soils;
b. Select the ones with higher productivity potentials and/or with special problems;
c. Together with other researchers, select the site(s) most adequate for the specific objectives of the research under question;
d. In case of diverse intensities of land use in the area, select the sites within the more intensively used region;
e. Assure the legal status of investigation and the political consent of the local officials.

In relation to site selection, there are two alternatives. One is to establish experiments in farmers' fields; the other is to select a site for an experimental project. In the first case, some of the basic items to consider are closeness to an agrometeorological station, accessibility to the site and availability of farm machinery and equipment, a highly motivated and collaborative farmer, and naturally an area with the representative soil previously chosen. In the second case, we should consider accessibility of the area, closeness to a source of labor, availability of water for the station and for potential irrigation, and the existence of large areas of the representative soil plus other representative soils considered on a regional basis.

In the selected site, a more detailed study of the soil(s) under question should be made, probably at the scale of 1:500 or 1:1000 for convenience. The aim is to understand the local variability for a better site selection of research plots.

A representative point in the landscape should be selected to dig a large pit for soil sampling and description. A quick check with a field kit can be made of such properties as pH, salts, and CO_3.

The morphological description should follow standard procedures, with slight variations according to the classification system under use. In the case of Vertisols, special attention should be given to describe structure at various levels of organization (primary, secondary, etc), roots, and pores. In the presence of gilgai and/or wavy horizons, more than one profile is convenient.

Samples by horizons should be analyzed in the laboratory for the standard properties, including:

- Particle size, including additionally fine clay
- Clay-sized $CaCO_3$
- Available water on undisturbed samples
- Moisture content at the time of sampling
- COLE, bulk density of large units
- Liquid limit and plastic index
- Dispersion index
- pH, CEC, exchangeable bases, total N, extractable P
- Organic carbon, electrical conductivity, SAR
- Al in case of pH less than 5.5

2. Research priorities for the measurement and evaluation of properties relevant for different kinds of available management systems.

In order to analyze and evaluate deficiencies in characterization of those properties important for management of Vertisols, we have listed a group of land qualities considered relevant for these soils:

Land qualities	Main deficiencies in their evaluation
Tilth	Evolution of structure over time
Fertility	P availability, pH-Al relationship in acid Vertisols
Water availability	Water limits in relation to roots
Oxygen availability	Air-filled porosity and critical levels
Root penetrability	Pore size and continuity measurements
Potential erosion	Structure and crack descriptions
Length of growing season	Water-balance model
Irrigability	
Drainability	
Trafficability	Effect of machinery on rheological properties
Salinity and sodicity	Critical levels of Na and salts

Research Priorities Suggested

General cases

1. Achieve a better understanding of the evolutionary changes of soil structure and associated voids when moisture changes occur.
2. Be able to predict the evolution of cracks under natural conditions, as well as under different management systems.
3. Develop and/or complete specific water-balance models for Vertisols to predict tillage timing, length of growing season, cropping patterns, irrigation schedules, etc.
4. Calibration of P-extraction methods under rainfed and irrigated systems.

Poorly Drained Vertisols

5. Studies of air-filled porosity levels and changes critical for key crops.
6. Precise field methods of detecting reduced conditions (dyes: dipindyl, benzidem, etc).

Acid Vertisols

7. Establishment of the relation between pH, Al saturation, base saturation, and salts at critical levels for plant stresses.

Sodic Vertisols

8. Establishment of critical levels of Na with and without salts in the water regime.

Recommendations

1. To hold a workshop or training sessions on the generally agreed methodology to physically characterize Vertisols in the field and in the laboratory.
1. To produce a document indicating in detail the minimum and desirable information (including methodologies) that are considered necessary for experiments of validation and transfer of technologies, as well as for research development.

Working Group No. 2

Research Priorities for Vertisols under Rainfed Conditions

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Asnakew Woldeab (Ethiopia)

Food production is generally low in the major Vertisol areas under rainfed conditions. This is true for both high- and low-rainfall areas. Rainfall ranges from as low as 250 mm annually on some cropland in the winter-rainfall areas in the Mediterranean to as much as 3000 mm annually in Caribbean regions. In the very large Vertisol areas of the Sudan, India, and Ethiopia, rainfall is mostly between 500 and 1500 mm. The reasons for low production are many, but the most obvious are surface drainage problems, lack of water in low-rainfall areas, and inadequate plant nutrients.

Goal: Increase food production on Vertisols cropped under rainfed conditions.

While the group does not think it is appropriate to set specific goals, it does recommend that, as projects are developed, scientists and policymakers in individual countries think in terms of specific target goals. This is necessary to realistically plan meaningful experiments. For example, the group feels that in some regions food production can be increased 50 to 100%, with relatively simple and low-cost changes in the traditional systems. To triple or quadruple yields, however, might require major changes in the system, as well as large capital expenditures. Initial efforts should be placed on putting into place the low-input changes that can increase yields and that will also serve as a foundation for additional technological steps. At the same time, some studies should be carried out to determine the maximum production potential by integrating all components of production.

Priorities for Research:

1. Tillage and Land Configuration
    a. Surface drainage
    b. Seedbed
    c. Stand establishment, emphasis on early plant establishment, row spacing, population
    d. Erosion control

2. Water Conservation and Use
    a. Rainfall patterns and probabilities
    b. Water harvesting
        i. Impounding runoff
        ii. Preventing runoff (in low-rainfall areas)
    c. Reducing soil evaporation

3. Nutrient Management
    a. Nitrogen
        i. Legumes for supplying N
        ii. Optimization of N fertilizer by characterizing rainfall probabilities and soil water storage
        iii. Combination use of N fertilizer and legumes
    b. Phosphorus fertilization and placement
    c. Long-term effects on nutrient management
    d. Rotation effects of nutrient management

4. Cropping systems
    Very important, but site-specific and highly dependent on socioeconomic conditions.

5. Combine components into a socially and economically viable technology for specific countries.

Recommendation:

IBSRAM and the international centers should identify specific research locations and document existing data bases, which would serve as a basis for the formation of the Network.

Countries indicating a desire to participate include: the Caribbean countries, Ethiopia, India, and the Sudan. Botswana, Zambia, and Zimbabwe expressed various levels of interest, but perhaps cannot be immediately included.

Additional Comments:

Attached is a list, not meant to be complete, of experiment stations located on Vertisols in possible network countries. The approximate annual rainfall is also listed for the experimental sites.

No consensus was reached, but there was some discussion in support of three mini-networks: (1) semi-arid summer rainfall area; (2) humid area; and (3) Mediterranean winter rainfall area.

Research Stations on Vertisols and Associated Soils

Location	Station	Rainfall (mm)
1. Sudan	i) Gezira	400
	ii) Gendarif	600
2. Ethiopia	i) Holetta, ILCA H.Q. Debre Zeit, Debre Berhan	
3. Caribbean (English-speaking)	Univ. of West Indies, Trinidad	2000-3000
4. Venezuela	Maracay	
5. Zimbabwe	i) Harare	
	ii) Marondera	
6. Botswana	(May have station) Soil Survey Agric. Res. Dept.	
7. India	Bellary	550
	Sholapur	700
	Dharwad	750
	ICRISAT Center	780
	Indore	900
	Nagpur	1000
	Jabalpur	1400
8. Syria	i) Ministry of Agric.	250–450
	ii) South of Damascus	457
9. Tunisia	INRAT Beja	600
10. Morocco	i) Settat	420
	ii) Jemmashian	440
11. Argentina	i) Concepcion del Uruguay	800
12. Zambia	i) Kafue Flats	400
13. Jordan		
14. Algeria		

Working Group No. 3

Research Priorities for Irrigated Use of Vertisols

Chairman: M.A. Rasheed (Egypt)
Rapporteur: Earl Burnett (USA)

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Introduction:

In the arid and humid regions of the world, where surface and/or subsurface waters are available, Vertisols are irrigated to produce a wide variety of crops suitable to the given climatic and socioeconomic conditions.

In most of the developing countries, the irrigated crops on Vertisols are generally produced with traditional technology. The level of inputs is low. Tillage operations are done with animals and ordinary tractor-driven plows. Furrow and field flooding are the common methods of irrigation.

Soil- and water-management requirements of irrigated Vertisols are different in many respects from the dryland Vertisols and other irrigated soils.

To date, in many parts of the world, irrigated Vertisols have not received the special attention warranted by the problems peculiar to them. Therefore, there is an urgent need to identify and evaluate the problems of irrigated Vertisols.

In this context, Working Group No. 3, through a deliberate discussion, has tried to identify the problems of irrigated Vertisols and research priorities for their solutions.

The group agreed to list activity areas, and each individual country submitted its priority for research. Egypt, Nigeria, Pakistan, Sudan, and Tunisia expressed great interest in participating in an Irrigated Vertisols Network.

Research Priorities:

Activity areas considered by the group were:

1. Drainage
   a. Surface
   a. Internal—waterlogging

2. Salinization and/or sodicity, including alkalinity
   a. Soil salinity problems

   b. Saline irrigation water
   c. Salinization from groundwater
   d. Salinization from using return flows

3. Irrigation scheduling
   a. Water requirements of irrigated crops
   b. Frequency of irrigation for each crop
   c. Limited supplies of water
   d. Water of poor quality
   e. Improved methodology, including delaying irrigation until cracks form to improve water entry

4. Crops and cropping systems
   a. Extend range of crops suitable for irrigation—maturity types, etc.
   b. Multiple crops for irrigation
   c. Relay cropping

5. Soil and land management
   a. Improved methods for water conservation in semi-arid areas with limited irrigation water.
   b. Use of limited crop residues for water conservation.
   c. Improved irrigation water management—forage, etc.
   d. Techniques to improve crop establishment due to crust formation, etc.
   e. Improved machinery to modify land microrelief to improve surface drainage
   f. Improved soil workability or tilth to improve water intake rates, crop establishment, etc.
   g. Improved fertilizer use efficiency, including placement, rates, timing, micronutrients.

6. Soil characterization
   a. Characterize Vertisols in network countries for improved technological recommendations—extent and kinds of Vertisols.
   b. Explain variability in productivity of adjacent Vertisol fields.

7. Other
   a. Weed control
   b. Soil testing and crop-yield responses under irrigation
   c. Standardized methods for evaluating nutrient deficiencies, as by soil testing, foliar analysis, and field trials.

Possible Experiment Stations for Irrigated Vertisols Network

Country	Organization/Location	Crop
Argentina	Concepcion del Uruguay Res. Stat.	Rice only
Egypt	National Research Centre, Cairo	
Nigeria	Lake Chad Res. Inst., Maiduguri	Wheat Barley Vegetables (e.g., onions, tomato) Rice (suppl.)
Pakistan	Pakistan Agric. Res. Council, Lahore (humid), Jacobabad (arid)	
Sudan	A.R.C., Gezira Research Station	
Tunisia	Centre de Recherches du Genie Rural, Tunis Direction des Soils, Tunis	
Venezuela	Estacion Calabozo, FONAIAP	Rice-pasture

Working Group No. 4

Priorities for Validation of Technologies

Chairman: R.P. Singh (India)
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Introduction:

The group concentrated on establishing priorities for validation of technologies. It was agreed that rather than concentrating on a given technology, components should be identified from the different improved technologies available elsewhere. First, the network should verify, test, and validate the improved technologies developed by various institutions such as ICRISAT, ICAR (AICRPDA), ACIAR, and the USDA Soil Conservation Service in Texas. It is essential that the proposed national cells consider these available improved Vertisol management technologies before selecting the components suitable to local needs.

It was suggested that the Vertisol management network should evaluate the following prerequisites for the establishment of national cells.

1. Establish a common objective and then set priorities.
2. Allocate resources by the national research programs for the network.
3. Identify the comparative advantages of various organizations having improved technologies to determine leadership.
4. Supply coordination and logistics, such as identification of a coordinator and the necessary infrastructure.
5. Look at the levels of interaction desired.
6. Link national cells with international, regional, and other related institutions.
7. Establish principles for selection of areas of activity.

The following approaches to transfer of improved technologies were suggested by the group:

- Simulation models available for crops such as wheat, corn, sorghum, and rice in developed countries and in various international organizations could be a useful means for transfer.
- Established statistical relationships are very well-known tools for technology transfer.
- Benchmark studies, which have been in existence for the last two decades, are very useful for analogue transfer.
- Although whole-farm models are least known, they are good for assessment of technologies.

Priorities for Research:

National cells having primary focus on the following research aspects were suggested for priority consideration:

- Resource-poor farmers
- Systems emphasizing food crops
- Systems using low monetary inputs
- Technologies concerned with ecological balance

In addition to these research aspects, the groups felt that the following three components should be emphasized for research on improved management of Vertisols:

- Soil and water management
- Crops and cropping systems
- Machinery and farm implements

Recommendations and Conclusions:

After considering specific objectives, mechanisms for transfer of technologies, and the priorities for research, the group suggested the following.

- The need for backstopping national cells (e.g., support by able institutions in basic research) should be considered.
- The validation could be for a package or a component.
- All the organizations—national, regional, or international—should be treated as equal partners in the network.

Tentative Proposal for Mediterranean Region Vertisol Network

This draft was presented as an example of a mini-network by climatic region.

Delegates from the Mediterranean Region felt that, due to the commonality of climate management problems and predominant crops on their Vertisols, there was a strong case for forming a Vertisol network for the Mediterranean region.

However, since only three countries (Jordan, Tunisia, Syria) were represented at the conference and since time was limited, the delegates proposed that a small and short workshop (under the auspices of IBSRAM) should be called in the future, which would bring together a greater representation of interested scientists.

It was thought that such a workshop could:

a. be held within 12 months
b. be funded independently from IBSRAM
c. be organized by scientists from the region.

It was suggested that this workshop could produce a tightly framed proposal, which would initially concentrate its efforts on wheat (the predominant crop grown on

Vertisols) and would involve the promoters in regional research, testing, and demonstration of simple improvements in management on farmers' fields. It was hoped that the proposal would include site characterizations through soil analyses and climatic data collection (principally rainfall), which would enable analyses of data across the region. Indeed, with a uniform trial design, a uniform set of treatments, a single crop, and a single soil type, this would be possible.

—Statement prepared by P. Cooper of ICARDA,
22 Feb 1985.

Outline for Preparation of an IBSRAM-sponsored Project Proposal by a Network Cooperator

This outline was prepared by participants as an example of what should be contained in a project proposal to be submitted to IBSRAM.

1. Brief statement of sociological setting, extant agriculture, etc.
2. Statement of the problems (*emphasize*)
3. Objectives of the project (*emphasize*)
4. Program of work
    a. Applied research and/or on-farm testing—Phase 1, 3 to 5 years
    b. Validation, if necessary—Phase 2, up to 10 years
5. National component
    a. Location and personnel
        i. Institutions and agencies—executing agency; director of project; responsible officer; etc.
        ii. Personnel resources—number of scientists, type and level of expertise; percentage of time to be spent on project.
        iii. Technicians—number and roles
        iv. Administrative and office support
    b. Physical resources
        i. Laboratory facilities and equipment
        ii. Field facilities, such as experimental sites and equipment
        iii. Transport
        iv. Other facilities, including housing; other infrastructural facilities, such as possible collaborating institutions, etc.
6. International component
    a. Personnel
        i. Visiting scientists—number, expertise, duration needed, and at which stage of project needed.
        ii. Technologies (if any)—number and specific needs
    b. Field work support
        i. Equipment, machinery, and supplies
        ii. Field operations
    c. Consultancies

7. **Budgets**
   a. National component
   b. Donor component
      Administrative costs—IBSRAM
8. **Names, titles, addresses (including telex or cable), official channels of communication.**

Project proposals should be sent to:

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