Proceedings of the

International Workshop on Soils

Research to Resolve Selected Problems of Soils in the Tropics

Townsville, Queensland
Australia
12–16 September 1983

Sponsored by
The Australian Centre for International Agricultural Research
(ACIAR)

Interim Committee of the International Board for Soil Research
and Management
(IBSRAM)

Correct Citation: ACIAR (Australian Centre for International Agricultural Research). 1984. Proceedings of the International Workshop on Soils, 12–16 September 1983, Townsville, Queensland, Australia.

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and
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Publication Editor
J.V. Mertin

ISBN 0 949511 02 1

The Australian Centre for International Agricultural Research (ACIAR) was established in June, 1982 by an Act of the Australian Parliament. Its mandate is to help identify agricultural problems in developing countries and to commission collaborative research between Australian and developing country researchers in fields where Australia has a special research competence.

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Foreword

The rapid growth of population in developing countries and the resulting pressure to expand the available agricultural land is causing widespread soil degradation.

Some of the factors responsible for this deterioration include the overgrazing of semi-arid rangelands leading to serious desertification, the clearing of tropical forests resulting in massive erosion and soil loss in rainfed farming systems, nutrient depletion due to over-intensive cropping practices, and salinization and water-logging in many highly productive irrigated soils.

The need to take measures to reverse this decline in soil productivity is urgent, as the rate of deterioration is accelerating and if not checked, will have serious implications for future food production in the developing world.

The low and declining productivity of many tropical soils is one of the major constraints limiting the realization of the improved genetic potential that is now available in most important staple food crops. There is a need to identify the research priorities and promote action on research to address this problem. The diversity of soils makes it necessary for research activities to be conducted in many locations and the responsibility for such activities must rest with national agricultural research and development organizations. These can be greatly strengthened by assistance from international organizations and from research institutions in developed countries.

The formation of the International Board for Soil Research and Management (IBSRAM) as a new international organization to support and coordinate soil research and management is a positive step in this direction.

The Australian Centre for International Agricultural Research (ACIAR) also provides an opportunity to assist in strengthening the capacity of the national programs through research collaboration with Australian scientists to undertake research on major soil problems.

This Workshop has been designed to explore opportunities for bilateral research collaboration on important soil problems between Australian and neighbouring countries and to develop a mechanism whereby the results can be shared on a wider regional basis.

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Preface

The Soils Workshop held in Townsville on 12–16 September 1983 was jointly sponsored by the Australian Centre for International Agricultural Research (ACIAR) and the Interim Committee of the International Board for Soil Research and Management (IBSRAM). Each organization had separate but closely interrelated reasons for sponsoring the meeting. For the IBSRAM committee the main purpose was to present the proposal for IBSRAM to the international aid donors and the soil science community. ACIAR's main purpose was to seek the guidance of this unique gathering of tropical soils experts in determining priorities for ACIAR's soils research program.

The meeting was attended by 61 soil scientists including 37 visitors from 22 countries. The names of the participants are listed in Appendix I.

The first two days of the meeting were devoted to IBSRAM business, which is summarized in Appendix II. Three papers on the need to strengthen soil research in Africa, Asia, and Latin America, which were presented to the IBSRAM meeting, have been reproduced in their entirety in this volume. On 14 September, after the IBSRAM meeting, which culminated in the election of the founding board of IBSRAM, participants were taken on a tour of the wet tropical areas north of Townsville. This tour provided an opportunity for many of the visitors to compare and contrast the soils and agriculture of wet tropical Queensland with conditions in their own countries.

The last two days of the meeting were devoted to the presentation and discussion of papers on six research topics, which are reported in these Proceedings. An Australian group firstly presented a keynote paper, which was followed by two short contributions on the same topic from overseas experts. This format catalysed a lively discussion, which in each case was led by an eminent Australian soil scientist. The final discussion was focussed on determining priorities for possible ACIAR support, using the urgency of a particular problem and the capacity of Australia's soil scientists to contribute as the main criteria.

The main objectives of the meeting were achieved — IBSRAM was launched as a much-needed international organization to strengthen and coordinate soil research in the tropics and ACIAR received the best advice available on the future direction for its program of soil research.

A number of individuals and organizations contributed to the success of the meeting. The Interim Committee of IBSRAM chaired by Drs D.J. Greenland and A.R. van Wambeke, supported by interim administrator Dr R.B. Miller, contributed a great deal of time and effort to the overall organization of the meeting.

The CSIRO Davies Laboratory, led by Officer-in-Charge Dr R.J. Jones, who welcomed the participants at the opening of the workshop, provided invaluable assistance with the local arrangements for the meeting. In particular, Mr G.G. Murtha of the CSIRO Division of Soils was largely responsible for the success of the field trip. Thanks are also due to the staff of the Division of Land Utilization, Queensland Department of Primary Industries, at Innisfail, who presented to the participants in the field trip, a report on their research on erosion of sugar-growing soils. The Bureau of Sugar Experiment Stations invited the participants to inspect a reference soil at their Tully Station.

Special thanks should also go to the Mayor of Townsville, Alderman Reynolds, who hosted a mayoral reception for workshop participants. The staff of the Townsville International Hotel made the visitors most welcome and Mrs B. Steward and P. Tart of the Australian Convention Travel Service ensured that all the conference and travel arrangements went smoothly.

Finally and most importantly, we express our appreciation to the contributors to the technical program. The high standards set by the authors of the papers, the discussants, the discussion leaders, and the participants ensured the success of the Workshop.

E.T. Craswell and R.F. Isbell
Co-ordinators

Session 1

Soil Constraints to Food Production in the Tropics

Chairman: D.J. Greenland

The Needs of Africa

R.A.D. Jones*

I have been asked to present to this Workshop 'The Needs of Africa' in relation to soil constraints that affect food production. I do not believe my shoulders are big and strong enough to bear such a responsibility, but I shall surely give it a good try.

It cannot be denied that the needs of Africa are many and multifaceted. Despite the fact that high yielding varieties have been developed by both national and international agricultural research institutions over the last two decades, average cereal production has remained around 800 kg/ha. A similar picture emerges for other crops such as the tubers and legumes.

There are many factors responsible for this sorry state of affairs — climate, disease, pests, soil constraints, social, economic, and political. However, even under the rather ideal conditions found in research stations, yields are still low and in this regard such low yields are mainly attributed to soil constraints. It is therefore of utmost importance that these soil constraints be alleviated or removed if the potential of the available high-yielding germplasm is to be realized.

The first OAU/STRC Inter-African Soil Science Congress in 1980 did make 12 recommendations with regard to soil constraints. These have been circulated as part of the Workshop papers.

The soil constraints that stand out foremost, in my view, are training; fertility maintenance under continuous cropping; land clearing and land preparation; water control, efficient water use in semi-arid zones; soil classification, soil science data bank and soil museum; and dissemination of information to farmers.

Training

In Africa there is a dearth of soil scientists, which is not limited to professionals; it also includes technicians. It would be futile to embark on programs designed to alleviate or remove soil constraints if the necessary trained manpower were unavailable.

In this regard one envisages a leading role to be played by IBSRAM. It should provide financial assistance to qualified personnel to undertake both professional (M.Sc. and Ph.D.) as well as short-term specialized training, preferably in developing countries that can best offer the relevant training courses as well as in international agricultural research institutions such as IITA and IRRI. It is also desirable that if already qualified, soil scientists be given opportunities to undertake short study tours (courses) in South American countries and in Australia, which have similar soil problems. IBSRAM in collaboration with the OAU/STRC, AAASA, ECA, UNEP, FAO should encourage and assist soil scientists to visit different African countries and help organize seminars and workshops at the subregional level.

On the technician level, one hopes that IBSRAM would assist in short-term training courses at regional institutions such as WARDA and IITA as well as within individual States.

Fertility Maintenance under Continuous Cropping

Work done at IITA, IRRI, and in many national research institutions has shown that crop productivity could be greatly improved and sustained continuously for many years not only if the correct levels of fertilizers are applied, but also if the best forms of fertilizer, e.g. rock phosphates against superphosphates, are applied. The importance of micro nutrients in agricultural production has been positively demonstrated in Latin America by Sanchez (1977) and Lopes (1979), and in Africa by Kang (1974, 1975), Ayotade (1977), and Jones *et al.* (1979).

One hopes, therefore, that IBSRAM would encourage and promote adaptive research, based on accumulated results, in as many African countries as possible. Again, one is of the opinion that collaboration with colleagues

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* Director, Rice Research Station, Rokupr, Sierra Leone.

within the continent and in Latin America is highly desirable, and in this regard one hopes that IBSRAM would play a leading role in such link-building.

Land Clearing and Land Preparation

Work done in Indonesia and Latin America by Sanchez (1977) and in IITA by Lal (1979) has shown conclusively that when the proper land clearing method is not used, the resulting effect on soil properties could be disastrous. Similarly, if the correct equipment is not used during land preparation, the soil could become so compacted that the crop fails to become established.

IBSRAM has a role to play in assisting to help set up adaptive research in this context in many African countries, particularly those located within the high rainfall areas.

Water Control

The wetlands in Africa provide a vast ecological zone where sufficient rice can be grown, but, because the water levels are not controlled, yields are fairly low. A lot of work has been done in water control in Asia, where irrigated rice is an ancient culture, and in Surinam. With the assistance of IBSRAM, this available technology could be transferred. IBSRAM should also provide assistance to train African manpower *in situ* in Asian countries as well as in Surinam.

Efficient Water-use in Semi-arid Zones

Work done by IRAT and more recently by ICRISAT has shown that yields in the semi-arid zones could be greatly improved if better use were made of the limited available moisture. It is hoped that IBSRAM can assist in the transfer of this technology to the Sahel countries, which have experienced a lot of hardships over the last decade because of drought.

Soil Classification, Soil Science Data Bank, and Soil Museum

IBSRAM, in collaboration with FAO, should assist African countries to classify their soils in cases where this has not been done. Additionally, in collaboration with FAO and OAU/STRC, IBSRAM should assist in the establishment of a soil science data bank as well as a soil museum. These two latter would assist greatly in the communication between soil scientists, and in the dissemination of soil information.

Dissemination of Information to Farmers

When all is said and done, the main beneficiary of all soil science research is the farmer. Thus, no effort should be spared in getting soil information passed on to the farmer. At present, very little information is conveyed because either the mechanism does not exist or the method used in unsatisfactory. In collaboration with various national institutions, IBSRAM should devise more effective methods in this regard.

It is the fervent hope that IBSRAM would contribute a lot towards realizing what Africa needs to remove or alleviate the soil constraints that affect food production. With the continued support of donors, such as Australia, Germany, Canada and the United States of America, and the assistance of FAO, the existing IARCs such as IRRI and IITA, I am confident that IBSRAM can more than meet the challenge to such an extent that within 10 years from now, an African representative to a similar workshop in this country would be reporting on the high levels of crop production in Africa.

Finally, I am happy to inform all participants that President Dr. Staka Stevens of Sierra Leone sends his regards to this Workshop and has mandated me to state that Sierra Leone would be willing to host any SMU that IBSRAM may decide to locate within the West African Subregion.

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The Needs of Asia

C.R. Panabokke*

A wide range of production systems has evolved over several centuries throughout the different agro-ecological regions of Asia. Wetland production systems comprise irrigated rice, rainfed rice, and deepwater rice; and dryland production systems comprise rainfed shifting cultivation, rainfed settled arable farming, and rainfed perennial tree crops. All these production systems occur over a wide range of soil and rainfall conditions.

A major proportion of the food requirements of the Asian population is derived from wetland rice production systems. The production levels of the various food crops grown under dryland production systems do not compare favourably with the production levels attained under wetland rice. Nonetheless, the various food grains and root crops that are grown under dryland production systems constitute a substantial proportion of the food needs of the Asian population.

Highly commercialized plantation agriculture with perennial tree crops has developed over the last hundred years in areas where soil conditions and rainfall have been found suitable for plantation tree crops. Soil research and management has had a significant impact in raising production levels in the tree crop plantation sector.

In the wetland production systems, soil research and management has made a significant impact in increasing the productivity of rice in the more stable rice growing environments. In the rainfed agriculture production systems only marginal gains in productivity have been achieved in recent years; they have been realized more from improved crop cultivars and less from improved soil management practices.

Since a greater part of the arable land area in Asia is already under some form of cultivation, increases in production will have to come largely from intensified cultivation and better management rather than large-scale increases in the cultivated area. The emphasis in this region should therefore be on improved soil management, which will increase per hectare yields.

Gaps in Knowledge Utilization

Most of the countries in the Asian region have, over the recent years, accumulated a significant body of information in respect of their soil resources. Soil maps at different levels of generalization are now available for nearly all the countries in this region.

There is, however, considerable variation among the Asian countries in the functional use and meaningful application of the available soil survey and soil classification data by the national agricultural research and extension agencies.

Institutional separation of the National Soil Survey from the National Agricultural Research and Extension Agency is usually one of the main reasons for this unsatisfactory situation. Weak or ineffective linkages and communication between the soil survey group and the soil research, management, and agronomy group is yet another reason.

The Malaysian rubber and oil palm industries afford one of the best examples of effective use and application of soil survey and classification data to plantation-crop agriculture. In the small-farm subsistence farming sector, especially in the dryland production systems, soil survey information is used in soil production and management studies, but there is little evidence of its proper application and translation by the extension services.

The International Rice Research Institute (IRRI) has been able to successfully stimulate the thinking of the national research programs in recognizing the implications and use of soil and hydrological data in the soil research and management studies on rice lands. As a result, soil research and management problems have become more clearly defined and better focused in the national programs. Even the breeding objectives for the different categories of rice lands are now being increasingly determined by

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a sharper description of the soil and hydrological characteristics of the rice lands. Some countries in Asia have recently been able to use rice land elements as the basis for soil management and fertilizer recommendations in a small-farm rice holding averaging 1–2 ha. This could be considered as a significant breakthrough in the application of modern scientific soil information to the small rice-farmer in Asia.

Proposed Target Areas

1. Wetland Soils

The needs for wetland soils have been very adequately elaborated in the proposed Wetland Soil and Water Management Unit. The sub-unit envisaged in the SAWMIRCS network assumes special significance at the present stage of rice production levels attained in Asia. The emphasis given to a better understanding of the influence of physical properties of rice soils on rice yields and the rice cropping system is accepted as an area of high priority.

There is a dearth of knowledge on the influence of easily measurable soil physical properties on the growth and yield of wetland rice. Very little is known about which of the soil physical characteristics that influence the yield and performance of arable crops under upland free-draining conditions, limits or influences the performance of the rice crop under wetland conditions. It is suggested that basic investigations of this nature be undertaken by universities or research institutes that have the resources and capability to spearhead these lines of work. IBSRAM could be the initiating force in this field of study. Such studies could strengthen and reinforce the work of the SAWMIRCS sub-unit.

The sub-unit proposed for the delineation and characterization of the problem wetland soils would also occupy a high priority position in the Asian context.

2. Shifting Cultivation on Ultisols of South East Asia

A greater part of the new land resources available for further expansion of settled agriculture for food production lies in the Ultisols (Udic) of South East Asia. Although proven technologies for commercialized plantation tree crops have been evolved for these soils, no acceptable technologies have yet been determined to replace the existing system of shifting cultivation with settled arable food-crop cultivation.

The proposed OXULT network has identified the research needs of the weakly buffered and infertile Oxisols and Ultisols. When compared with tropical America, the estimated extent of Ultisols in tropical Asia is more significant than the extent of Oxisols. Of the 29 research and development components that have been identified for the OXULT Soil Management Unit, there would be some that would score a different priority rating if considered for the Udic Ultisols of Asia alone.

Further subdivision of the Ultisols that occur in Asia down to the Great Group level of Soil Taxonomy would be greatly helpful in selective testing and transfer of available technologies.

3. Settled Arable Farming on Alfisols

The more stable forms of settled rainfed arable farming, especially in South Asia, have taken place on the Alfisols (Ustic and Udic). The existing production systems, however, are under severe stress because of the increasing population densities and the low crop yields that are being obtained. The dominant cause for low and variable crop yields is the frequent occurrence of unsatisfactory soil-moisture regimes. A lack of suitable technology for better water utilization and some soil fertility limitations are primary constraints to higher and more stable production.

The adaptation and testing of technologies developed at IITA and ICRISAT to small-farmer conditions is being carried out in some national programs. A SMU is not proposed for this production system. Instead it is proposed that IBSRAM assists in the dissemination and adaptation of technologies among the national programs.

Suggested Approaches

Research needs and priorities in any country should be determined by its own national goals and by feed-back from extension services and, above all, by the demands of its farming systems and commodity-oriented research. Soil management research programs should cater to low and medium input farming, which is what most farmers in this region are practising anyway.

Inventory and communication among soil scientists at the regional level should be enhanced by acceptance of common international classification systems in addition to the national systems. This would be further enhanced by the establishment of a regional data bank for soil and crop information. It will be necessary to identify lead institutions in each country to provide networks for soil inventory and management.

Identification of soil constraints to increased agricultural production and the establishment of technical working groups to tackle these problems would be one indicated course of action to increase production on marginal lands. For example, regional technical working groups to exchange experiences could be set up to deal with sandy soils, acid sulphate soils, soils on steep lands, and LAC soils.

The weak institutional linkages between the soil survey group and the field extension service could be identified as one of the main constraints to proper diagnosis of soil-related problems in the field. IBSRAM could give the leadership in exploring the appropriate methodologies that could be adopted to strengthen these linkages.

Other areas in which IBSRAM could make significant contributions would be:

1. Providing the physical data for proper site characterization of both commodity and farming system research.
2. As an aid in land-use planning by providing better definition of land types as well as land-utilization types.
3. Strengthening or supplementing analytical services where these are lacking or deficient.
4. Training, seminars, exchange of visits, and organizing workshops.

The Needs of Latin America

A.S. Lopes*

Tropical Latin America comprises a total land area of 1 683 million ha and includes the following countries or regions: Brazil (851 million ha), Mexico (197), Peru (128), Colombia (114), Bolivia (110), Venezuela (91), Central America (52), Guyanas (47), Paraguay (41), Ecuador (28), and Caribbean (24). However, less than 5% of the total land area was under cultivation by the fifties, largely as a result of adverse soil, geographic, or climatic conditions.

Developments over the last three decades have drastically changed this picture. The total harvested area of Latin America doubled from 53 million ha in 1950 to 97 million ha in 1976, with 10 million ha brought into production between 1973 and 1976 alone. The major part of this increase occurred in Brazil (17.5 to 44 million ha) while Paraguay, Panama, Mexico, Ecuador, Bolivia, and Costa Rica also substantially expanded (FAO 1978). By 1979 approximately 50 million ha of cereals, tubers, and pulses were harvested in Tropical Latin America (FAO 1981).

About 575 million ha in tropical Latin America are estimated to be suitable for cultivation, of which less than 25% is presently utilized. However, many of these new lands are known to possess major constraints. For instance, it is estimated that 90% of the soils in the Amazon region, one of the most important frontiers, suffers from low natural fertility (Sanchez 1977). Although extension of agricultural frontiers offers possibilities for increasing food production, most of the easily occupied land is already in use, and intensification of land use appears to be also of increasing importance. This holds particularly true for Mexico and the Andean region where prospects for expanding cropland are dim.

Although crop production in Latin America grew by 3.5% annually since the early fifties, yields have risen by only 1.1%, reflecting the emphasis on new lands. However, if Brazil were excluded, changes in yield would account for 50% of the increase in crop production. The increase in fertilizer use by a factor of 20 over the last 25 years is an indicator of the intensification of land use.

These data indicate that both approaches, i.e., incorporation of new lands in the productive process and increased yields in the areas already under cultivation will definitely be important to increase food production in Latin America in the near future.

However, to achieve our possible food production goals in the next two decades, many problems have to be overcome. We feel a need for the action of an international coordinating body in terms of soil science, that can help Latin American countries to alleviate soil constraints and promote an increase in food production on a stable continuing basis.

A summary of the diversity of agro-ecological conditions, the main soil constraints that occur in soils of Latin America, as well as our thoughts on how a coordinating body such as IBSRAM can help to remove these constraints and increase food production in this region, is presented in the following sections.

Major Farming Systems, Crops, Soils and Soil Constraints in Latin America

Diversity in farming systems in Latin America is typical and even within short distances one can observe large sugar cane, coffee, cacao, rubber, bananas and pineapple, soybeans, and rice plantations side by side with subsistence tillage and other systems. Shifting cultivation through slash and burn, is, by far, the major system in humid Tropical America, mainly in the area of the Amazon and Orinoco Basin. The second system in land area importance is livestock ranching, which is typical of the cerrado (savannah) in Brazil and Llanos Orientales in Colombia. Settled subsistence farming is the

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major system along the Andes Cordillera in South and Central America (Figure 1).

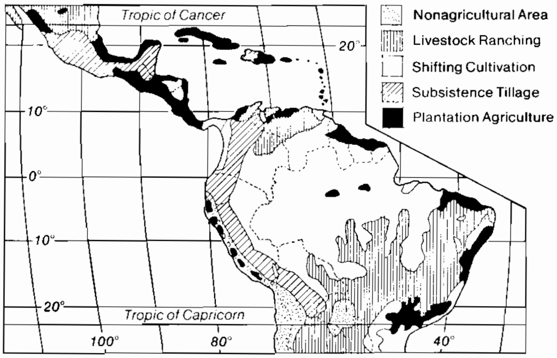

Figure 1. Management systems in tropical America (Adapted from Sanchez 1976).

Modern plantation systems are the common situation in Sao Paulo State and the Coastal Forested area in Northeast Brazil; scattered areas in the Andes, Guyanas, Venezuela, throughout Central America and Caribbean countries are mainly dedicated to export crops.

A considerable effort was made in the late seventies mainly in the cerrado area in Brazil to extend advanced plantation systems to some food crops (mainly soybeans, wheat, rice, and beans), similar to those already used in the south, outside the tropical region. However, high investments in fertilizers to improve soil to support adequate yields, and the slow down in government action through removal of subsidies seriously affected this program.

This diversity in farming systems in tropical Latin America is a constraint to allow extrapolations of technology from one region to another, unless adequate screening through a coordinating body is done to evaluate the best management approach to use the available natural resources, taking into account local social behaviour and financial capabilities. We must recognize many failures when trying to transplant United States or European practices without significant adaptive research and without taking these factors into consideration.

The relative importance of the eleven major food crops in tropical Latin America is presented in Table 1. The nutritive values of these crops vary considerably. The present average yields of root crops and plantains far outstrip the cereals in total energy production per crop. Soybeans and potatoes are the highest protein and energy production crops. On a daily basis the most productive crops in terms of both energy and protein production are sweet potatoes and soybeans. Data in Table 1 show that the present yield of many crops is well below the potential of existing varieties. In many countries reduction in yields has been observed mainly due to a decline in soil fertility and inadequate soil management. This problem cannot be solved simply by making better crop varieties available.

There is considerable variation in the areal distribution of soils in tropical Latin America. More than 50% of the total land area is dominated by highly weathered, leached soils as Oxisols and Ultisols, followed by Inceptisols, Alfisols, Entisols and other soil orders that are locally important (Table 2).

Table 1. Relative importance of the eleven (11) major food crops in tropical Latin America.

Food Crop	Production (million metric tons)	Area (million ha)	Yield (t/ha)
1. Cassava	31.4	2.7	11.6
2. Corn	41.6	24.0	1.7
3. Rice	14.8	8.0	1.9
4. Potatoes	8.4	0.8	10.5
5. Wheat	5.8	3.2	1.8
6. Beans	2.3	8.1	0.3
7. Sweet potatoes and yams	1.8	0.3	6.0
8. Sorghum	8.2	2.9	2.8
9. Soybeans	16.0	9.3	1.7
10. Peanuts	0.6	0.5	1.2
11. Other grain legumes (pulses)	3.0	8.9	0.3

Source: Computed from the FAO 1981 Production Yearbook.

Table 2. Generalized area distribution of soils in tropical Latin America.

Soil associations dominated by:	Area (10^6 ha)	Percentage (%)
Oxisols	502	33.6
Ultisols	320	21.4
Inceptisols	204	13.7
Alfisols	183	12.3
Entisols	124	8.3
Mollisols	65	4.4
Andosols	31	2.1
Aridisols	30	2.0
Vertisols	20	1.3
Spodosols	10	0.7
Histosols	4	0.3

Source: Adapted from Sanchez and Salinas (1981).

The geographical extent of major soil constraints in tropical Latin America, without reference to the main soil orders associated with these constraints, is presented in Table 3. Nitrogen and P deficiency are by far the most limiting soil constraints in terms of percentage of total area. Potassium deficiency, high P fixation, Al toxicity, S, Zn, Ca, and Mg deficiencies are a problem in about 50% of the area. Water stress (more than 3 months), low water-holding capacity, high erosion hazard, copper deficiency, waterlogging, compaction hazard, and Fe deficiency complete the list of the already identified soil constraints.

Considering the four main regions in tropical Latin America, the following summary of soil-

Table 3. Geographical extent of major soil constraints in tropical Latin America (23°N–23°S).

Soil Constraint	Tropical America ($1493\ 10^6$ ha)	
	10^6 ha	%
N deficiency	1332	89
P deficiency	1217	82
K deficiency	799	54
High P fixation	788	53
Al toxicity	756	51
S deficiency	756	51
Zn deficiency	741	50
Ca deficiency	732	49
Mg deficiency	731	49
H_2O stress > 3 months	634	42
Low H_2O holding cap.	626	42
Low effective CEC	620	41
High erosion hazard	543	36
Cu deficiency	310	21
Waterlogging	206	20
Compaction hazard	169	11
Laterite hazard	126	8
Fe deficiency	96	6
Acid sulfate soils	2	0
Mn toxicity	?	?
B deficiency	?	?
Mo deficiency	?	?

Source: Adapted from Sanchez and Salinas (1981).

related constraints for food crops production, according to the Proposal for the Establishment of IBSRAM, January, 1981 is:

1. Humid (including periodically humid areas such as the Brazilian cerrado and the Venezuelan and Colombian llanos).
    (1) Soil acidity, primarily associated with Al toxicity problems.
    (2) Deficiencies of P, N, K, S, Ca, Mg, Zn and other nutrients.
    (3) Intermittent drought occurrence, magnified by poor root development in the usually highly acidic subsoils.
    (4) Erosion associated with poor land-clearing methods and poor crop management.
    (5) Mechanical impedance to seedling emergence and root developments; more important in the drier (ustic) than the wetter (udic) parts.
2. Semi-arid
    (1) General water deficiency, associated with poor entry into the soil and inadequate storage of plant-available water in the profile.
    (2) Deficiency of N, P and S.
    (3) Mechanical impedance to seedling emergence and water entry, associated with crust formation at the soil surface.
3. Steep Lands
    (1) Erosion and sedimentation problems, and related problems of water storage control.
    (2) Deficiency of N and other nutrients associated with high costs of fertilizers because of difficulties in access to these areas.
    (3) Stoniness and physical problems associated with generally poor conditions for root proliferation.
4. Wet Lands
    Although lowland or irrigated rice is not a traditional agricultural system in tropical Latin America, the potential of many areas for this purpose has been demonstrated in the last decade. Soil constraints for these conditions are:
    (1) Deficiency of N associated with low efficiency of N fertilizers.
    (2) Deficiencies of P, Zn, S and other nutrients.
    (3) Toxicities of Fe and occasionally B and Mn.
    (4) Salinity in some semi-arid areas.
    (5) Excess water and poor drainage conditions and intermittent water deficits.
    (6) For crops grown after rice, cloddiness and poor physical conditions restricting root growth and extraction of water and nutrients.

Objectives for IBSRAM in Latin America

Considering the diversity of social, economic, and political factors in Latin American countries and also the diversity of climate, soils, management systems, research capabilities, effectiveness of extension services, lack of adequately trained soil scientists, and above all, the number of soil related constraints already identified, it would be difficult to achieve our food production goals in the next two decades, by working only individually as a nation.

We feel a need for a coordination body like IBSRAM that would be able to:

1. Convince top decision-level administrators of a country to increase their research investment in soil management in order to sustain and increase productivity of food crops.
2. Promote and initiate training activities on research planning, research methodology, resource allocation and human needs in order to adequately prepare top researchers and managers.
3. Help national programs in tropical Latin America to fully identify specific soil constraints that limit adequate food crop production, and to identify the needs for research priorities in order to overcome these constraints.
4. Disseminate through tropical Latin America the present knowledge on soil use, and management technology that has been determined in tropical Asia and tropical Africa and vice-versa within similar agro-ecological zones, in order to overcome those soil constraints already identified.
5. Encourage the need for a multidisciplinary approach mainly with geneticists to make better use of research budgets and to allow

further extrapolation of the results to farmer level.

6. Evaluate at national level the needs of highly trained personnel at various levels in different aspects of soil science to fill the gaps and to define the training priorities and the best options for specific training programs.
7. Promote integration and coordination of national and international network programs to focus on soil research, technology, and management already operative in Latin America and to suggest initiation of new networks.
8. Promote definite action to convince local governments of the need for research on soil and water conservation, and soil biology, which are generally bypassed by other areas of soil science.

We emphasize the following specific actions for IBSRAM in tropical Latin America:

1. The technology developed at the Cerrado Research Center at Brasilia and at CIAT in Colombia in order to produce adequate levels of grain crops in the cerrado and Llanos Orientales regions has been proved to be technically and economically feasible. Revalidation of the research results in farmers' fields within these regions and other similar agro-ecological zones with similar soil constraints throughout the world could save years of basic research. Coordination of these network studies of revalidation is expected to be a definite action for IBSRAM.
2. Similarly, soil management technology developed at Yurimaguas, Peru, involving land-clearing methods in rain forests, dynamics of nutrients, and fertilizer use to sustain food crop yields at reasonable levels would also save years of research, if these results can be transfered to farmers in similar agro-ecological zones. Actions of IBSRAM to improve the effectiveness of the research network for the Amazon region and revalidation of these results are also expected.
3. Knowledge of physical, chemical, and biological transformations of newly incorporated lands (rainfed, irrigated, and wetlands agriculture) is meager in most tropical Latin American countries. The lack of expertise in these fields is a limitation to the total potential of the lowland areas recently incorporated in the productive process in Latin America. National programs must be convinced of the need for highly trained personnel and expert consultancy to identify soil constraints under flooded conditions, as well as adequate management of these soils.
4. Surveys of production systems by regions, according to socio-economic conditions, is an important approach to evaluate the possible cause-effect relationship of low crop productivity. Technical and economic studies of the performance of production systems (representative of a given region) against new alternatives is necessary when trying to transfer management technology. Actions to convince extension specialists in the national and international networks about the value of this approach would be a great contribution by IBSRAM in Latin America.
5. In many of the steeplands already under cultivation in Latin America, there is a definite need to develop stable methods of rational land use and to avoid soil degradation and erosion. In many cases, farmers passed direct from the hand hoe to the tractor on slopes not suitable for advanced machinery. Intermediate steps via the use of animals as a source of energy would be more appropriate to these local conditions. Validation of integrated management technology for these conditions is totally desirable for many areas in this region through possible action by IBSRAM.
6. Finally, some actions of IBSRAM applicable worldwide would include an increase in and an improvement of laboratories for soil and plant analysis, organization of national soil data banks, assist more dynamic dissemination of research results, and integration of soil science knowledge by storage, translation, and dissemination of relevant information suitable for use in other similar agro-ecological zones.

These are only broad ideas on what we think an international body like IBSRAM could do to help Latin America achieve its food-crop production goals in the near future. We believe that actions by IBSRAM will convey highly significant scientific knowledge to agricultural production in this region.

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Session 2

Taxonomy of Tropical Soils

Chairman: R.A.D. Jones
Discussion Leader: R.C. McDonald

Soil Classification Problems in the Tropics and Subtropics

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Over the past decade much attention has been focused on agrotechnology transfer, with particular attention being paid to the underdeveloped lands of the tropics and subtropics. Numerous workshops and conferences have been held on this topic, and much emphasis has been devoted to the subject in the research programs of the various international agricultural institutes concerned with the undeveloped world tropics. Additionally, more specific studies have also been instigated, a prime example being the Benchmark Soils Project (Beinroth *et al.* 1980).

Nix (1968) pointed out that the assessment of biological productivity in new lands is based heavily on concepts of transfer by analogy, i.e. extrapolation from experimental sites or from on-farm experience to analogous situations elsewhere. He noted that much less attention had been given to site-factor methods that seek to relate key parameters to biological productivity within a given environment. Also in this paper Nix drew attention to the need to study and develop systems analysis and simulation methods to understand and describe the behaviour of complex biological systems. It is true to say that fifteen years later the situation with regard to agrotechnology transfer has not changed a great deal.

It is obvious that in the widely used analogy approach, the role of soil, and particularly soil classification, is all important. In its simplest terms the assumption is usually made that if the soil at an experimental site is characterized and classified at the appropriate level of detail, then a soil similarly classified at a new site in a similar environment should behave in a predictable manner. Moore (1978) has discussed the roles of soil survey and soil classification in transfer by analogy, and also notes there is an equal need for these activities, particularly classification, in site-factor methods.

Given the importance of soil classification in the context outlined above, it follows that there is a particular need for effective soil classification systems in the tropics and subtropics where there is a great need for agrotechnology transfer. This paper will highlight some of the present problems with soil classification in these regions.

Some General Principles and Limitations of Soil Classification

In 1978 W.M. Johnson, who was then head of the Soil Conservation Service, United States Department of Agriculture, remarked that the trouble with soil classification is that no one knows much about it, except pedologists. I generally agree with this, but would go further and state that there are also many pedologists who do not appear to understand some of the fundamental principles and limitations of soil classification. Even worse, arguments about various aspects of soil classification by some pedologists are based more on emotion than logic.

Essentially, soils — like other objects — are classified in order to organize our knowledge and thus reduce complexity, as an aid to remember their properties, to bring out and understand relationships among soils, to correlate information about soils, and to provide a means of transferring information about them. Most importantly, classification aims to group soils in a manner useful for practical, applied purposes such as predicting their behaviour, identifying their best use, and estimating their productivity.

It should be realized that there are two components of soil classification, just as there are in the classification of any other natural phenomena. One is the grouping of like soils into classes, and the other is the assignment of an unknown or new entity to an appropriate existing class. This latter operation is better

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called identification (or allocation), and is usually most conveniently carried out by means of a key (Moore *et al.* 1983). The term 'taxonomy' is also widely used as a synonym of 'classification', although it also may have two meanings according to Webster's Third New International Dictionary. One is the study of the general principles of scientific classification . . ., the other is the systematic distinguishing, ordering and naming of type groups within a subject field . . . . It is this second meaning that may be thought of as being synonomous with the first meaning of 'classification'. In this paper the terms classification and taxonomy are used interchangeably in this sense.

It is repeatedly stressed in the scientific literature that no classification scheme can remain static. As new knowledge is gained, so should soil classifications be modified and improved. When any particular soil classification scheme is devised there is never a complete knowledge of the universe of soils, even on a local scale. In effect the classification is erected on the basis of a 'sample' of the soil population, and it is unlikely that the 'samples' on which most classification schemes are based are chosen in an unbiased fashion. The result is that all existing classification schemes are imperfect to some degree, and must benefit from modification in the light of new knowledge.

Most systems of soil classification tend to use the hierarchical system of biological classification as a model, although there are a number of philosophical objections to such an approach. However, there are a number of benefits such as enabling abstraction at various levels, and facilitating the construction of keys for identification. Unfortunately, many users of hierarchical systems do not always appreciate some of the basic implications of such schemes. One of the most important was made by Orvedal and Edwards (1941) — as soils are grouped into larger and more inclusive groups or classes, the assertions that can be made of any groups become progressively fewer. Not appreciating this principle is the reason why some people have been known to remark that the Inceptisols, for instance, are a very diverse group of soils and few generalizations can be made regarding their properties or behaviour at the order level.

Finally, it must be remembered that most existing soil classifications are what have become known as general purpose schemes. In effect, they try to cater for all likely users of soil. It is little wonder then that dissatisfaction arises from particular users who feel that such general purpose schemes fail to fulfill their needs. An alternative is the construction of special purpose or so called 'technical' classification schemes. While there are some of these in use, e.g. the Unified Soil Classification (FAO 1973) widely used by engineers, it is obvious that the number and kinds of special purpose classification systems that could be devised are almost unlimited.

Soil Classification and Soil Mapping

Much criticism of soil classification is caused by a lack of understanding of the fundamental difference between soil taxonomic units and soil mapping units. Soil mapping units are delineations on a map devised to best represent, in simplified form, the natural occurrence of soils in the landscape. Such map units are of necessity 'impure' in the sense that they almost always contain soils that have characteristics outside the range permitted by definition for a specific taxonomic unit (Buol *et al.* 1980). The apparent discrepancies between soil mapping units and taxonomic units normally increase with decreasing map scale.

This question of scale is an important one and is often not appreciated by map users. If a soil map of the world at a scale of $1{:}10^8$ shows a map unit labelled Alfisols, few readers would assume that all such areas labelled on the map consist solely of Alfisols. Yet at more commonly used larger scales this question of map unit purity is often forgotten. Most soil mappers have had the experience of having their map greatly enlarged by a user, who then complains that the soils within a mapping unit are too variable for his purpose.

The problem of lack of soil maps of a scale adequate for the intended purpose is one of particular relevance to many underdeveloped lands in the tropics and subtropics. In such cases reliance often has to be placed on maps of an undesirably small scale. No matter how adequate the particular taxonomic units used in constructing the map may be, the practical use of maps of this kind will be jeopardized unless the user is aware of their inherent limitations.

National and 'International' Soil Classification Systems

Scientists from other disciplines express surprise on learning that there in no universally accepted, world-wide system of soil classification as there is in the case of say plants, and perhaps to a slightly lesser extent, rocks. The reasons for this state of affairs are many. Certainly by their very nature soils are difficult objects to classify, and the science of soil is relatively young. Also, it is likely that the problem is related to the diversity of uses to which soils are put, and the wide range of scientific interests of those who are concerned with the study of soil. Perhaps another compelling reason is that to some extent the nature of soils tends to be more local than many other phenomena, and it is only to be expected that a particular region or country will be more concerned with what soils occur within it than the world as a whole.

In practice there are many local (essentially national) soil classification systems. Some of these have been devised almost entirely by the region or country concerned, others are a modification of schemes developed elsewhere. It is logical to assume that if such local schemes have been continually updated in keeping with increasing soil knowledge, they should in general be more appropriate for the country or region concerned than an 'international' scheme that has not been based on the total population of soils. I am not in a position to judge the effectiveness of the many national schemes, although it is worth noting that two schemes with relevance to the tropics and subtropics (those of the French and Brazil) are currently being revised. In the case of Australia, a revision of the two schemes presently in widespread use (the great soil group system of Stace *et al.* (1968) and the Factual Key of Northcote (1979)) is clearly needed. The former was largely based on Stephens (1962) and the latter has had only minor revisions since 1960. Both schemes were primarily based on the soils of temperate Australia, and no longer adequately cater for the great increase in soils knowledge resulting from studies over the past two decades throughout Australia.

In the context of communication, and the role of soil classification in technology transfer, it is obvious there are a number of defects in relying solely on national systems as a means of information transfer. The language problem is one concern, but of greater importance is the widely differing concepts and differentiae used in establishing classes in different systems. This may make it virtually impossible to relate a taxonomic class in one system to a class in another system.

During the past decade two soil classification schemes have been published that have gained a degree of international currency. The first, the World Soil Map Legend (FAO-UNESCO 1974), was designed to facilitate mapping the soils of the world on a uniform basis at a small scale (1:5 000 000). The scale of the intended map obviously had an important bearing on the construction of the legend, that is now referred to, although perhaps somewhat inaccurately, as a soil classification system. Equally obviously, some existing national soil classification systems played an important part in its formulation.

The other classification scheme, which is now becoming a *de facto* international system, is that of Soil Taxonomy (Soil Survey Staff 1975). This system, devised originally for the soils of the United States, although with considerable input from Western Europe, was developed over a 20 year period through seven approximations.

A brief account of the general advantages and disadvantages of the above two schemes has been given by Moore *et al.* (1983). Both, however, offer a means of international communication, and for this reason the remainder of this paper will deal with some of the problems that have arisen when both schemes are applied to the soils of the tropics and subtropics.

Some Classification Problems in Soils of the Tropics and Subtropics

The soils of the tropics and subtropics are not uniquely different from those of the more temperate regions. Many, but by no means all, fit the older concepts of being highly weathered and strongly leached, and often very old. The soils of the tropics and subtropics are highly diverse, and like elsewhere are often strongly site-dependent. What is apparent is that there is a much higher proportion of certain kinds of soil in the tropics, and until relatively recently these kinds of soils had been little studied and were poorly understood. In fact, *Soil Taxonomy* specifically states in the Preface that the classification of tropical soils needs more testing. Similarly, most work on the World Soil Map Legend was completed prior to 1970.

Over the past decade much new soil knowledge has been gained from previously little-known areas of the tropics and subtropics. This experience has highlighted a number of problem areas regarding soil classification, and has led to the formation of a number of international committees under the auspices of the United States Department of Agriculture (USDA), assisted by the U.S. Agency for International Development, to try to improve Soil Taxonomy in areas where weaknesses have become apparent.

The various problems discussed below are essentially of two general kinds. First, the inadequacy or ambiguity of definitions leads to difficulties in consistent identification; second, the existing class limits may lead either to soils that are diverse both in properties and use being included in the one taxon, or essentially similar soils being separated.

Diagnostic Horizons

A feature of both the FAO and USDA systems is the widespread use of defined diagnostic horizons that are used in differentiating classes. In many cases the diagnostic horizons are essentially the same in both systems, and this is so for those discussed below. Two problems may arise: (a) consistent identification, and (b) the significance of the diagnostic horizon in various soils.

Argillic horizon:

This concept is of fundamental importance to the structure of both classification systems. In Soil Taxonomy particularly, it is used at high categorical levels to separate what might otherwise be very similar soils. Problems concerning identification and the significance of the argillic horizon, particularly in tropical soils, have been extensively reviewed, e.g. Eswaran and Sys (1979), Cline (1980), Isbell (1980a, 1980b), McKeague (1983). The question has also been discussed by the international committee dealing with the classification of low activity clay Alfisols and Ultisols. This has resulted in a proposed kandic horizon (Moormann and Buol, unpublished) as an alternative to the argillic horizon in these soils. If adopted, this proposal would remove many of the present difficulties with argillic horizon identification in the highly weathered soils of the tropics. It is also noteworthy that a very similar proposal has been made in the first approximation of a new French classification (Fauck *et al.* 1979), which has used much recent information on tropical soils.

The problem of the argillic horizon in non-oxic soils still remains, and although difficulties of consistent identification might be resolved by improving the definition, there is still the important question of the relevance of the concept. As noted by Isbell (1980b), the significance of two key aspects has yet to be adequately examined, viz. the importance of clay skins in relation to plant growth (Smith 1979), and the relevance of a specified clay increase to water relations of soils.

Natric horizon:

As earlier pointed out by Isbell and Williams (1981), many Australian soils irrespective of latitude have strongly sodic argillic horizons that do not qualify as natric horizons under the present definition. This is because they do not have prismatic or columnar structure, or do not have tongues of an eluvial horizon extending more than 2.5 cm into a blocky structured argillic horizon. There is also mounting evidence (Isbell and Williams 1981) that a lower limit of exchangeable sodium percentage (ESP) at 15 is too high. A more meaningful limit may be around 6%, as has been widely used for delineating sodic soils in Australia. This question has been raised in India (Sehgal *et al.* 1975), and will probably occur elsewhere. It is accentuated by the fact that at present no 'natric' subgroups are defined in Soil Taxonomy. Hence in this system soils with management constraints that are sodium-induced are not identified if ESP is < 15. However, in the FAO scheme provision is made for separately grouping soils with an argillic horizon with an abrupt textural change and an ESP of > 6 as Solodic Planosols.

Plinthite:

This concept, devised in an attempt to remove the confusion resulting from loose usage of the older term 'laterite', is used in both classification systems. In Soil Taxonomy it is used for defining a number of great groups and subgroups. In spite of recent attempts (e.g. Daniels *et al.* 1978) to clarify its morphology and to suggest field methods of identification (particularly with regard to the specification requiring irreversible hardening on repeated wetting and drying), identification of this material is still very subjective.

Although plinthite is by no means confined to the tropics and subtropics it is certainly common in this region, even though Sanchez and Buol (1975) have effectively dispelled the myth that vast areas of the tropics consist of 'laterite'. Daniels *et al.* (1978) have also discussed the significance of plinthite in relation to water movement, and have shown that the kind of plinthite (nodular or platy) is important in this context. They also raise the question if it may not be more appropriate for the classification of plinthite-containing soils to be based on the associated reticulately mottled horizons that appear to be more relevant in terms of soil water relations.

Soil Moisture Regimes

Few soil scientists or those concerned with the use of soil would deny the importance of soil moisture, or indeed argue that it is not a property of soil. The main contentious issues are how soil moisture regimes should be defined, how they may be determined, and at what categorical level in a classification they should be used. In Soil Taxonomy soil moisture regimes constitute a fundamental part of the system, in particular at the suborder level, whereas in the FAO system they are used only to define two aridic soil groups and to separate soils with hydromorphic properties.

The definition of soil moisture regimes:

Soil Taxonomy uses the concept of the soil moisture control section (SMCS) to facilitate the estimation of soil moisture regimes from climatic data, and the definition of the various soil moisture regime classes is essentially based on the length of time the SMCS is dry or moist in most years. Isbell and Williams (1981) have pointed out several theoretical and practical objections to the class definitions; probably the most important is that the water status of the SMCS is dependent on, but is only part, of the soil profile available water capacity.

The determination of soil moisture regimes:

Water balance models appear to be the only practical means by which an estimate of the soil moisture regime can be obtained. The model MOREG3, developed by Franklin Newhall of the USDA Soil Conservation Service, is widely used for the purpose and is based on monthly means of rainfall and temperature. Isbell and Williams (1981) have noted a number of shortcomings in this model, particularly the use of the Thornthwaite method of estimation of potential evapotranspiration from monthly temperature data. This may greatly underestimate the potential evapotranspiration (and hence the actual evapotranspiration used in MOREG3) for many areas outside the region of the United States for which the temperature/evaporation correlations were developed. Isbell and Williams give some examples of how changes in estimates of potential evaporation could change the predicted soil moisture regime for a number of Australian stations. For instance, the following Queensland stations in the tropics and subtropics would change from udic to ustic: Brisbane, Cardwell, Gladstone, Mackay, and Toowoomba.

Another shortcoming of MOREG3 pointed out by Isbell and Williams (1981) is the fact that the available water capacity (AWC) of the profile (used to determine the number of days the SMCS is moist or dry) is fixed at 200 mm. This represents the high end of the range for many soils, and hence those with an AWC of substantially less than 200 mm will be classed by MOREG3 as wetter than they actually are.

Use of soil moisture regimes at high categorical levels:

Objections raised by some people about the use of soil moisture regimes in soil classification would probably disappear if their use were restricted to low categorical levels, e.g. at the family level. However, it would not be possible to do this without drastically restructuring a number of the present orders of Soil Taxonomy. Again, some of the criticisms of the present usage would disappear if it were possible to readily measure actual soil moisture regimes over a period of time. This of course is rarely feasible. At the moment all that is practical is to further subdivide the present broad classes of soil moisture regimes. Such an approach has recently been attempted by Van Wambeke (1981, 1982).

Soil Temperature Regimes

As in the case of soil moisture regimes, there are also reasons why soil temperature should be regarded as a soil property and should be used as a diagnostic criterion in classification. Similarly, the main arguments revolve around its determination, the definition of soil temperature regime classes, and at what level they should be used in a hierarchical classification. In Soil Taxonomy, soil temperature is used at different levels in the system, but is particularly definitive at the family level. In the FAO system it is used only in relation to the definition of aridic soils.

The determination of soil temperature:

Unlike soil moisture, mean annual or seasonal soil temperatures can be readily estimated by actual measurements over a relatively short time period. Even so, such data are still lacking for many areas of the tropics and subtropics. Soil Taxonomy also provides guidelines for the estimation of soil temperature at 50 cm depth (the diagnostic level in the profile) from mean air temperatures. It may be noted that in at least some parts of the world, including the Australian tropics, different estimates may be obtained by using the three hottest months or the months as specified in Soil Taxonomy. This could lead to discrepancies in reporting of 'iso' or 'non-iso' regimes. Murtha (in press) has shown that similar discrepancies occur in measured 'summer' and 'winter' temperatures in tropical Queensland.

It has also been noted (Murtha *et al.* 1980) that soil temperature at 50 cm depth may change markedly depending on the vegetative cover. An example of this has been documented by Murtha (in press) in tropical Queensland, where clearing a rainforest to produce a bare soil for cropping, changes the temperature regime from 'iso' to 'non-iso'.

Definition and use of soil temperature classes:

In Soil Taxonomy soil temperature regimes are used as family differentiae in all orders, but in addition are used elsewhere at different categorical levels as high as the Order. In the case of the lower altitude tropics and subtropics most argument relates to the usefulness of the 'trop' concept and whether there should be a class to cater for soils hotter than hyperthermic.

The main argument against the use of the 'trop' concept at high levels is that apart from uncertain agronomic considerations, evidence of important co-varying soil properties is generally lacking. In the case of the hotter soil temperature regimes, there is increasing evidence to show that it is high surface and near-surface soil temperatures that are most likely to be of agronomic importance (e.g. Lal 1978; McCown *et al.* 1980). There are as yet no published data available to see if useful predictions of near-surface temperatures can be made from mean temperatures at 50 cm depth either an annual or seasonal basis.

Transient Soil Properties

It is somewhat paradoxical that most general purpose soil classifications rely more on subsoil properties as class differentiae than on surface soil properties, which are more likely in most instances to influence plant growth. The reasons for this are simple. Many surface soil properties are transient in that they are subject to modification by man's use of the soil, and hence classification may be changed. Those who construct soil classifications aim to have a degree of permanence in the classes they create. Thus it is easy to understand the emphasis given in both Soil Taxonomy and FAO-UNESCO to subsoil characteristics.

In both schemes, however, some surface soil properties are used. The mollic epipedon for example is diagnostic at the Order level in Soil

Taxonomy, and defines several units in the FAO system. Perhaps surprisingly, this seems to have caused few problems. In other instances, however, the use of transient surface soil properties does lead to difficulties. Two examples may be given:

1. Humic groups. The use of a specified amount of organic carbon to a depth of 1 m has been found to be an ephemeral property in the case of some rainforest soils. Following clearing and cultivation, organic carbon levels in surface horizons decline relatively rapidly (Sanchez 1976) and hence the cultivated soil may no longer remain in a humic suborder or great group. This is of particular relevance in the tropics where increasing areas of virgin forests are being cleared and cultivated.
2. Mixing of surface horizons. This situation is almost a converse to the above, in that a diagnostic criterion for Vertisols is based on the upper 18 or 20 cm that have been mixed, as by ploughing. A good example of the problem here is afforded by many Australian soils that have thin (say 10 cm) A and often E horizons of say loam to clay loam texture that abruptly overlie heavy clay B horizons. Using the mixing rule, most of these will classify as Vertisols. It can be argued that this is appropriate for some practices, but it obscures important properties of these soils when they are to be used for other purposes where the nature of the surface soil may be of some importance, e.g. sowing of plants by means of very shallow or even no-cultivation techniques. Similarly, the sodic nature of a B horizon may be obscured if a thin-surfaced Natrustalf is classified as a Vertisol as a result of the mixing rule.

Some Other Problems Concerning Class Definitions

While it is probably possible to allocate any soil to a class currently defined in either Soil Taxonomy (at least to the great group level) or in the FAO scheme, this does not mean that such an allocation is the most appropriate. Clearly, improvements or possible extensions to both schemes are needed. It is worth mentioning here several difficulties not yet discussed, which have been encountered in the Australian tropics and subtropics.

Distinction between Aridisols and Alfisols:

As noted by Isbell and Williams (1981) there are many soils within the Australian arid zone that possess an argillic horizon but have an epipedon that is massive and hard when dry. Apart from the subjective nature of 'hard', it may be questioned if such a criterion should be used as a differentia at the order level as co-varying properties (apart from possibly surface clay content) are not evident.

Alfisol diversity:

Isbell and Williams (1981) have commented that perhaps the most striking feature of the Australian semi-arid to sub-humid lands is the widespread occurrence and diversity of Alfisols, particularly Ustalfs. It would seem desirable that a greater subdivision be made below the suborder level. It would be simplest to increase the present number of subgroups, but a more appropriate revision would be to increase and probably redefine the existing great groups. A particular concern is the abrupt texture change or lack of clay decrease criteria as alternatives in the definition of Paleustalfs. This leads to the inclusion of some very diverse soils in this great group.

Spodsols:

Thompson and Hubble (1980) have drawn attention to some of the problems concerning the classification of eastern Australian subtropical podzols. Apart from the definition of the spodic horizon, difficulties arise with the 2 m depth criterion in Soil Taxonomy (but not in the FAO system). This excludes the well-known 'giant' forms from Spodosols. Such soils are common elsewhere in the world tropics (see references in Thompson and Hubble). The important ecological implications of a chronosequence of podzols in subtropical southern Queensland have been documented by Walker *et al.* (1981). This clearly shows the limitation of an arbitrary lower depth limit for 'soil' for classification purposes.

Conclusion

It would seem undeniable that soil classification is, and will continue to be, an essential component of soil research and agrotechnology transfer. Moore (1978) has argued that soil mapping is not necessary for information transfer. Nevertheless it is widely used for this purpose, and in this paper I have commented on some of the pitfalls in interpreting soil maps. These can usually be avoided if sufficient care is taken with map legend construction, and if users become more familiar with the limitations of soil maps, particularly in relation to scale.

It has been pointed out by Van Wambeke and Dudal (1978) that it is not possible in any soil classification system to serve global, regional, and local objectives equally well. Yet for well-known reasons, some of which are given in this paper, the ideal goal is a comprehensive global system. Beinroth *et al.* (1980) note that uniform procedures for making and interpreting soil surveys are also needed, and comment that soil interpretation on an international scale today remains an art. It needs to be made a science.

This paper has discussed some limitations of the two general-purpose classification schemes that are being widely used in an international context. A particular disadvantage of the FAO scheme is that it is essentially a two category system designed for a particular small-scale purpose — a function that it has served admirably well. In the case of Soil Taxonomy, one of its main disadvantages is the relatively narrow (in a world-wide context) data base on which it was constructed. For example, as *Soil Taxonomy* points out, the classification of Oxisols was essentially based on the soils of Hawaii and Puerto Rico, which are far from being representative of the world's Oxisols. With reference to Australia (comparable in size to the USA) it may be noted that Mollisols probably occupy only one or two percent of the area, compared with 25% of the USA. In contrast, Vertisols in Australia occupy up to 15% of the country compared with 1% of the USA. The extent of these soils in the USA helps to explain why there are some 260 subgroups established for Mollisols as against 25 for Vertisols. However, as Beinroth *et al.* (1980) have noted, what may appear to some observers to be a deficient classification system is merely a reflection of the stage of its development.

What is needed if a universally acceptable soil classification system is to be achieved, is a recognition of the following:

1. A data base as representative as possible of the world's soils must be used. This will avoid some of the present problems caused by systems developed for one part of the world not working equally well in other parts where the overall soil population is markedly different.
2. The classification should preferably not be predetermined as was the case for sections of Soil Taxonomy. It is understandable, as Smith (1981) has noted, that one of the aims of this system was to classify the soil series of the United States without requiring more changes in their definitions than necessary to improve interpretations. The concept of zonality was strongly entrenched in the United States prior to Soil Taxonomy, and was reflected even at the series level. Hence it is not surprising that the architects of the new system looked for criteria that would preserve the status quo. As Smith (1981) has indicated, the use of soil climate permitted this, and so we find statements such as: 'The best way to reintroduce the zonality seemed to be to use the soil climate' (Smith 1981, p8). The danger in the predetermined approach is that a commitment made for one area may be inappropriate for another. For example, while a general zonality has been shown to occur in the higher latitudes of the northern hemisphere, there are good reasons why this is not to be expected (and indeed is not found) in the older soil landscapes of lower latitudes, particularly in the southern hemisphere.
3. Definitions must be clear and unambiguous so that consistent interpretations of diagnostic criteria and consistent class allocations may be made. In the case of Soil Taxonomy, Cline (1980) has written that the numbers of taxa and the quantitative precision of definitive criteria require complicated definition and keys that demand intense concentration and substantial competence if they are to be applied precisely. Cline also noted that

these demands are major obstacles where Soil Taxonomy is relatively new or is not used regularly, especially where English is not the common language of the users.

4. In spite of the above criticism, the idea that a good system is simple enough to be clear to any layman is erroneous. Soil is complex and although the general ideas of the taxonomy should be explainable in simple terms, the definition of taxa must be complex in some instances (Canada Soil Survey Committee 1978).
5. Attributes used as class differentiae must be known to have relevance for various purposes, be they of engineering, agronomic or 'scientific' importance. This necessarily involves a greater understanding of the degree of co-variance between soil properties than is presently available.
6. Given the many obvious problems with the use of transient surface soil properties, it may be best to accommodate these by the wider use of complementary technical classifications, one example of which is the fertility capability system of Sanchez *et al.* (1982).

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H. Eswaran* Discussant — 1

Recent Efforts to Refine Soil Taxonomy for the Classification of the Soils of the Tropics

Soil Taxonomy is emerging as the de facto international soil classification system. With its greater use in intertropical areas, and with the recognized deficiencies of the soils systems of the tropics, Soil Management Support Services (SMSS) is making a concerted effort to refine the soil classification system.

This contribution explains briefly the activities of SMSS to internationalize Soil Taxonomy. Two groups of soils are considered — low activity clay soils and volcanic ash soils — to illustrate the attempts being made to improve the system.

At the time *Soil Taxonomy* was published (Soil Survey Staff 1975), the classification of some of the soils in the tropics was inadequate. Also, as knowledge grew, classification changes were needed to make use of the new knowledge. The inherent weakness of the classification system of the soils of the tropics lay in the absence of detailed investigation of these soils. Many countries in the tropics did not have and still do not have detailed soil surveys. The few data available were from isolated soil pits. Consequently, the geographic extent and, in particular, the landscape relationships of some of these soils could not be established.

The authors of *Soil Taxonomy*, viz. the Soil Conservation Service (SCS) of the U.S. Department of Agriculture, had sought the assistance of soil scientists throughout the world to develop the system. Since the publication of *Soil Taxonomy* they have continued to rely on these inputs to refine the system. A workable mechanism to maintain a dialogue with non-U.S. soil scientists became possible with the creation in October 1979 of the Soil Management Support Services (SMSS).

SMSS, the international wing of SCS, was charged with the task of internationalizing Soil Taxonomy. Internationalization implies the expansion of our knowledge base and the free interaction of soil scientists everywhere so that Soil Taxonomy can be refined for fuller use and application.

SMSS has established eight international committees (ICOMs) to discuss and develop proposals for refining specific areas of Soil Taxonomy. The work of these ICOMs is supported through soil classification workshops, which are organized in developing countries where the soils under consideration are very extensive. Six such workshops have been organized. Technical monographs and newsletters supplement these efforts to internationalize the system. A series of training courses, apart from teaching the system, also enables the testing of the system in different parts of the world. Internationalization is a two-way effort with heavy reliance on inputs from scientists in the tropics, because they know their soils, and can inform us of management-related properties. They are also most qualified to make proposals for criteria and limits.

In this paper, only the low activity clay (LAC) soils and the volcanic ash soils are discussed. The areas that are being considered for revision are indicated and some thoughts on the approach needed are elaborated.

The Oxisol-Ultisol Interphase

Many soils in the tropics are dominated by low activity clays (LAC). These LAC soils have an effective cation exchange capacity (NH_4OAc bases plus aluminium) of < 12 m equiv. per 100 g soil, or, if the soil pH is > 6.5, they have a CEC IN NH_4OAc at pH 7 of < 16 m equiv. per 100 g clay. Some of the LAC soils are Oxisols *s.s.*, while others may be Ultisols, Alfisols, and even Inceptisols and Mollisols. Some of the LAC soils show a marked clay increase with depth, which is diagnostic for an argillic horizon, but do not have the associated features of clay skins or cutans; in other situations, and particularly where erosion has truncated the soil, clay skins are present but the required clay increase is not met. Soil Taxonomy has provided for these

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different situations, but the descriptive text was interpreted in various ways by users. Further, identification of clay skins is difficult in kaolinitic-sesquioxide systems. Therefore, because of these and other difficulties, Soil Taxonomy was being used incorrectly.

Two international committees — the International Committee on Low Activity Clay Soils (ICOMLAC) and the International Committee on Oxisols (ICOMOX) — have deliberated on these and other aspects of the classification of LAC soils. ICOMLAC has now submitted a draft proposal which will be distributed internationally for testing.

ICOMLAC has developed the concept of the kandic horizon. Soils with this horizon have the following set of properties:

1. The kandic horizon has an ECEC of less than 12 m equiv. per 100 g clay at a depth of 30 cm from the top of the horizon or above a lithic, paralithic, or petroferric contact. If the pH is 6.5 or higher in water, then it has a CEC (NH_4OAc) of $<$ 16 m equiv. per 100 g clay at this depth.
2. A coarse-textured surface horizon at least 18 cm thick and having at least 40% clay.
3. A clay increase such that if the surface horizon has less than 20% clay, the kandic horizon has 4% more clay, and, if there is 20–40% clay, the kandic horizon has 8% more clay.
4. The kandic horizon is at least 30 cm thick or at least 60% of the depth to a lithic, paralithic, or petroferric contact within 50 cm of the soil surface.

As the Oxisols are keyed out earlier than the soils with kandic horizons, the definition of the order of Oxisols will contain a statement that will eliminate the soils with kandic horizons.

This change has consequences throughout Soil Taxonomy. Some of the more critical ones are explained here. First are the LAC soils with more than 40% clay in the surface horizons that meet the clay increase requirements for an argillic horizon (many of these may key out as Ultisols or Alfisols today). These soils will be classified as Oxisols and come under a special great group to be termed Kurorthox or Argiorthox.

The kandic horizon is diagnostic for two great groups as illustrated in Table 1. Because the kandi great groups are defined as having a CEC of less than 16 m equiv., kandic subgroups in non-kandi great groups are provided and are defined as having a CEC (NH_4OAc) of less than 24 m equiv. Table 2 shows some of the subgroups provided for in selected kandi taxa.

With the exception of the 'acric', the remaining subgroups carry definitions current in Soil Taxonomy. The 'acric' subgroups have an ECEC of less than 1.5 m equiv. per 100 g clay within 1.25 m of the soil surface.

Finally, it is possible that some soils classified as Inceptisols will, with the new proposal, be classified as Ultisols or Alfisols. This is primarily because the stipulated clay increase has become an important diagnostic criterion, and if the other requirements are met, the soils will be classified in the Ultisols or Oxisols.

Table 1. Great groups in two suborders to illustrate the use of kandi taxa.

	Alfisol		Ultisol
HEA	Agrudalf	FDA	Plinthustult
HEB	Natrudalf	FDB	*Kandiustult*
HEC	Ferrudalf	FDC	*Kanhaplustult*
HED	Glossudalf	FDD	Paleustult
HEE	Fraglossudalf	FDE	Rhodustult
HEF	Fargiudalf	FDF	Haplustult
HEG	*Kandiudalf*		
HEH	*Kanhapludalf*		
HEI	Paleudalf		
HEJ	Rhodudalf		
HEK	Hapludalf		

Table 2. Subgroups in selected kandi taxa.

	Kandiudalf	Kandiustult	Kanhaplohumult
1.	Aquic	Acric	Acric
2.	Arenic	Andic	Andic
3.	Arenic plinthic	Andic udic	Andic ustic
4.	Grossarenic	Aquic	Anthropic
5.	Grossarenic plinthic	Arenic	Aquic
6.	Mollic	Arenic petroferric	Epiaquic
7.	Plinthaquic	Arenic	Lithic
8.	Plinthic	Aridic	Sombric
9.	Rhodic	Petroferric	Ustic
10.		Plinthic	

Andisols

Since their creation, the Andepts were considered by many as a misfit in the Inceptisols. The committee of Andisols (ICOMAND) is developing proposals to create a new order — Andisols. No firm proposals have been made to date. The following account is a review of current thinking.

One suggestion is to define an 'andic soil material' as mineral soil materials having the following set of properties:

1. At least 30 cm thick.
2. A pH in 1N NaF of > 9.8.
3. A bulk density of 0.9 or less.
4. An anion retention capacity of more than 90%.

The use of variable charge, by itself or as a ratio to ECEC, was considered but an agreement could not be reached on suitable limits.

In the key to the soil orders, it is felt that Andisols should be keyed out early. One suggestion is to key it out after the Histosols. The minimum thickness of andic soil materials that would be permitted if the soil were to be classified as an Andisol is a function of the underlying material — lithic or paralithic contact or, if there is a buried soil, the nature of the soil. ICOMAND is considering these aspects. Tentatively, the suborders of Aquands, Torrand, Xerand, Ustand, Udands, and Orthands have been proposed, each with its own set of great groups and subgroups.

Andic subgroups in non-Andisols are more difficult to define and ICOMAND has not yet deliberated on this issue. Two kinds of subgroups may be envisaged: (a) where there is a thin surface layer of andic materials, and (b) where the soil has subordinate andic properties. The latter is the situation where soil formation, or andic materials, has resulted in another kind of soil, such as an Ultisol or even an Oxisol.

Finally, some soils dominated by halloysite present special problems for classification. These soils are common in the wet tropics, as in Kalimantan and Costa Rica. They have a low CEC and may even have a field morphology of an Oxisol. Their performance is like Oxisols but they generally contain a large amount of weatherable minerals. Because of continuous moist conditions, allophanes do not break down and the soils react to NaF, but the soils will not qualify for Andisols because of the high bulk density. Many of these soils have been classified as Oxic Dystropepts, but it is felt that this is inappropriate.

Conclusion

The other ICOMS are working on specific aspects of Aridisols, Vertisols, Spodosols, and also on soil moisture and temperature regimes. The work of these ICOMS is necessarily slow as many of their discussions occur through correspondence.

The structure of Soil Taxonomy is such that new information can be incorporated with minimal distortion of the system. At the same time, its structure requires that changes in one part of the system will necessitate careful evaluation of the entire system and incorporation of any other needed changes. Consequently, even after receiving a proposal that has been tested and verified, it takes considerable time to finalize the amendments. Amendments that have been accepted are published in the *Soil*

Taxonomy News, a newsletter of SMSS. It is hoped that a new edition of *Soil Taxonomy* will be published by the end of the decade.

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S. Panichapong* **Discussant — 2**

Problems Associated with the Application of Soil Taxonomy in Thailand

Prior to the advent of *Soil Taxonomy* (Soil Survey Staff 1975), the classification system used in Thailand was that elaborated by Dudal and Moormann (1964). The goal of the soil survey program at that time was a general assessment of the soil resources of the Kingdom and this was achieved with the publication of the soil map of Thailand by Moormann and Rojanasoonthon (1968). By this time, we had begun the systematic soil survey of the country. We were using the soil series concept and the specifications of the USDA Soil Conservation Service (SCS). We were also actively following the developments of the new classification being developed by the SCS and in 1972 had the first opportunity to test the system in the north eastern region. We had mixed results. The language was new to us and so were many of the concepts. We decided that we had to go through a learning period and partly for this reason we hosted the Second International Soil Classification Workshop in 1978. We were also fortunate that during this period many of our staff were trained in the USA and we could apply the system with greater confidence.

In 1979, we published the first general soil map using Soil Taxonomy. The map scale is 1:1 000 000. We considered this an important achievement though we recognized that the map only reflected our knowledge at that time and that more work had to be done to improve its accuracy.

We had to continue our staff training and in this respect we are very fortunate to receive assistance from the Soil Management Support Services (SMSS). Together with SMSS, in 1983 we organized the Fourth International Forum of Soil Taxonomy during which we had a detailed discussion on Soil Taxonomy. It was interesting to note the marked change of many of my colleagues who made important contributions to the discussion. This was clear indication that they had appreciated the system and were now in a position to propose changes to improve the system.

The present paper attempts to highlight some of the problem areas. Already SMSS has several international committees working towards solving these problems.

Field Application

In the past, we had echoed the sentiments of many other persons that we cannot use Soil Taxonomy as it required too many laboratory analyses. Our experience has shown that though complete supporting data are necessary for a correct classification, as a result of our knowing the system and knowing the region, we can arrive at a fairly good first approximation of the classification. We believe that, we have now reached a stage where we need only a few selected analyses for a correct placement. This has resulted in a considerable savings in our cost of laboratory analysis but more important, it has resulted in considerable savings in our cost of laboratory analysis but more important, it reports.

There are, however, a few areas that could be improved to facilitate the field identification.

Argillic Horizon

Identification of the argillic horizon persists as a problem though, as a result of monitoring with thin-sections, we have fewer arguments than a decade ago. We support the proposal of the International Committee on the Classification of Low Activity Clays (ICOMLAC). With this proposal, soils with less than 40% clay in the top 18 cm, and having a prescribed clay increase with additionally a subsurface horizon having oxic properties, are all brought together as the Kandi taxa, in the Ultisols, Alfisols, or Mollisols. If the surface horizon has more than 40% clay and an oxic horizon, the soils are

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considered as Oxisols even though they may have the clay increase of an argillic horizon and even though they may have clay skins. The attractive feature of the ICOMLAC proposal is that it can be readily applied in the field. In addition, the two kinds of soils have distinct management implications and so the classes are not artificial.

Oxic Horizon

Although limits in Soil Taxonomy were made to create mutually exclusive classes, as the oxic horizon has at least 15% clay, soils with a lesser clay content have no real place in the system. The sandy Oxisol-Psamment boundary must be changed and Thai pedologists have proposed a 10% clay limit for the oxic horizon.

Lateritic Materials

It is unfortunate that Soil Taxonomy considers laterite as stones and brings it in only as a family modifier. Many times, in our regional development programs, we have to map and interpret these soils. Some of these are gravel while others are recemented blocks while others may even form pans. The fact that recementation takes place suggests that the process is current. In the recent ICOMOX proposal, it was even suggested to confine oxic horizons to materials with less than 85% gravel.

In Thailand, it is felt that the classification of lateritic soils is a problem and particularly when one has to decide if there is an argillic horizon or any other horizon. We tend to lean towards the suggestion of the past chairman of ICOMOC (Dr Hari Eswaran) who placed all lateritic soils in the Oxisols and specifically in the 'Pale' great groups. Different kinds of laterites or the depths at which they occur, both of which affect the use and management of the soil, are spelled out at the subgroup level.

Aquic Moisture Regime

Thailand is one of the few countries where man creates the aquic moisture regime. In creating the environment to grow his rice, the Thai farmer develops a perched water-table and through generations of this activity, changes the profile morphology. Such soils have no place in Soil Taxonomy. The peculiarity of these soils is that they are flooded in the rainy season and stone-dry during the dry season. The pedons have reduced surface horizons and reddish brown to red subsurface layers and some may have plough pans.

Moormann (1978) has used the term anthraquic for similar soils but we think that a study is needed to examine a range of soils to evaluate the variations and make recommendations.

Vertic Properties in Wet Soils

We feel that many of our wet soils, which have a high shrink-swell potential and are currently classified as Tropaquepts, may be misclassified. The problem arises from the definition of the Vertisols, which is essentially a morphological definition. Due to the cultural practices, these heavy clay soils do not shrink or swell and so do not have slickensides or parallelepipeds tilted to 60° to the vertical and do not have cracks. But their engineering properties are those of Vertisols.

We think that there is a need for an Aquert suborder in Vertisols and the definition should include: (a) the high clay content (> 60%), (b) the high CEC (> 75 m equiv./100 g clay), and (c) the high COLE (> 0.09).

Laboratory Application

The specificity of some of the definitions, particularly with analytical data, has created some problems. There is a need to re-evaluate some of the methods and develop new methods for soils of the tropics. Some areas of concern are presented here.

Cambic Horizon

Cambic horizons in soils with aquic soil moisture regimes should not have the irregular distribution of organic carbon characteristic for Fluvents. We have many soils that have a distinct B horizon in terms of color, structure, and other properties. They were originally Fluvents but through pedogenesis have formed a cambic horizon. However, pedogenesis has not erased the irregular distribution of organic carbon due to the high water-table. The soils are actually Aquepts and are present in association with Aquults and Tropepts. Due to the specific requirement of the cambic horizon, the soils are forced into Fluvents and we believe this is an error.

Our additional problem is the organic carbon determination by the wet digestion process of Walkley and Black, in acid sulphate soils. A large error is created when pyrite or jarosite is present which over-estimates the organic carbon. As these minerals are present at specific depths, a plot of carbon with depth may also show an irregular distribution. Organic carbon determination through dry combustion techniques is possible but the equipment is expensive. We have also noted similar problems in soils high in manganese.

Family Mineralogy Criteria

The family mineralogy criteria are defined quantitatively. We have X-ray diffraction equipment and our mineralogist insists that quantitative estimates cannot be given. So for the moment, our mineralogy class is an estimate and we are not comfortable with this.

The ferritic and oxidic class limits warrant re-examination. The 40% Fe_2O_3 limit for ferritic class is too high and we have no such soils. A limit of 20% is pedo-chemically more reasonable as published work shows that there are marked changes in the charge characteristics when this limit is passed. The limit of 0.2 for the ratio of iron plus gibbsite to clay is also too low. We seem to have more oxidic classes in loamy families than in clayey and we suggest that the limit should be 0.3 for loamy and 0.25 for clayey families.

General Problems

Language of Soil Taxonomy

We in Thailand thought that we could not understand Soil Taxonomy because our English was poor. However, we found out that others had the some problem. Although Soil Taxonomy avoids ambiguity, we would appreciate it if it can be written in a more straightforward manner.

Soil Moisture Regimes

We have used the Franklin Newhall model to estimate our moisture regimes from atmospheric data. For a national evaluation, this is excellent and gives the broad agro-ecological zones. However, within one zone, we may have soils that are sandy, loamy, or clayey and each has its own storage capacity. The soil moisture regime in each of the soils can be different although the estimate from the atmospheric climates states that it is udic. Consequently, we need a model that is more site-specific. For management purposes, we also need more moisture-regime classes and the classes should also reflect the seasonal-moisture content patterns in the soil. Further, though the moisture-regime control section is a useful conceptual parameter for taxonomic purposes, it ignores the top soil that is so crucial to annuals.

Family-Soil Series Gap

The Soil Series is considered as the sixth category of the system. Our experience suggests that there is a discontinuity between the Family and the Soil Series. The system can be improved if a sub-family is introduced. The sub-family should be defined on the surface-soil characters such as the moisture content and also a few fertility parameters.

Future of Soil Taxonomy

In his lecture on the problems of the application of Soil Taxonomy to tropical soils with low activity clays (LAC), Smith (1979) stated 'that an attempt to define its taxa in unambiguous terms by specifying methods and limits between taxa was imperfect because of three principal reasons: (a) limited number of soils with LAC that were available for study in the United States; (b) limited knowledge about methods for their study and the general lack of knowledge about their chemistry and reasons for their peculiar behaviour; and (c) the pressing need to develop a system for classifying soils in the United States, which left little time and few funds for the study of intertropical soils'.

The soil scientists in tropical countries have in addition three major handicaps. One is the lack of technology to conduct research; second is the poor funding and support from the government on research programs, and third is that the pedologists in developing countries spend most of their time surveying the development project areas. There is not much time left for them to concentrate on research towards the improvement of the soil classification system. All they can do, as in Thailand's case, is to follow the established definitions as much as possible and modify certain points when necessary as information becomes available in order to complete the assignments.

Despite all the problems, criticism, and controversy the Soil Taxonomy has made good progress toward becoming an International Soil Classification System. However several improvements have to be made, some of which are:

1. Try to make the philosophy or logic of the system understandable to potential users, especially to those who have English language difficulties.
2. All the existing practical problems can be solved through collaboration with the relevant established International Committees; ICOMLAC, ICOMOX, ICOMAND, ICOMERT, ICOMORT. The activities of such international committees must be accelerated.
3. While waiting for official adoption of the proposed revisions, pedologists of each country must use their own practical judgment to classify the soil in each individual country and be ready to revise them when the official decision is made.
4. Attempts should be made to rewrite the *Soil Taxonomy* text into more simple language and if possible, it should be translated into different languages.
5. Programs to standardize the analytical procedures as well as training courses for the laboratory technicians must be initiated.
6. SMSS should play an important role in promoting all the activities.

As one of the users of Soil Taxonomy, I would like to end my presentation by quoting Dr. G. D. Smith (1980), 'It is time for a new generation to take over the responsibility for Soil Taxonomy. It will be necessary for the pedologists, chemists, biologists, and physicists to work together with horticulturists, agronomists, range conservationists, foresters, agricultural engineers, highway-planners, city planners, and others to decide how different soils are best classified, and to find definitions that can be applied in the field to classify them in the best way. This was how we arrived where we are, and many points of view will have to be compromised if Soil Taxonomy is to attain its potential value'.

Acknowledgement

The author wishes to thank Dr. Hari Eswaran for his assistance in discussing and reviewing the manuscript.

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Session 2
Taxonomy of Tropical Soils

Summary of Discussion

R.C. McDonald*

For effective transfer of agrotechnology there is need to identify key soil parameters. Agronomic criteria can indicate where soil problems exist, then key soil parameters causing problems need to be defined.

There is a clear need for a verbal shorthand for transfer of soil information, such as in an international classification scheme which, ideally, groups soils into classes suitable for practical agriculture. No soil classification scheme can remain static and needs modification to accommodate new knowledge continually becoming available. The work of the Soil Management Support Services and its eight international committees is seen as being a very progressive, necessary and effective vehicle for implementing necessary modifications to Soil Taxonomy. The international committees are seen as a welcome part of the SMSS/USDASCS system to consider problem areas but the various chairmen and committee activities are not known widely enough. Also, to make Soil Taxonomy more relevant there needs to be work with other disciplines. There is need for additional committees to deal with soil fertility relationships and this is under consideration by SMSS which is sponsoring a workshop on the relationship between Soil Taxonomy and fertility. IBSRAM could also take up this work. In the Chinese soil classification system, the low level in the hierarchy of the soil species is based on fertility attributes, for example, phosphorus level. Rice paddy fields may be mapped at the species level.

It is seen as very important that where amendments to Soil Taxonomy are considered and implemented, confusion in nomenclature must be avoided.

Both general purpose and special purpose or technical classifications are needed. Because of the transient nature of some properties of epipedons or surface horizons such as organic carbon content and mixing of the upper 18 cm, these properties may be better incorporated in complementary technical classifications.

Continually updated national classification schemes should be more appropriate for a country or region than an international scheme. As soils do not have genes and cannot inherit properties there is a strong tendency for soils to be unique. Thus national schemes are unlikely to be an effective means of international transfer of agrotechnology. While there appears to be a simultaneous need for national schemes and an international one, concern was shown at the proliferation of national systems, which make it more difficult to transfer knowledge among countries. There was the opinion that national scientists should compromise and accept international systems though it may still be true that a strong and effective international scheme depends on the existence of strong, effective national classifications. For Soil Taxonomy to develop into an effective international scheme it is probably best if nations use it in their soil survey programs, thus defining proposals for its improvement as has been done, for example, in Thailand. It may be most appropriate if proposals for change are referred to an international committee for final ratification.

Although the units of the FAO-UNESCO Soil Map of the World legend have been used for classification and agrotechnology transfer, the system is not a classification but a legend for small scale mapping. It is not comparable with Soil Taxonomy, which is a classification system, not a legend.

Soils artificially created by man present classificatory problems in Soil Taxonomy. Though every soil in the world can be classified, the argument is not so much whether soils can

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be classified or not but whether they can be better classified. If sub-families are to be introduced into Soil Taxonomy, permanent properties of the soil should be used rather than transient properties.

Australia is putting a lot of effective effort into soil science though it has not, until quite recently, used internationally recognized classification systems for identifying soils. The rest of the world would benefit from Australian soil scientists using internationally recognized systems such as Soil Taxonomy. CSIRO and the Queensland Department of Primary Industries, in their soil survey programs, are now identifying their soils in the categories of Soil Taxonomy. ACIAR could provide funds to provide greater Australian input into SMSS to ensure greater Australian involvement.

There is a real need for clearer, unambiguous, more straightforward English in *Soil Taxonomy*. A description of the intent of some complex definitions would be very useful to users.

Session 3

Nutrient Availability in Acid Soils of the Humid Tropics

Chairman: R.A.D. Jones
Discussion Leader: D.G. Edwards

Nutrient Availability in Acid Soils of the Tropics Following Clearing and Cultivation

G.P. Gillman*

When well-drained, highly weathered tropical soils are cleared of protective cover, particularly rainforest, and brought under cultivation, their physical, chemical, and biological properties are profoundly affected. This paper deals with one aspect of the chemical changes that can occur, namely surface charge properties, and attempts to show how a more complete understanding of these properties can facilitate the allocation of soils into separate groups for research and management strategies.

The assessment of the fertility status of soil is often biased in favour of nitrogen, phosphorus, and potassium content because these macronutrients are used in relatively large amounts. Two other macronutrients, calcium and magnesium, have not always received so much attention, as many soils, particularly in the world's temperate regions, are well supplied with these nutrients. With the advent of increasing research on highly weathered tropical soils, it is now realized that the well-drained, kaolinite and/or oxide dominant soils of the tropics can rapidly become deficient in calcium, magnesium, and potassium when brought into crop production, and increasing effort is being directed towards finding ways of alleviating this problem.

Consider the data in Table 1 that refers to an agronomically important north Queensland soil formed on basalt and that is classified as a Haplic Acrorthox (Soil Survey Staff 1975). The exchangeable cation content of a rainforest site is compared with that of a nearby site that has been cleared for 50 years, and planted to sugarcane for the past 17 years. Under rainforest, modest amounts of cations are present in the 0–15 cm depth only, whereas the cultivated site is practically devoid of cations throughout the profile although it is known that 390 kg Ca/ha and 1230 kg K/ha had been applied over the 7 years prior to sampling. One objective of this paper is to explain the above observations in terms of classical chemical theory using a simple, semi-quantitative model of the relationships between exchangeable cations and the soil particle surface. A further objective is to demonstrate how prediction of soil behaviour should be improved if appropriate characterization methods are used in the laboratory.

Theory

The term 'variable charge soil' is now firmly established in the literature. It refers to a soil in which a significant portion of charge on the particle surfaces, responsible for cation retention, is dependent upon the pH, concentration, and composition of the solution in contact with those surfaces. The surface charge is variable because protons are able to dissociate from or associate with surface functional (principally hydroxyl) groups to produce negative and positive charge respectively, as the solution conditions are changed. The functional groups are situated on the edges of kaolinite and on oxide surfaces, i.e. minerals that are residual following extreme weathering, and that are ubiquitous in the humid tropical environment. Another important source of variable charge is soil organic matter in which protonation/deprotonation reactions can occur on functional groups.

Van Raij and Peech (1972) successfully used the classical theory of the electrical double layer to explain the surface charge characteristics of some Oxisols and Alfisols from Brazil. This study was the catalyst for confirmatory studies around the world proving the general applicability of Gouy-Chapman theory, at least qualitatively, to highly weathered soils. The development of more complex models, e.g. Bowden *et al.* (1977), may lead to a more accurate prediction of experimental findings, at least for pure oxide systems, but the author believes that a simple model containing a minimum number of variables is adequate and

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Table 1. Exchangeable cation content and other relevant data for a Haplic Acrorthox under rainforest and under nearby sugarcane in north Queensland.

Depth (cm)	Ca	Mg	K	Na	H+Al	pH	Org. Matter (%)	Clay (%)
	(m equiv./100 g soil)							
Rainforest								
0–15	2.0	1.2	0.28	0.10	0.6	5.1	8.8	74
15–30	0.4	0.3	0.12	0.06	0.4	4.9	5.0	67
30–60	0.3	0.2	0.05	0.03	0.3	4.8	3.1	66
60–90	0.2	0.1	0.03	0.04	0.2	4.8	1.5	69
Sugarcane								
0–15	0.3	0.1	0.08	0.02	0.7	4.6	3.6	62
15–30	0.1	0.1	0.05	0.01	0.4	4.5	2.6	62
30–60	0.1	0.1	0.03	0.01	0.2	4.6	1.5	64
60–90	0.1	0.1	0.01	0.01	0.2	4.7	1.0	71

more convenient for explaining the cation retention properties of whole soils.

The Gouy-Chapman equation, which relates net charge in the electrical double layer, and hence surface charge σ_o, to the surface potential ϕ_o, is

$$\sigma_o = \left(\frac{2n\,\varepsilon\,kT}{\pi}\right)^{1/2} \sinh\frac{ze\phi_o}{2kT} \qquad \ldots (1)$$

where n is the concentration of electrolyte solution of dielectric constant ε, z is the counterion valency, e is the charge of an electron, k is the Boltzmann constant, and T the absolute temperature.

The surface potential ϕ_o, of an hyroxylated surface, where protons are potential-determining ions, can also be described by the Nernst equation

$$\phi_o = \frac{kT}{e}\ln\frac{a_{H^+}}{a^o_{H^+}} \qquad \ldots (2)$$

where a_{H^+} is hydrogen ion activity and $a^o_{H^+}$ is the activity when ϕ_o is zero.

Equations (1) and (2) can be combined, and hydrogen ion activity can be expressed as pH to produce the equation

$$\sigma_o = \left(\frac{2n\,\varepsilon\,kT}{\pi}\right)^{1/2} \sinh 1.15z\,(pH_o - pH) \qquad \ldots (3)$$

where pH_o is the pH where net surface charge is zero.

This equation tells us that the sign of the net charge on a variable charge surface where protons are the potential-determining ions can be positive, zero or negative, depending on the pH relative to pH_o. Furthermore, once the sign of the surface charge is fixed by pH, its magnitude is governed by the absolute difference between pH and pH_o, and by the concentration and composition of the equilibrium electrolyte solution.

Equation 3 is illustrated graphically in Figure 1, and qualitative agreement between these theoretical curves and experimental curves for whole soils may be found for instance in van Raij and Peech (1972), Keng and Uehara (1974), Gillman (1974), Espinoza *et al.* (1975), Gallez *et al.* (1976), and Gonzales-Batista *et al.* (1982).

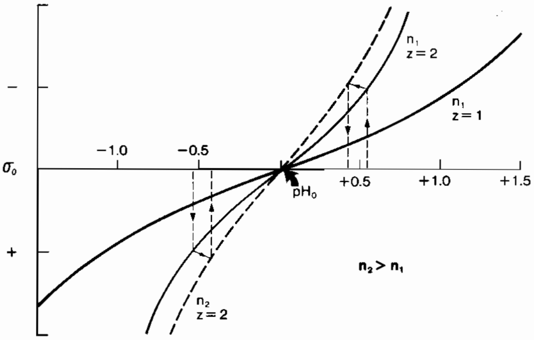

Figure 1. The effect of pH, electrolyte concentration, and valency, on the surface charge of an oxide surface.

Although soils composed entirely of variable charge components exist, it should be more usual to find highly weathered soils which consist of a mixture of variable and permanent charge components. The latter acquire their surface charge from substitution of an ion in the crystal lattice by an ion of unequal charge. The total net surface charge in a soil, σ_T, may be represented as

$$\sigma_T = \sigma_P + \sigma_V \qquad \ldots (4)$$

where P and V refer to permanent and variable, respectively.

A model for mixtures of variable and permanent charge components proposed by Uehara and Gillman (1980) suggests a method for measuring the magnitude of charge contributed by each component. If the zero point for the variable charge components, pH_0, can be located, this is the pH where these components have equal amounts of negative and positive charge. The total surface charge can then be measured at this pH, and an excess of negative or positive charge will be the net permanent charge.

Application of Theory to North Queensland Soils

For the soils referred to above (Table I), pH_0, σ_P and the distribution of negative and positive charge with pH at an ionic strength of approx. 0.006 have been determined for each of the eight soil samples. Results are summarized in Table 2, and charge curves for the 0–15 cm and 60–90 cm samples from each location are presented in Figure 2.

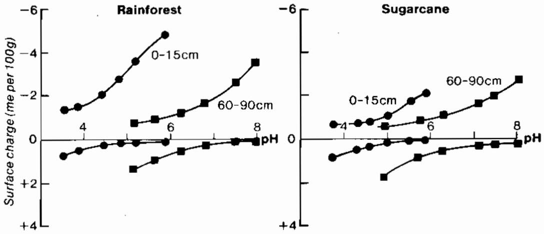

Figure 2. Negative and positive charge curves for 0–15 cm and 60–90 cm samples of north Queensland Haplic Acrorthox under rainforest and under nearby sugarcane.

In the surface rainforest sample, there is about 1 m equiv. per 100 g of permanent charge, but pH_0 has a relatively low value and the difference between soil pH and pH_0 is 1.3 units. Thus at soil pH (5.1) surface negative charge is 3.5 m equiv. per 100 g and this corresponds to the sum of basic cations that were present under field conditions. With increasing depth in the profile, even though there is little change in soil pH, pH_0 values move steadily up the pH range, hence negative surface charge on the variable charge components decreases while positive charge increases. Thus even though there is about 1 m equiv. per 100 g of permanent charge at depth, repulsion of cations by positively charged surfaces reduces the cation retention capacity to values lower than the permanent charge.

In the surface 0–15 cm cultivated soil, soil pH is less and pH_0 is greater than the corresponding rainforest soil, and soil pH is less than pH_0 throughout the profile under cultivation. Thus with little permanent charge in the upper horizons, and relatively large amounts of

Table 2. Surface charge characteristics of a north Queensland Haplic Acrorthox.

Depth (cm)	Soil pH	pH_0	σ_P	Neg. charge at soil pH	Sum basic cations
			m equiv./100 g		
Rainforest					
0–15	5.1	3.8	−0.9	3.5	3.6
15–30	4.9	4.9	−0.7	1.0	0.9
30–60	4.8	6.1	−1.7	0.6	0.6
60–90	4.8	6.7	−1.2	0.5	0.4
Sugarcane					
0–15	4.6	4.7	−0.5	0.7	0.4
15–30	4.5	5.7	−1.0	0.4	0.2
30–60	4.6	6.5	−1.1	0.4	0.2
60–90	4.7	6.8	−1.1	0.4	0.1

positive charge at depth, the whole profile has little capacity to retain nutrient cations.

An inspection of Figure 2 shows that the charge curves for surface and subsurface soils are roughly parallel (some allowance has to be made for permanent charge), and this illustrates the importance of the position of the zero point, pH_0. Obviously, a low value for pH_0 is necessary if this soil is to possess a significant amount of negative charge, i.e. cation exchange capacity. Iron oxides have pH_0 values in the region 7–9 and since the soil in question has a dithionite extractable Fe_2O_3 content of about 20% throughout the profile, this explains the pH_0 values measured at 60–90 cm depth. At shallower depths, increasing amounts of organic matter (which has a low pH_0) causes the overall soil pH_0 to shift to lower values. The striking influence of organic matter on pH_0 for a number of surface and subsurface samples of the same soil series is depicted in Figure 3.

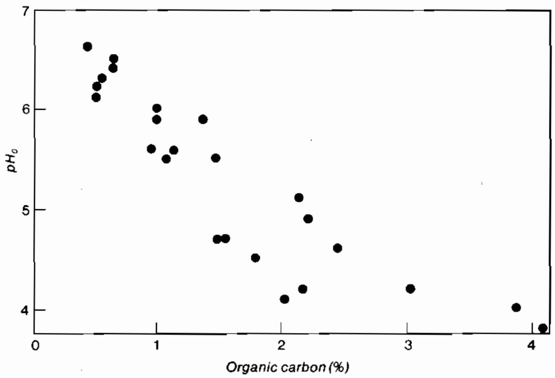

Figure 3. Relationship between organic carbon content and pH_0 for red basaltic soils in north Queensland.

It was mentioned above that negative and positive charge curves were determined at ionic strength of about 0.006. This was accomplished by measuring the adsorption of Ca^{2+} and Al^{3+}, and Cl^- from a 0.002M $CaCl_2$ solution. Earlier studies (Gillman and Bell 1978) showed that the soil solutions of highly weathered soils in north Queensland have an ionic strength of about 0.006. Since the dominant cations in these soils are usually divalent, the use of 0.002M $CaCl_2$ to measure the soil's capacity to retain nutrient cations meets the n and z requirements of equation 3.

Thus a relatively simple characterization of surface charge properties, based on classical chemical principles, is able to explain the low exchangeable basic cation content of this highly weathered soil, but more importantly, an understanding of the system should point to management strategies aimed at the most efficient utilization of such soils. This approach is in contrast to the more usual assessments of charge where inappropriate solution conditions in the laboratory often result in CEC values that are not relevant to the field situation.

Work currently in progress at Townsville is aimed at separating the soil of the wet coastal zone into management groups based on their charge characteristics. The limited number of analyses to date show that charge variation with pH, as illustrated in Figure 2 for a basaltic soil, may also be found with soils formed on granitic and metamorphic parent material though the latter usually have more permanent negative charge and very little positive charge. Examples of soils from the three types of parent material are depicted in Figure 4. We cannot assume,

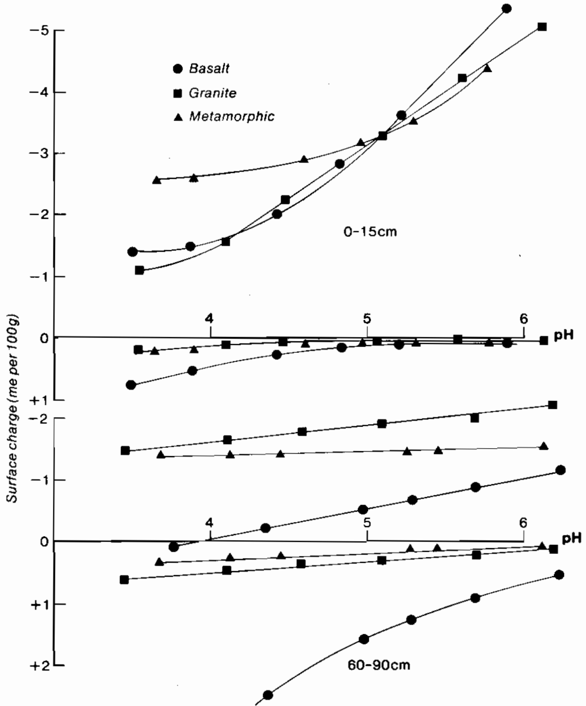

Figure 4. Surface charge curves for three north Queensland soils occurring on basalt, granite, and metamorphic parent material.

however, that the three soils will require the same management strategy because of the similarity in their charge curves in the surface horizons. As explained above, pH_0 value of the basaltic soil is dependent upon organic matter content, but the data in Table 3 show that this is not the case for soil formed from the other two parent materials. Though no clay mineralogical analyses for these samples are yet available, it may be assumed from the analyses of other profiles in the region that the three soils are kaolin dominant, with the basaltic soil also having significant amounts of haematite and goethite while the granitic and metamorphic soils have some vermiculite and interstratified chlorite respectively. The latter two soils have low amounts of free iron oxide (about 2%) compared with about 20% for the basaltic soil. It is the high oxide content that sets the soil formed on basalt apart, and it is clear that if they are to have a significant cation retention capacity, their organic matter contents should be carefully preserved. Such considerations further strengthen the contention that a firm understanding of the causes of charge variation in highly weathered soils should lead to better fertility management and transfer of results between locations.

Problems Associated with Soil Acidity

The concept of soil pH, and its measurement, has exercised the minds of many eminent soil scientists over the years. In fact, it is still not at all clear what is being measured when a glass electrode is placed in a soil suspension and its potential relative to a calomel electrode is recorded. This uncertainty should make the standardization of pH measurements in soil all the more imperative if results from various sources are to be collated.

It is generally true that most soils of the humid tropics are acid, with pH values of less than 6 (Sanchez 1976), and soil pH values between 4 and 5 are commonly reported. When rainforest is felled and burned, incorporation of ash into the surface horizons results in a pH increase, but if leaching occurs and/or ammonium fertilizers used, pH values can fall, as instanced in Table 1.

Based on temperate region experience, a clay soil with pH less than 5 would be expected to contain large amounts of exchangeable Al and would require an appreciable amount of lime for good plant growth. However, the amounts of H + Al extracted with 1 M KCl from the Acrorthox (Table 1) are quite low for a soil with a clay content of over 60% and with pH values between 4.5 and 5.0. From the data in Table 3, it appears that the amount of H + Al extracted is very dependent upon the pH of the KCl extractant after it has interacted with the soil. (Actually the amounts of H in the extract would be negligible at these pH values, so that H + Al is really Al). It is well known that Al is quite insoluble in water between pH 5 and pH 7, so that as pH_{KCl} increases towards pH 5, H + Al decreases. Theory helps us to explain the variation in pH_{KCl} between the different soil samples. With reference to Figure 1 (dotted lines), if soil pH $>$ pH_0, solution pH will decrease when the ionic strength is increased, and this is the case with the 0–15 cm basaltic sample and all granite and metamorphic samples. However, if soil pH $<$ pH_0, solution pH will increase with increasing ionic strength, and this explains the low H + Al values recorded for the subsoils of the basaltic sample. At equal values of pH_{KCl}, differences between samples reflect the amount of surface negative charge and its degree of occupation by basic cations, the presence of Al compounds that may be solubilized, as well as Al bound to organic matter.

Table 3. Selected data for three virgin highly weathered soils from north Queensland.

	Acrorthox on basalt					Tropudult on granite					Acrorthox on metamorphics				
Depth (cm)	OM	pH_0	Soil pH	pH_{KCl}	H+Al	OM	pH_0	Soil pH	pH_{KCl}	H+Al	OM	pH_0	Soil pH	pH_{KCl}	H+Al
0–15	8.8	3.8	5.1	4.9	0.6	4.7	3.6	5.5	5.2	0.2	5.9	3.7	4.7	4.3	1.7
15–30	5.0	4.9	4.9	5.0	0.4	1.9	4.2	5.2	4.9	0.3	3.2	4.2	4.8	4.5	1.4
30–60	3.1	6.1	4.8	5.2	0.3	1.2	4.2	5.0	4.8	0.5	1.7	4.3	4.7	4.5	1.2
60–90	1.5	6.7	4.8	5.5	0.2	0.6	4.2	4.7	4.6	1.0	0.7	4.4	4.6	4.5	1.2

The data in Table 2 indicates that not all of the H + Al extracted might be exchangeable, since the amount of negative charge is accounted for by the basic cations extracted. Amedee and Peech (1976), when examining Oxisols and Ultisols from Brazil and Puerto Rico, reached a similar conclusion when they found that the cumulative amount of Al obtained by exhaustive extraction with KCl was dependent upon KCl concentration. Their explanation is consistent with predictions based on equation 3, viz. that if pH $>$ pH_o, an increase in n will cause an increase in σ_o that is accomplished by a release of potential-determining ion (H^+) from the surface. The increased solution acidity then dissolves aluminium hydroxides present in the soil. Amedee and Peech (1976) found that for successive extractions, (pH-⅓ pAl) was constant and close to 2.8, indicating that aluminium hydroxide solubility was controlling solution Al.

The damaging effect of toxic levels of Al in soils, indicated by poor and distorted root development, has been well documented (e.g. Sanchez 1976). In some studies however, yield depression has been associated with Al toxicity when it is possible that Ca deficiency may also have been implicated. In highly weathered soils, relatively high KCl-extractable Al values are usually associated with low exchangeable Ca. The development of acidity results in a lowering of negative charge with a concomitant loss of exchangeable Ca and also in the bringing into solution of Al that may or may not become associated with the charged surface. Since plants are not able to translocate Ca to the root tip, this element must be continuously supplied by the soil at the root growing point if roots are to develop normally (Bangerth 1979).

In an examination of several major soils of the Coastal Plain of the southeastern USA, Adams and Moore (1983) were able to separate the effects of Al toxicity and Ca deficiency by studying growth and appearance of primary roots of cotton growing in acid soils treated with either $CaSO_4$, MgO, or $Ca(OH)_2$. Calcium deficiency was found to be more widespread than anticipated and occurred in soil horizons where Ca saturation (Ca expressed as a percentage of all exchangeable ions including KCl Al) was 17% or less. Visual aluminium toxicity symptoms were also widespread, but the authors were not able to relate measured chemical properties to Al toxicity. They did however, find that Al stress occurred only in eluvial and not in illuvial horizons despite much higher Al concentrations in the latter. They suggested that solution Al in illuvial horizons is chelated to organic matter and poses no problems to plants. Using Oxisols and Ultisols from Brazil, Pavan *et al.* (1982) showed that the Al^{3+} species in soil solution, as distinct from complexed Al such as $AlOH^{2+}$ or $AlSO_4^{+}$, was responsible for reduction in growth of coffee seedlings.

The obvious management practice for alleviating the effects of soil acidity is lime application. Practical experience has shown that some highly weathered soils require large lime inputs to raise soil pH even to pH 6, and that the effect is relatively short lived. Gillman (unpublished) applied portland cement at the rate of 5 t/ha to an Acrohumox in north Queensland and raised soil pH from 5.0 to 6.2. Two years later, after 7 820 mm of rain had fallen, and after N fertilizer application, which may have been as much as 1 000 kg N/ha, pH had reverted to 4.9. The current cost of lime is such that the reasons for using it need to be fully understood in order to obtain the maximum benefit from the minimum necessary application.

Several factors need to be considered when estimating the lime requirement of highly weathered soils. Firstly, the soil pH has to be raised to a level where soil solution Al, other than that complexed to organic matter, is reduced to a very low level (Adams and Moore 1983). Kamprath (1980) suggests that the KCl extractable Al value should be the criterion for lime application, but acknowledges that more lime is necessary than its chemical equivalent. In fact, some soils require three times the Al equivalent. This is because variable charge soils will neutralize added base by deprotonation in addition to the Al precipitation reactions. Deprotonation of hydroxy groups is desirable if the negative charge is low, since the additional negative charge generated is needed for retention of nutrient cations such as Ca, Mg, K, and NH_4. Hence the creation of surface negative charge, or cation exchange capacity, is the second factor in lime application.

A third consideration is the volume of soil to which lime should be mixed. Since Ca has to be supplied at the actual growing tip of a plant root, soil Ca has to be distributed through the whole soil volume in order to obtain good root proliferation. This then allows maximum exploitation of soil water and other soil nutrients. Ritchey *et al.* (1980) have demonstrated the practical advantages of applying lime in conjunction with ordinary superphosphate to Brazilian Oxisols. The combination was particularly successful in causing calcium to leach to depths that would greatly expand root growth. In a subsequent paper, Ritchey *et al.* (1982) showed that correction of Ca deficiency is far easier than having to correct Al toxicity at depth and we need to delineate the high Al soils with low Ca, from those that are low in both Ca and Al.

Fourthly, one has to consider the effects on other exchangeable cations when liming a variable charge soil. If calcium carbonate is applied to a soil that is only marginally supplied with Mg and K, the additional charge developed will be saturated with Ca and an imbalance created. The use of dolomitic limestone will alleviate a Mg deficiency, but applied K could be a poor competitor for exchange sites. Magdoff and Bartlett (1980), however, showed that even though lime addition to a Spodosol caused a selectivity for Ca over K, there was sufficient 'pull' on solution K by the increased CEC to greatly reduce solution K. They calculated that 500 kg K/ha would have to be added if this soil were limed to pH 6. The fate of applied K to limed variable charge soils would be a fruitful area of research.

Finally, the acidifying effects of applied NH_4-N need to be taken into account. Since the majority of highly weathered tropical soils are acid, nitrification rates might normally be relatively slow. Ironically, the addition of lime to a soil to which NH_4-N has also been added could promote nitrification and hence produce acidity, requiring more lime for neutralization.

Conclusion

Attempts to manage the cation chemistry of highly weathered soils from humid tropical regions must be based on as good an understanding of the processes controlling cation retention in these soils as current research permits. There is sufficient evidence now to show that these soils have low amounts of surface negative charge even in an undisturbed state, and that poor management can exacerbate this condition. Inappropriate laboratory characterization in the past masked the cause of their extreme cation poverty, but in the light of recent research, this situation need not continue. Laboratory characterization similar to that outlined in this paper, to identify those soils that would be considered to be chemically fragile, should be a necessary prerequisite to any cation management studies.

For soils that derive most of their negative charge from the organic matter present, great care should be taken to minimize organic matter loss if uncleared sites are being brought into production. Management strategies for conserving organic matter would make a profitable area of research, and the approach advocated by von Uexkull (1982) employing minimum topsoil disturbance during land clearing and keeping the soil continually covered is a good example of thoughtful manipulation of soil properties. Where soil organic matter has already been diminished by clearing and cultivation, strategies that make optimum use of applied cations especially in the presence of other fertilizers such as N and P need to be devised to minimize losses through leaching, and at the same time permitting controlled transfer to the full rooting depth.

The results of field trials that demonstrate the leaching of nutrients through, or the effects of amendments on, highly weathered tropical soils would be better understood and would have more widespread applicability if appropriate laboratory measurements were carried out in conjunction with the trials.

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E. Pushparajah* Discussant — 1

Nutrient Availability in Acid Soils of the Tropics following Clearing and Cultivation with Plantation Crops

Hevea brasiliensis, or rubber, plays a fairly important role in the agricultural sector in South East Asia, particularly in Malaysia, Indonesia, and Thailand. In other countries, e.g. India, People's Republic of China, Ivory Coast, Brazil etc., there is a continuing expansion in the area under rubber. As *Hevea* is an acid-loving tropical plant, the acid soils in the tropics form an ideal environment for this crop. Generally, these soils are low in nutrients and therefore in almost all rubber growing areas, N, P, K and at times Mg fertilizers are applied (Pushparajah 1983). As the rubber plants are established in rows (generally on a spacing of 2–3 m along rows and 7–10 m between rows, giving a density of 450–600 trees/ha), the fertilizers are applied on the tree rows on a strip extending to about 1 m on either side of the trees. The interrow space has various vegetation.

This paper considers changes in soil pH, carbon, nitrogen, and cations with time; both in the interrow areas where no fertilizers are used and in the tree rows where fertilizers are applied.

Changes in Nutrient Status in the Interrow

In converting a forest into plantation agriculture, or in replanting existing plantations, the area is felled, the timber removed and the residue of stumps, branches etc. is burnt. In an experiment initiated in **1959**, all debris including stumps, unburnt branches etc. was removed and different cover conditions established (Watson *et al.* 1964). Initially there was a dramatic change in the pH with bare plots showing a rapid decrease in pH (Table 1). However, with time the difference in the pH between the different cover conditions became negligible.

The establishment of legume covers led to an increase in the percentage carbon over the initial burnt area by the second year. In the sixth year, a decline in carbon content was observed but by the sixteenth year, the percentage carbon under legume cover had increased (to 1.31%) and was similar to the carbon present at the time of planting of covers (i.e. 1.39%). On the other hand, where the ground vegetation was kept bare, there was a rapid deterioration of carbon and a very low level of 1.01% was observed at 16 years after initiation of the different treatments.

The influence of cover condition was also reflected in the nitrogen content in the top soil. The level of nitrogen under the bare plots declined very rapidly and remained at a very low level of 0.09–0.11%, very much less than that observed at the commencement. On the other hand, where a cover was established, the nitrogen levels increased in the initial years, but declined with time and were higher than under bare conditions.

The levels of exchangeable Ca, Mg, and K were generally maintained at a higher level when covers were present. However, with time and the fading out of the covers due to shading by the closure of the canopy of rubber, a rapid decline in these exchangeable cations was observed even under the different covers. Nevertheless, the levels found in the soils under different covers were still significantly higher than under bare conditions. These levels were below the levels considered satisfactory for good performance of rubber.

Effect of Fertilizer Application on Soil

In rubber cultivation, fertilizer containing N as ammomium sulphate, P as rock phosphate, and K as potassium chloride is commonly used. Pushparajah *et al.* (1976) investigated the long term effects of fertilizers on different soils under rubber. The applications of N as ammonium sulphate at the rates used, reduced pH on most

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Table 1. Changes in soil (0–15 cm depth on a Typic Paleudult) under different covers with time.

	pH (water)			Carbon (%)				Nitrogen (%)			
Covers[a]	3	6	10	3	6	10	16	3	6	10	16
Legume	4.70	4.50	4.63	1.73	1.55	1.39	1.31	0.142	0.141	0.117	0.143
Grass	4.75	4.62	4.65	1.64	1.47	1.44	1.31	0.125	0.123	0.119	0.131
Naturals	4.73	4.62	4.63	1.55	1.35	1.20	1.11	0.128	0.118	0.107	0.126
Bare	4.28	4.50	4.57	1.36	1.32	1.16	1.01	0.107	0.106	0.092	0.110
Min. 5% sig. diff.	0.23	0.17	0.05	0.25	0.24	0.20	0.23	0.020	0.026	0.019	0.024
Control: year 0		4.73			1.39				0.130		
: under forest		4.40			1.86				0.163		
	Exchangeable Ca (m. eq/100g)			Exchangeable Mg (m.eq/100 g)				Exchangeable K (m.eq/100 g)			
Legume	0.430	0.125	0.085	0.213	0.093	0.065	0.308[b]	0.173	0.070	0.058	0.180[b]
Grass	0.560	0.198	0.098	0.235	0.103	0.062	0.310[b]	0.125	0.062	0.056	0.178[b]
Naturals	0.615	0.166	0.113	0.300	0.148	0.070	0.335[b]	0.195	0.087	0.053	0.180[b]
Bare	0.283	0.100	0.070	0.083	0.075	0.045	0.280[b]	0.055	0.050	0.040	0.160[b]
Min. 5% sig. diff.	0.233	0.178	0.038	0.112	0.103	0.013	0.056	0.054	0.044	0.012	0.035
Control: year 0		0.24			0.18				0.11		
: under forest		0.44			0.13 (0.65)[b]				0.10 (0.41)[b]		

Note: The values 3, 6, 10, 16 refer to the year after inception of the trial. Data for year 3 from Watson *et al.* (1964).

a. Legumes — mainly *Pueraria phaseoloides* and *Centrosema pubescens*; Grass — mainly *Ischaemum timorense* and some *Ottochloa nodosa*; Naturals — *Tremma, Hornstedtia, Solanum, Macaranga* etc.

b. 6N HCl extractable values.

soils by about 0.4–0.5 units. However, the percentage carbon was increased in most cases. This increase in percentage carbon was ascribed to the large turnover of leaf litter from the rubber trees receiving N. At the same time, the N applied as ammonium sulphate resulted in a reduction in exchangeable cations K, Mg, and Ca (Table 2). Such reductions were more noticeable in soils that had relatively high levels of these exchangeable cations, i.e. about 0.20 m equiv./100 g soil and above.

Applications of P as rock phosphate increased pH by 0.1–0.3 units and at the same time, increased the acid extractable and exchangeable calcium in the soils (Table 3). Where both ammonium sulphate and rock phosphate were

Table 2. Effect of nitrogenous fertilizers on pH, carbon, and exchangeable cations in surface soil (0–15 cm)[a].

Soil	Duration of trial (yrs)	Rate (kg/ha) and type of fertilizer[b]	pH (water)	C %	Exchangeable cations (m.equiv.%) K	Mg	Ca
Plinthic haplorthox	12	nil	4.6	1.66	0.33	0.17	0.56
		9 690 A/S	4.2	1.75	0.28	0.14	0.49
		19 380 A/S	4.1	1.81	0.27	0.11	0.30
		L.S.D. ($P < 0.05$)	0.07	0.19	0.03	0.03	0.22
Typic paleudult	14	nil	4.6	1.22	0.12	0.06	0.17
		9 765 A/S	4.3	1.38	0.12	0.06	0.16
		3 650 Urea	4.5	1.29	0.13	0.05	0.16
		L.S.D. ($P < 0.05$)	0.06	0.13	0.02	0.01	0.08
Typic sulfaquept	11	nil	4.2	2.67	0.36	0.41	0.56
		5 700 A/S	3.8	3.37	0.29	0.17	0.38
		2 880 Urea	4.1	3.14	0.32	0.32	0.48
		L.S.D. ($P < 0.05$)	0.08	0.53	0.04	0.04	0.21

a. After Pushparajah *et al.* (1976).

b. Actual rate per ha is low but as application is concentrated on strips, effective rates appear high.

A/S = ammonium sulphate (21% N); Urea (46% N).

Table 3. Effect of phosphates on pH, soluble phosphate, and calcium in surface soil (0–15 cm)[a].

Soil	Duration of trial (yrs)	Rate (kg/ha) and type of fertilizers[b]	pH (water)	Soluble P[c] (ppm)	Calcium (m.equiv.%) Acid extractable	Exchangeable
Plinthic haplorthox	12	nil N or P	4.57	6	0.50	0.22
		4 845 R/P	4.64	84	2.24	0.32
		19 380 A/S	4.04	5	0.47	0.10
		4 845 R/P + 19 380 A/S	4.14	111	2.14	0.18
		L.S.D. ($P < 0.05$)	0.13	37	1.07	0.38
Typic paleudult	14	nil	4.4	7	0.15	0.08
		5 775 R/P	4.6	114	1.28	0.29
		5 355 S/P	4.4	152	0.16	0.11
		L.S.D. ($P < 0.05$)	0.1	25	0.22	0.08
Typic sulfaquept	11	nil	4.0	34	1.2	0.22
		3 680 R/P	4.1	150	3.0	0.77
		L.S.D. ($P < 0.05$)	0.08	49	0.81	0.21

a. After Pushparajah *et al.* (1976).

b. A/S = ammonium sulphate; R/P = rock phosphate (34.5% P_2O_5), and S/P = superphosphate (37% P_2O_5).

c. By Bray's No. 2 method.

applied together, the effects were intermediate. Where triple superphosphate was used, there was hardly any effect on pH or on soil calcium. However, where either form of P was used, there was a considerable build-up of both as a strong acid extractable P (total P) and soluble P (Bray's No.2). Pushparajah *et al.* (1977) showed that where superphosphate was used, a large fraction of the P was fixed as aluminium P, particularly in the surface 0–7.5 cm. On the other hand, where rock phosphate was used, a large fraction was in the Ca-P fraction. A relatively large proportion of the P was also in the Fe-P fraction when either form of fertilizer was used. A large portion of the residual P is available both to the legume cover crop as well as to the stands of rubber (Pushparajah *et al.* 1977).

The use of K generally gave transient increases in exchangeable K on most soils. However, on soils with some 2:1 clays, particularly the Typic Sulfaquepts and the Typic Plinthudults derived from argillaceous shale, continued use of K resulted in a build-up of both acid extractable and exchangeable K.

Discussion and Conclusion

The inherent fertility status of Malaysian soils is low (Guha and Yeow 1966; Law and Tan 1977). The clearing of forests for agriculture leads to rapid deterioration in the carbon, nitrogen, and exchangeable cations. The practice of establishing covers in the interrow areas arrests these processes. Covers return organic matter and thus increase the carbon and nitrogen content of the soil. In fact, in the early years of establishing covers, they increase the content of exchangeable cations in the surface soils possibly by absorbing nutrients from lower depths and cycling them to the top.

With time, however, there is also a depletion of nutrients even in areas that had a cover initially, though the levels are higher than where no covers were maintained. This decrease could be due in part to the loss in leaching, but is more likely due to the uptake and immobilization in the trees. Pushparajah and Tajuddin Ismail (1982) showed that by the sixteenth year of establishment of rubber, uptake by the rubber trees is about 900–1000 kg K/ha. The drop in the content of exchangeable K from 0.173 to 0.058 m equiv. in the 0–15 cm soil would account for just over 100 kg K/ha. If this is projected to a soil depth of 0–45 cm, supply would have been about 320 kg K/ha (assuming soil weight at 6.76×10^6 kg/ha and a bulk density of one). Similarly, the changes in the other nutrients can be accounted for by the crop.

On the other hand, the depletion in the bare plots was evident within two to three years of clearing and was possibly due to leaching losses.

Where fertilizers are applied, as expected, there are changes in soil nutrient status. In particular, ammonium sulphate adversely affects pH and exchangeable cations. However, phosphate in most soils is low and application of P fertilizers is needed. For *Hevea*, rock phosphate (with about 10% citric soluble P_2O_5) was equally as efficient as soluble phosphates (Pushparajah *et al.* 1974). Rock phosphate, being cheaper, is therefore the preferred source. Subsequent investigations (Pushparajah *et al.* 1977) showed that the residual value of P from rock phosphates was larger. The use of rock phosphate (often containing about 40% CaO) has also been found to reduce the deleterious effects of ammonium sulphate on soil pH and exchangeable cations.

However, continued use of phosphates during the first few years of planting of rubber, results in a build-up sufficient to satisfy the trees' needs in subsequent years. Continued use could result in adverse effects due to the excess Ca from the phosphate (Pushparajah 1966). On the other hand, discontinuing the use of calcium-containing fertilizer would lead to adverse effects on soil pH and exchangeable cations. Such efforts may be reduced by the use of urea in place of ammonium sulphate. However, in rubber cultivation where fertilizers are applied by broadcasting, the volatilization loss of N is high and the efficiency of urea in promoting growth and yield of rubber is low (Pushparajah *et al.* 1982). Investigations on encapsulation of urea with NR latex shows promise for reducing losses and improving efficiency (Soong *et al.* 1976).

Finally, research on the basic chemistry of Malaysian soils should be considered. Zulkifli (1981) has used a plot of pH against concentration dependent hydrogen (CDH) to characterize the pH-charge relationship in the soil. The cross-over point at the pH axis was termed zero net concentration dependent hydrogen (PZCH). This pH was found to be almost equal to point of zero net charge (PZNC) or commonly termed point of zero charge. pH H_2O registered values either slightly higher or lower than PZCH; the difference between these two was narrow at 0.35 to −0.2 pH units. Based on this finding, it has been suggested that pH H_2O could form a simple test to monitor changes in soil surface charges.

Nevertheless, for the maintenance of long-term fertility of soils under rubber, it is essential to establish a legume cover on clearing of the land. There is an urgent need to use less acidifying nitrogenous fertilizer to minimize deleterious effects on soil pH and exchangeable cations.

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P.A. Sanchez* Discussant — 2

Nutrient Dynamics Following Rainforest Clearing and Cultivation

Changes in the availability of soil nutrients in acid soils of the humid tropics after land clearing and cultivation depend mainly on sampling methodology employed and on the following factors: soil properties, land clearing method, and post clearing soil management.

Methodology

The two main sampling procedures used are: sampling the same site with time, and sampling nearby areas with known history at the same time. The first procedure is the preferred one as it truly measures dynamics, while the second confounds time and space variability. Unless an extremely detailed morphological characterization indicates that the soils are identical, it is dangerous to assume that the differences encountered between an undisturbed forest site and a nearby cultivated field of known age are due to the effect of cultivation. In fairly uniform areas the confounding of time and space variability may be less, but one should be absolutely sure that the soils belong to the same series, type, phase, and landscape position and that this is demonstrated by morphological characterization including particle-size distribution and color changes with depth. The main factors affecting nutrient dynamics are:

1. Soil Properties
   In general, the higher the original value of a parameter, the faster it is going to change upon land clearing. A good example is Bram's (1971) work in Sierra Leone where he measured a faster drop in organic matter in a soil that had 4% organic C than in one with only 1.5% organic C.
2. Land Clearing Methods
   Considering the generally low level of nutrients in undisturbed soils of the humid tropics, measuring nutrient dynamics could be quite boring except for the changes imposed during the land clearing process. If burning is involved, considerable amounts of nutrients are added to the soil as ash. If bulldozing is involved, part of the topsoil is carried away and serious compaction can take place (Seubert *et al.* 1977; Couper *et al.* 1982). The amounts of ash fall are quite variable (Smyth *et al.* 1982) and its composition often depends on individual tree species (Silva 1981). Table 1 shows some differences in ash composition of an Ultisol of Yurimaguas, Peru, and an Oxisol in Manaus, Brazil.
3. Post Clearing Management
   The effects of cropping systems and fertilization practices greatly affect soil dynamics. Changes under arable cropping are believed to be more drastic than under pastures or tree crops, but a proper comparison of various farming systems at the same location and as a function of time has not been done.

A summary of some changes in soil properties during the first 8 years after clearing a fine loamy, siliceous, isohyperthermic Typic Paleudult at Yurimaguas, Peru follows (Sanchez *et al.* 1983): Three adjacent fields under a 17-year-old secondary forest were slashed, burned, and planted to three crops per year with or without fertilization. Ash from the burn temporarily increased soil pH, available N, P, K, Ca, Mg, and some micronutrients, and decreased exchangeable Al (Figures 1,2,3,4). Six months after burning, however, the levels of available N and K were so reduced that deficiency symptoms of these two elements appeared along with sporadic S, Cu, and B deficiencies. Topsoil organic C and total N decreased at an annual decomposition rate of 25% during the first year but approached an equilibrium afterwards (Figure 5). The rapid organic matter decomposition probably released OM-bound Al that reversed the liming effect of the ash. Phosphorus

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and Mg became deficient during the second year, Ca within the first 30 months and Zn and Mn during the fourth year. Molybdenum deficiencies occurred sporadically, particularly when locally produced legume seed was used. Yields of the second and third consecutive crops without fertilization declined to essentially zero.

In the fertilized and lime plots, yields were adequate until the second year when K fertilization produced a Mg/K imbalance that triggered Mg deficiency, and the unexpectedly short residual effect of lime terminated. After these constraints were identified by soil tests and corrected, grain yields remained stable averaging about 3 t ha^{-1} of upland rice, 3.9 t ha^{-1} of corn (*Zea mays*), 2.6 t ha^{-1} of soybeans, and 3.4 t ha^{-1} of unshelled peanuts (Figure 6).

Soil chemical properties have improved with continuous cultivation because of liming and fertilizer additions. After 8 years and 21 crops, topsoil pH increased from 4.0 before clearing to 5.6, exch. Ca from 0.3 to 5.0 cmol(+) kg^{-1}, effective CEC from 2.8 to 5.5 cmol(+) kg^{-1}, available P from 5 to 39 mg kg^{-1} while Al saturation has decreased from 82 to 1%. No significant changes in exch. K and Mg and available Zn have been observed (Table 2). The 15–50 cm layer of the subsoil has undergone significant increases in exch. Ca and Mg and a decrease in Al saturation (Figure 7). This should promote deeper root development and less water stress during drought periods.

The time at which different nutrient deficiencies appeared and the amounts of fertilizer and lime needed to correct them varied substantially between the three fields, despite their close proximity, same preclearing vegetation, geomorphic position and same soil classification at the family level. The quantity of ash produced by the burn is suspected to be a major cause of this variability. Monitoring the nutrient dynamics during the first three years when the soil was undergoing a transition from forest to cropland provided the key for continuous cultivation in this Ultisol of the humid tropics.

Table 1. Nutrient contribution of ash after burning forests on a Typic Paleudult in Yurimaguas, Peru, and a Typic Acrorthox in Manaus, Brazil.

	Yurimaguas	Manaus	
Element	Forest Fallow (17 yrs)	Forest Fallow (12 yrs)	Virgin Forest
		kg/ha	
N	67	41	80
P	6	8	6
K	38	83	19
Ca	75	76	82
Mg	16	26	22
Fe	8	22	58
Mn	7.3	1.3	2.3
Zn	0.5	0.3	0.2
Cu	0.3	0.1	0.2

Source: Smyth *et al.* (1982).

Table 2. Changes in topsoil (0–15 cm) properties after 8 years of continuous cultivation and 20 harvests of upland rice-corn-soybean rotation with complete fertilization in Yurimaguas, Peru.

Soil property	Before clearing (September 1972)	94 months after clearing (May 1980)	Significance[a]
pH (1:1 H_2O)	4.0	5.7	*
Organic matter (%)	2.13	1.55	*
Exch. Al (cmol(+) kg^{-1})	2.27	0.06	*
Exch. Ca (cmol(+) kg^{-1})	0.26	4.98	*
Exch. Mg (cmol(+) kg^{-1})	0.15	0.35	*
Exch. K (cmol(+) kg^{-1})	0.10	0.11	ns
Effective CEC (cmol(+) kg^{-1})	2.78	5.51	*
Al saturation (%)	82	1	*
Avail. P (mg kg^{-1})	5	39	*
Avail. Zn (mg kg^{-1})	1.5[b]	3.5	ns
Avail. Cu (mg kg^{-1})	0.9[b]	5.2	*
Avail. Fe (mg kg^{-1})	650	398	*
Avail. Mn (mg kg^{-1})	5.3[b]	1.5	*

a. * = at 5% level or less.

b. 30 months after clearing.

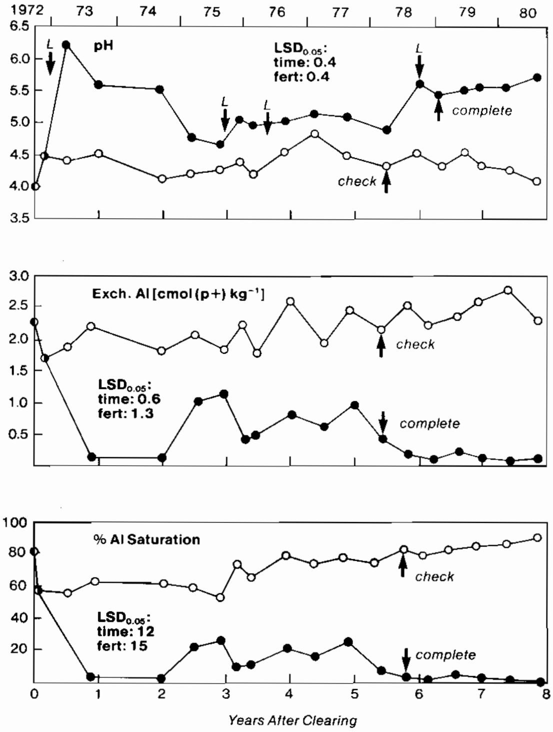

Figure 1. Soil acidity dynamics in Chacra I. Arrows with L on top indicate times of lime application.

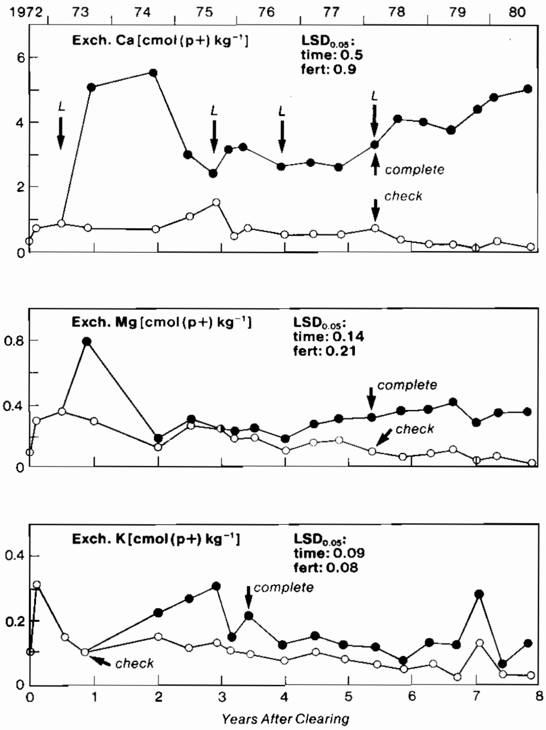

Figure 2. Dynamics of exchangeable bases in Chacra I.

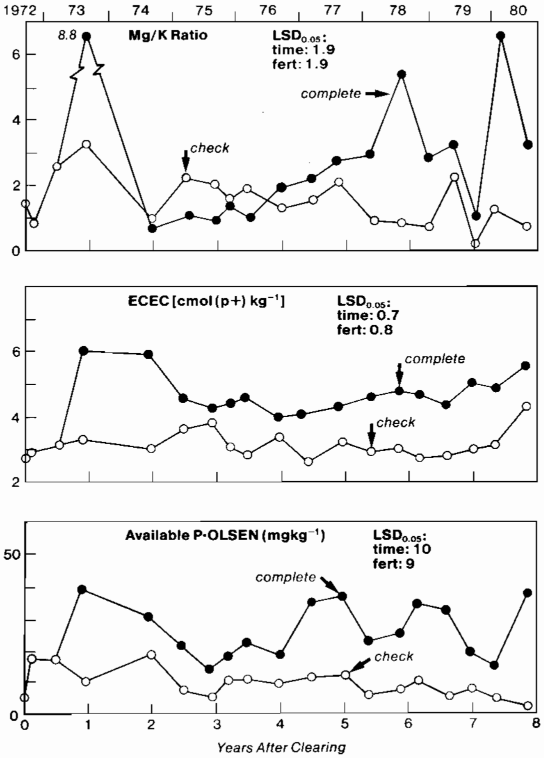

Figure 3. Dynamics of Mg/K ratios, effective cation exchange capacity, and soil test P (modified Olsen procedure) for Chacra I.

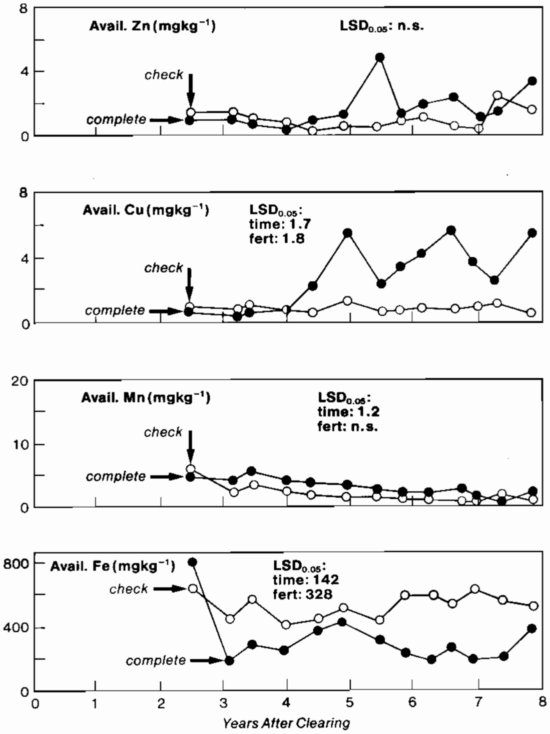

Figure 4. Micronutrient dynamics for Chacra I.

Session 3
Nutrient Availability in Acid Soils of the Humid Tropics

Summary of Discussion

D.G. Edwards*

The keynote paper in this session described a simple yet very realistic and conceptually sound laboratory approach to the description and understanding of ion exchange systems in highly weathered tropical soils. The approach is an extension of the theories developed on ion adsorption on variable charge mineral surfaces by the group at the University of Western Australia (Bowden *et al.* 1977). Gillman's approach allied with the recognition that different types of ion exchange systems exist in tropical soils, viz. layer silicates, oxides, and oxide-coated layer silicates (Sanchez 1976), will provide the necessary basic foundation for an enhanced understanding of cation retention by and losses through leaching from such soils. Description of the charge characteristics of these low activity clay soils will be much more profitable if pursued from a mineralogical basis rather than from the broad assumption that tropical and temperate soils are fundamentally different.

The difference in stability of charge between simple protonation/deprotonation reactions and coordination complexes was raised. The former is a very easy process that will readily flow backwards and forwards with change in soil pH. On the other hand, where charge arises from an adsorbed anion such as phosphate a very stable bridging link is established. The practical aspects of using phosphate in this way were discussed and it would appear that at realistic rates of application there are not real effects on effective CEC of these highly weathered soils. The use of silicates for this purpose was raised and reference made to Gillman's work in which the application of crushed scoraceous basalt caused some increase in negative charge of surface soils.

The discussant Pushparajah reported work on acid Malaysian soils that showed that soil pH values measured in water were not greatly different from the pH at the point of zero charge and suggested that soil pH measured in water could provide a simple test to monitor changes in soil surface charges. Interest was expressed in this suggestion. Consideration of Gillman's equation (3):

$$\sigma_o = \left(\frac{2n\,\varepsilon\,kT}{\pi}\right)^{1/2} \sinh 1.15z\,(pH_o - pH)$$

with electrolyte concentration zero, the surface charge σ_o is zero and the use of pH measured in water as an approach to the point of zero charge becomes a useful suggestion. Practically, the electrolyte concentration never reached zero, but the ionic strength of soil solutions from tropical soils is usually low — much below that of most temperate soils.

The importance of maintaining organic matter in the surface horizon of acid tropical soils and its contribution to negative charge in such soils was discussed. The benefits of organic matter maintenance were seen in the data from the two outstanding long-term field studies reported by the two discussants. The role of modest fertilizer inputs in maintaining fertility of soils under a perennial crop (rubber) and an annual crop rotation system involving rice, maize, and soybean was well illustrated in those papers. The contribution of organic matter to the effective CEC of acid tropical soils was queried; this was considered to be a difficult matter to assess, but some guidance is often available by comparing the effective CEC of the topsoil with that of the subsoil, which is often much lower in organic matter content. This approach is not totally satisfactory.

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The general question of providing guidelines on the development of tropical lands for agricultural production was raised and the suggestion made that IBSRAM should play a major role in evaluating nutrient dynamics in tropical soils. More specifically, it was suggested that long-term research studies of the type discussed by Pushparajah and Sanchez should be identified, assembled, and critically debated in order that some effective guidelines might be developed. The value of having charge measurements made on soil samples from long-term field studies of the type described by Pushparajah and Sanchez was raised. Sanchez indicated that soil samples from his study were available for such measurements.

The important issue of appropriate soil measurements from the point of view of plant growth was discussed. Pearson (1975) and others have advocated using the soil solution rather than exchangeable cations on the grounds that the soil solution more directly reflects the soil chemical environment to which the plant root system is exposed. In the case of aluminium toxicity, which is recognized as the major limitation to plant growth in acid tropical soils, some evidence does exist that soil solution aluminium is a more appropriate parameter than exchangeable aluminium or aluminium saturation of the CEC. Poor and distorted root development, the so-called classical symptoms of aluminium toxicity, cannot be relied upon as evidence of aluminium limitations to plant growth; such reliance in the past has led to a gross underestimation of areas of land in which plant growth is restricted by less severe aluminium toxicity. The sensitivity of the nodulation process *per se* in legume production to aluminium toxicity is an area of concern.

The finding that ionic strength is low in soil solutions extracted from highly weathered and acid tropical soils is of importance also in respect of the severity of aluminium toxicity. Activity coefficients for monomeric aluminium species, one or more of which are responsible for aluminium toxicity, are high and consequently for a given concentration of aluminium in the soil solution greater toxicity problems can be expected than occur in temperate soils, which generally have higher ionic strengths. Studies of aluminium in soil solutions need to discriminate between monomeric and the innocuous polymeric species.

The question of selection of tolerant plant genotypes as a management tool in these soils was raised; this is an important approach to the problems of acid tropical soils, but in many situations the most successful approach may lie somewhere between the two extreme approaches, viz. amending the soil to suit the plant and fitting plants nutritionally to soils.

The need to extend the rooting depth of plants growing in acid soils to secure water and nutrient supplies was raised and in particular the need to move calcium down into the subsoil was discussed. Movement following lime application to the surface is often too slow, but the use of calcium sulphate (a component of superphosphate) has proven effective in acid savannah soils of Brazil.

The impact of the types of approaches discussed in the three papers, and in particular the need for fertilizer inputs to maintain productivity, on shifting cultivators was raised. An opinion was offered that shifting cultivators are not particularly happy with their lot, particularly in regions where settlement is occurring and that if they are to progress to more stable production systems, fertilizers will indeed play an important role.

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Session 4

Soil/Environment Interactions in the Semi-Arid Tropics

Chairman: C.F. Bentley
Discussion Leader: J.S. Russell

Characterization of the Soil-Climate Constraints for Predicting Pasture Production in the Semi-Arid Tropics

J. Williams* and M.E. Probert*

The constraints to pasture production in the semi-arid tropics, as for any crop, are essentially those of soil and climate. This paper deals with an approach to characterization of these constraints in a manner that generates a prediction of production from a specified set of soil, plant, and climate information, utilizing a general understanding of the processes operating in the soil-plant-atmosphere system. This approach, while not new, is only rarely used, in spite of its numerous advantages over the more frequently used alternatives.

Generally in soil-plant production studies, both in Australia and overseas, there has been a tendency to separate and isolate aspects of chemical and physical fertility. The processes of interest to the soil chemist, soil physicist, and agro-climatologist have only rarely been studied simultaneously in an integrated manner in contrast to the integration that occurs naturally. The need to consider them together is particularly important in the semi-arid tropics as will become evident in this paper.

Most soil-plant studies fail to provide a means of predicting production beyond the site of experimentation. This is due not only to a lack of integration of the various key physical and chemical processes, but in addition the methods of analysis have been essentially statistical tests of treatment differences. Greenwood (1983) outlines the problem very well when he states 'Plant nutrient stress of one form or another limits plant yield in much of the world yet it frequently is very difficult to discern the causes of stress in a given field or to forecast the best ways of minimizing it at minimum cost. These difficulties are the consequences of the variability in soil and weather conditions and of the associated problems in interpreting the results of field experiments. Often the results of well planned experiments covering a range of conditions are interpreted by statistical procedures with a disappointing outcome'.

The National Soil Fertility Project (Hallsworth 1969) and the Benchmark Soil Project (Beinroth *et al.* 1980) from our understanding are notable examples. The main weakness in these methods of interpretation is that they rely on equations with no foundations in terms of accepted concepts of the phenomena they seek to represent. These studies make little use of any of the principles that have been evolved in any branch of soil science or plant nutrition and so forego the most powerful means of transcending the location specificity of their results.

The theoretical base in soil physics, soil chemistry, microclimatology, and plant physiology is generally well developed and rarely a limitation to the development of plant growth models. However, process models which incorporate existing knowledge in a rigorous manner can become so complex as to be impractical for agricultural development purposes.

For predictive models it is essential to restrict the number of variables and the cost of the input data without significant sacrifice of the theoretical principles or the predictive capability. To achieve these goals particular attention must be paid to the isolation of the key processes that drive plant production. Therefore the processes to be quantified are in the first instance only those that exert a dominant and determining influence in the soil-climate system under examination.

We shall attempt to outline such an approach to characterize the soil-climate interactions and provide a means of predicting production of legume-based pastures. The paper sets out matters of principle, describes progress to date, and outlines the difficulties and research needs that lie ahead.

The Physical Environment

The environment in which a plant grows provides

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the ultimate constraint to the production of a particular accession once edaphic and cultural constraints have been removed by good agronomy. A quantitative treatment of climate variation on plant growth is given by Monteith (1981). We will however restrict our consideration to the manner in which the physical environment determines vegetative production.

Water and Temperature Stress

In the semi-arid tropics, water is the paramount environmental constraint to plant growth. Early work by Briggs and Shantz as summarized by Shantz and Piemeisel (1927) set a foundation for predicting plant production as related to water stress by demonstrating a strong and consistent relationship between transpiration and plant yield (Hanks and Rasmussen 1982). This results from the fact that the processes of photosynthate production and transpiration are closely linked as shown by the theoretical work of Penman and Schofield (1951) and later by the experimental work of Boyer and McPherson (1975). The processes are linked because the transport of CO_2 and water are controlled by the stoma and it follows that cumulative water use can be used as a basis to predict yield.

Thus yield is some function of (ΣT) ... (1)

where ΣT is accumulated transpiration.

De Wit (1958) pioneered the further examination of such relationships

to show that yield is some function of $\Sigma (T/E_o)$ ... (2)

where $\Sigma (T/E_o)$ is the ratio of accumulated transpiration divided by potential evapotranspiration of free water during the measurement period. He and many others (e.g. Hanks *et al.* 1969; Fisher and Turner 1978) have shown this to be a robust relationship.

Following Rose *et al.* (1972) we set down a simple rational basis for equation (2). In the absence of nutrient stress and assuming complete light interception by the pasture, the gross photosynthesis can be written

$$A = f_1(R(1 - \alpha)) \qquad \ldots (3)$$

where R is the incoming global radiation and α the albedo. Respiration can be considered to be an approximate function f_2 of A, and thus net photosynthesis (NP) is written

$$\begin{aligned} NP &= f_1(R(1 - \alpha)) - f_2[f_1(R(1 - \alpha))] \\ &= f(R(1 - \alpha)) \qquad \ldots (4) \end{aligned}$$

where f is a net photosynthetic function. Clearly f is itself dependent on temperature and this will be dealt with later.

Evapotranspiration can be estimated by use of the Bowen ratio, β, such that

$$ET = (R(1 - \alpha) + R_L)/((1 - \beta)L) \qquad \ldots (5)$$

where R_L is net long wave radiation, and L is the latent heat of vaporization of water. From (4) and (5) we write

$$\frac{NP}{ET} = \frac{f(R(1 - \alpha))(1 - \beta)L}{R(1 - \alpha) + R_L} \qquad \ldots (6)$$

The implications of equation (6) are that the relationship between Σ NP and Σ ET would be almost unique and could be close to linear as β, α, and R_L vary little over a growing season, although over a short time scale R_L and β can vary greatly. The variation in these meteorological variables can be accounted for by resort to the inclusion of a potential evapotranspiration term. Net radiation (R_n) is written as

$$R_n = R(1 - \alpha) + R_L \qquad \ldots (7)$$

and thus upon substitution (6) becomes

$$\frac{NP}{ET} = \frac{f(R(1 - \alpha))(1 - \beta)L}{R_n} \qquad \ldots (8)$$

A generalized expression for the potential evaporation from a wet canopy can be written (Monteith 1980)

$$ET_o = \frac{a\,\Delta\,Rn}{(\Delta + \gamma)L} \qquad \ldots (9)$$

in which a is an empirical constant, Δ is the rate at which saturated vapour pressure changes with temperature and γ is the psychometric constant.

From (8) and (9)

$$NP = f[R(1 - \alpha)].[\frac{(1 - \beta)\,a\,\Delta}{\Delta + \gamma}].\frac{ET}{ET_o} \qquad \ldots (10)$$

Thus we have a relationship in which a net photosynthetic rate is dependent in a multiplicative manner on shortwave radiation, a group of meteorological parameters and constants, and the ratio of actual to potential evapotranspiration. Although this analysis has shortcomings it provides a physical basis for a model whereby net photosynthesis can be expected from first principles to be related to the ratio of actual to potential evapotranspiration.

Temperature influences plant production through metabolic processes involved in both growth and development and, as already mentioned, in photosynthesis. The photosynthetic rate and the growth processes are linked and both are dependent on temperature (Monteith 1981). To incorporate the influence of temperature and radiation on net photosynthesis we write

$$NP = g\,[R(1-\alpha)]\,.\,[\frac{(1-\beta)\,a\Delta}{(\Delta+\gamma)}].[\frac{T-T_o}{T_m-T_o}].\frac{ET}{ET_o} \qquad \ldots (11)$$

where $g\,[R(1-\alpha)]$ is the functional relationship between photosynthesis and radiation for a given plant canopy. Fitzpatrick and Nix (1970) used the relationship $NP = NP_m\,(1 - e^{-3.5x})$ where $x = R/R_c$, NP_m is maximum photosynthetic rate, and R_c is the shortwave solar constant. The term $(1 - e^{-3.5x})$ is a radiation index. The term $(T-T_o)/(T_m-T_o)$ is a simple linear temperature response in which T is mean ambient temperature, T_o is temperature when production is zero and T_m is the temperature when production is at a maximum. When $T < T_o$ production is zero and when $T > T_m$ production is no longer limited by temperature.

Dry matter production is the result of the accumulation, over an appropriate time step, of the net photosynthetic rate and is given by

$$DM = \xi\Sigma\,[1-e^{-kx}].[\frac{T-T_o}{T_m-T_o}].[\frac{ET}{ET_o}] \qquad \ldots (12)$$

where ξ combines the plant and meteorological parameters. We can simplify this expression for dry matter production to

$$DM = \xi\Sigma\,[RI.TI.WI] \qquad \ldots (13)$$

where RI, TI and WI are the radiation, temperature and water indexes respectively. In our work to date with pastures we have assumed that the pasture canopy photosynthesis is not constrained by light and have used the expression $DM = \xi\Sigma\,[TI.WI]$ in which we term the combination of these two indices in a multiplicative way, the Growth Index (GI).

This analysis provides a basis for the multiplicative model first used by Fitzpatrick and Nix (1970) and recently adopted by Squires *et al.* (1983) to describe the influence of temperature, water and radiation on leaf extension of millet. The water index used here is similar to the R-index of Yao (1969) and the Z index of Sakamoto (1978).

Over the time step t_s for which the Growth Index is estimated, the growth time (t_g), when water and temperature are not limiting production (McCown 1981a), is

$$t_g = t_s\,(GI) \qquad \ldots (14)$$

The growth time for plant production (n_g), or the cumulative growth index as used in Figure 2, becomes

$$n_g = \int t_s.GI \qquad \ldots (15)$$

We may now write,

$$DM = \xi\, n_g \qquad \ldots (16)$$

so that dry matter can be expected to be directly proportional to the growth time of the crop when it is not constrained by either water or temperature.

Predicting Plant Production

The soil water and nutrient constraints to production of *Stylosanthes hamata* cv Verano have been extensively investigated at the CSIRO experimental site on 'Redlands', 180 km west of Townsville. These studies have provided a data base from which we are currently developing a dry matter production model for Verano in response to water, temperature, and phosphorus.

Figure 1(a) illustrates the response of stem elongation in Verano to water stress. When the relative leaf water content at 1300 hrs falls below approximately 75% the elongation rate is small, usually less than 2 mm day^{-1}; above 75% RLWC small rates of elongation occur when mean daily temperatures are low. Associated studies have demonstrated that dry matter production and stem elongation of Verano is limited by mean night temperatures below approximately 22°C and mean daily temperatures below 25°C (Williams and Gardener 1983).

A soil water balance model (McCown 1981 a) was used with a weekly time step to estimate ET/ET_o from rainfall and US class A pan evaporation. The mean weekly screen temperature and a response function as used by McCown (1981 a) generated the weekly temperature index.

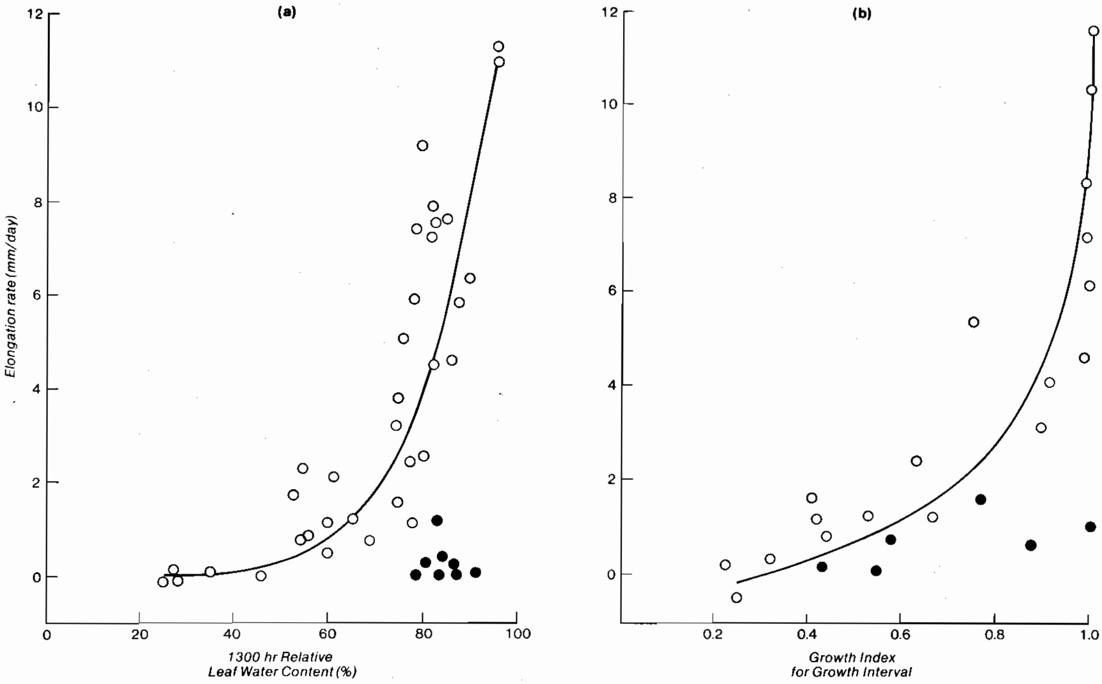

Figure 1. Relationship between stem elongation and (a) 1300 hour relative leaf water content; and (b) cumulative growth index for S. hamata *cv Verano. Solid symbols refer to time intervals when mean daily temperature was less than 25°C. (Unpublished data of authors).*

In Figure 1(b) extension growth of Verano is related to the computed cumulative growth index. Extension was substantially reduced when the growth index fell below 0.5. This estimation of environmental stress compares favourably with that shown in Figure 1(a) where only plant water status was used. Nonetheless, at times during April and May (closed circles on Figure 1(b)), it is still less than satisfactory and we believe this reflects the fact that the temperature response function so far used for Verano requires adjustment as better data become available.

The dry matter yield of Verano under both non-limiting and limiting phosphorus nutrition as a function of wet season rainfall and Cumulative Growth Index (as defined by equation (15) for GI $\geq$ 0.5) is set out in Figure 2(a) and 2(b) respectively. Over the seasons studied it is apparent that a robust relationship exists between yield and this Cumulative Growth Index, which is the growth time of the crop when it was not constrained by either water or temperature. The data from McCown (1973) for *S. humilis* grown with adequate phosphorus on the Townsville coastal plain has been shown by Williams and Gardener (1983) to agree well with that found for Verano at 'Redlands'. Both soil and climate are very different at these sites and therefore the agreement is encouraging.

Referring to Figure 2, the 1980/1981 season was characterized by high wet-season rainfall accompanied by low solar radiation and this is reflected in the relatively poor legume yield. Introduction of a simple light index for 1980/1981 results in this point moving closer to the relationship established for other years (Figure 2(b)). Clearly a light index that describes canopy saturation needs to be incorporated in future work.

For conditions in which water and temperature are the only factors constraining dry matter production of Verano, it is possible to estimate dry matter production at a given site from profile water store, rainfall, evaporation, and temperature. Williams and Gardener (1983) compared estimated and measured yields for several sites in northern Australia (Figure 3). We

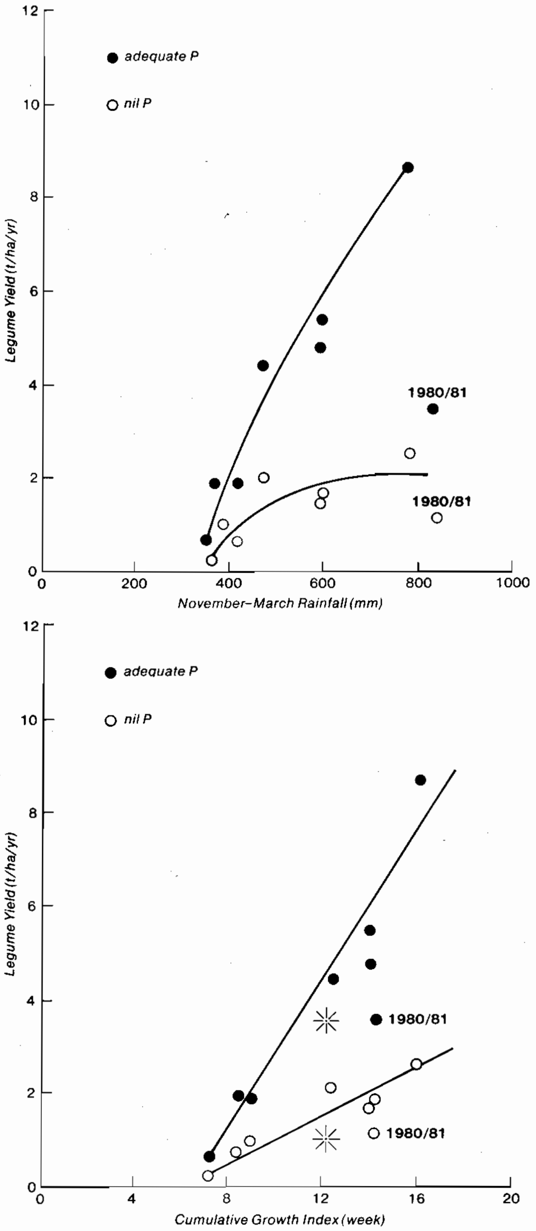

Figure 2. Relationship between dry matter yield and (a) wet season rainfall (November to March); and (b) cumulative growth index GI or growth time (n_g) for S. hamata *cv Verano. Solid and open symbols are for adequate and nil P treatments respectively. Note the influence of adjustment of 1980/81 yield for radiation stress. (Unpublished data of authors).*

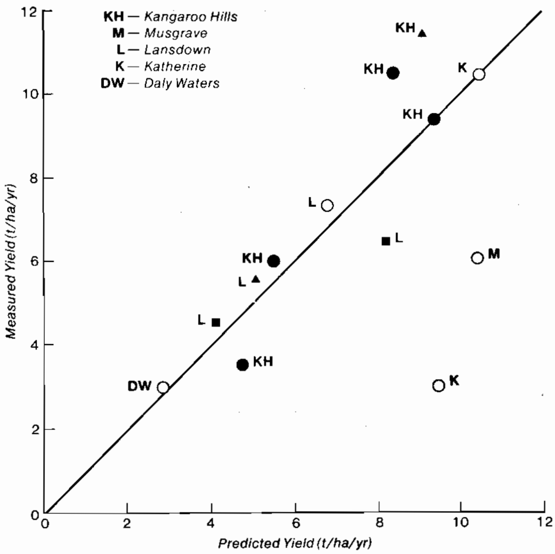

Figure 3. Relation between predicted yield and measured yield for S. hamata *cv Verano for five locations in northern Australia. The various symbols depict results of authors set out in Williams and Gardener (1983) from which it has been redrawn.*

consider the level of agreement between predicted and estimated yields to be good. From records not included in the published data it is claimed that the Katherine (Northern Territory) experiment suffered from both poor establishment and serious weed competition (L.A. Edye, pers. comm.) whilst at Musgrave (Queensland) the sward was probably suffering from sulphur deficiency despite the use of a basal dressing (Jones 1973). This validation of the model gives us sufficient confidence to estimate the dry matter production of Verano in the semi-arid tropics of northern Australia (Figure 4). The estimates are based on long-term means that can be misleading, but they do serve to generalize the production potential for Verano.

Risk Analysis

At any given location it is possible from long-term records to derive the probability of obtaining a specified yield in much the same way as did Byrne and Tognetti (1969) and McCown (1981 b). The analysis of probability provides a direct measure of risk as a consequence of soil

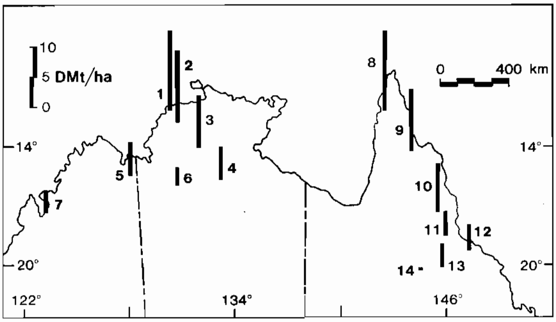

Figure 4. Mean yield estimates of S. hamata *cv Verano based pasture at selected locations in northern Australia. The estimates consider only environmental constraints to vegetative production. Locations and soil moisture regime are as follows: 1 — Darwin (Ustic); 2 — Adelaide River (Ustic); 3 — Katherine (Ustic); 4 — Derby (Aridic); 8 — Weipa (Ustic); 9 — Musgrave; 10 — Mt. Garnet; 11 — Kangaroo Hills (Ustic); 12 — Lansdown/Woodstock (Ustic); 13 — Pentland (Aridic); 14 — Hughenden (Aridic). (Redrawn from Williams and Gardener 1983).*

physical and environmental constraints. This has been done in Figure 5(a) for four locations in northern Australia. The semi-arid tropics are characterized by highly variable plant production over the wet season. In Figure 5(a) it is apparent that our Redlands site (Queensland) encompasses the full range of production potential encountered by any site examined for northern Australia. The important measure of risk for agricultural development is this probability/yield relationship.

The near linear relation for Woodstock and Redlands in Queensland indicates that highly variable production must be expected. This is in contrast to the Katherine site (Northern Territory) where production is reliable. The probability of obtaining zero production is also important; this is estimated to occur in zero, 6, 20, and 54% of years for Katherine (Northern Territory), and for Woodstock, Redlands and Hughenden (all in Queensland), respectively. The increasing risk of complete failure of legume pasture increases quite rapidly with distance inland from Townsville although in some years very substantial yields will be obtained at these inland semi-arid sites.

It is worth noting that in terms of Soil Taxonomy, Redlands has an aridic soil moisture regime, yet in some years the plant production can be equal to or greater than the mean production for most ustic and perhaps some udic environments (see Figure 4 and Figure 5). The use of such static criteria that take no account of variability have a limited value in the semi-arid tropics.

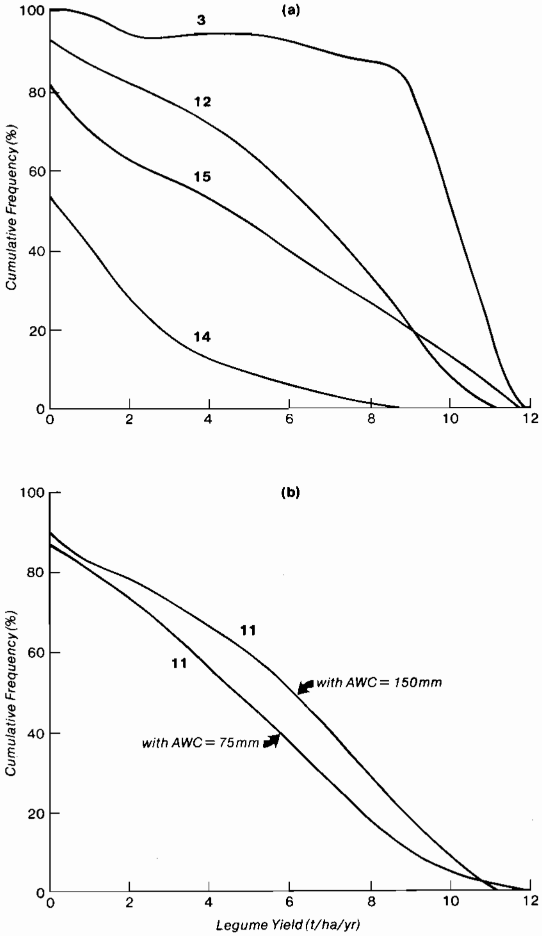

Figure 5. Relationship between cumulative frequency of obtaining at least the specified dry matter yield of S. hamata *cv Verano. (a) For locations 3 — Katherine; 12 — Lansdown; 14 — Hughenden; 15 — Redlands, using a profile water store of 150 mm. (b) For 11 — Kangaroo Hills, using a 75 mm and 150 mm profile water store.*

The influence of the soil-profile water store on the probability/yield relation is demonstrated in Figure 5(b) for Kangaroo Hills (Queensland). An increase in profile water store from 75 mm to 150 mm confers an additional 1 t ha^{-1} of DM production in 50% of the years examined and is equivalent to about 25% of the mean annual dry matter production. This is consistent with the earlier findings of McCown (1973) for Woodstock.

A soil water balance analysis conducted by Williams *et al.* (1983) for sorghum cropping at Katherine is set out in Figure 6. Unless a profile water store of 100 mm is present there is less than a 30% probability that the water requirement of a sorghum crop will be met. A profile water store of 200 mm in the same climate can guarantee that the water needs of sorghum will be met with a probability of 70%. The risk involved is clearly reduced by selecting soils or soil management options that lead to larger profile water stores. The magnitude of the profile water store is a major factor open to some degree of management to maximize water available to the pasture or crop.

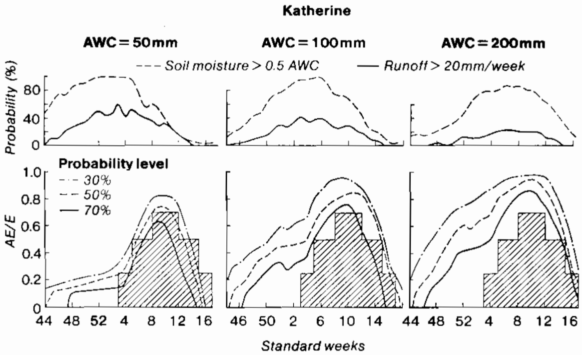

Figure 6. Simulated soil water balance for sorghum at Katherine, Northern Territory, using a 50, 100 and 200 mm profile water store. (Redrawn from Williams et al. *1983).*

Soil Water Balance

The soil water balance, which is of fundamental importance to agricultural production in the semi-arid tropics, is the result of the interaction between soil, plant, and climate. Besides determining plant available water, it also determines runoff and deep drainage which, in turn, are the keys to erosion and loss of some nutrients from the system.

Erosion

For erosion to take place both a source of sediment and a means of transporting the sediment must be created. In the semi-arid tropics high intensity rainfall mobilizes large amounts of detached material. In north Queensland Williams and Bonell (unpublished data) have measured rain splash detachment rates that exceed by a factor of two those reported for semi-arid regions in western USA and humid areas of western Europe. On the massive sesquioxidic soils (Red and Yellow Earths) under high intensity rainfall, surface hydraulic properties decline through surface sealing and there is sufficient overland flow to transport and detach further material. Consequently runoff and erosion are serious problems under conventional cropping and heavy grazing.

Crop residues and mulches are one of the most effective means of stabilizing the hydraulic properties of the soil surface (Lal 1980), whilst efforts in zero-tillage and ley-farming systems (McCown *et al.* 1983) should tend to minimize surface detachment and maximize infiltration. Lal's pioneering work as summarized by Lal (1983) was conducted in the humid tropics of West Africa. There is a pressing need for similar studies in the semi-arid tropics where the options for management of the lower quantities of plant material are fewer.

Soil Water Store and Plant Water Extraction

There are two primary hydraulic properties of a soil that determine the response of the profile to a rainfall event. These are moisture characteristic (the $\psi(\theta)$ function) and the hydraulic conductivity water content relation (the $K(\theta)$ function). The first property describes water retention by a soil and the second the rate of water movement through the soil.

Williams (1983a) in his Figure 32.16 illustrates the interaction between soil texture and rainfall properties on the magnitude of the water stored by a profile following rainfall. For a uniform profile the time series nature of the rainfall is able to interact with the $K(\theta)$ and $\psi(\theta)$ properties in such a way, that for a rainfall sequence of 75 mm distributed over two or three days, as is common during a wet season, the storage of water in the profile is optimal in light textured soils. Under larger rainfall inputs the reverse is true as the loss from drainage in light textures now exceeds the runoff, which begins to occur in loams and clays. This illustrates the dynamic interaction between soil and rainfall that determines the water stored in the profile for extraction by the plant.

From data presented by Williams (1983b) for Australian soils it can be expected that the plant available profile water store will range from 60 to 360 mm, depending on rooting depth.

At Redlands, on a deep Red Earth (Oxic Paleustalf) the water extraction and root density distribution with depth are depicted for Verano in Figure 7. This deep-rooted species is able to exploit water from considerable depths, although Williams *et al.* (1980) have shown that deep drainage beyond the root zone does take place during the wet season. The implication of this deep drainage to loss of nutrients will be discussed subsequently.

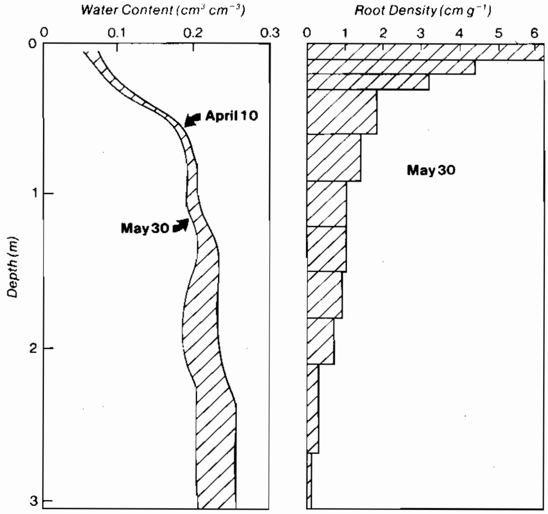

Figure 7. Soil water extraction and root density as a function of depth for S. hamata *cv Verano on a Red Earth (Oxic Paleustalf) at Redlands in Queensland. (Unpublished data of authors).*

Not only are the perennial *Stylosanthes* species able to root deeply, they appear to be able to extract water to water potentials considerably less than the −1.5 MPa traditionally associated with the lower limit of available water. This is evident in Figure 8.

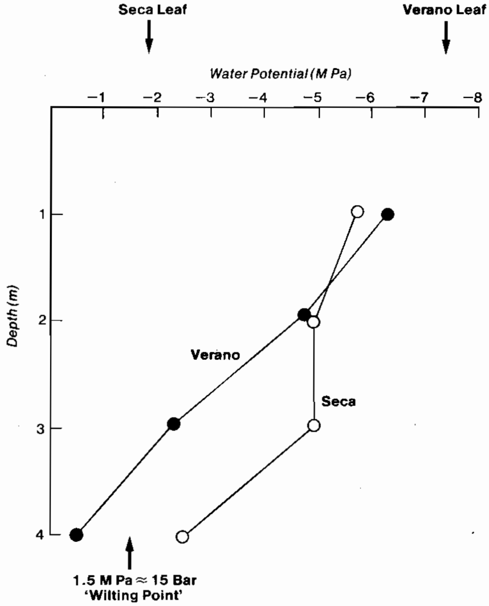

Figure 8. Leaf water potential of S. hamata *cv Verano and* S. scabra *cv Seca and the soil water potential as a function of depth beneath these pastures following drought at Redlands. (Unpublished data of authors).*

The water potential in both the plant leaf and the soil profile is illustrated after a 10 week drought. The reported measurements using dewpoint hygrometry were made on and beneath well established swards of Verano and *S. scabra* cv Seca. At a leaf water potential of −7.6 MPa the leaf of Verano was near desiccation although when placed in free water, leaves fully regained their turgor. In contrast the leaf water potential of Seca at the same time was −2.4 MPa. It follows that the root system of Seca must be in contact with soil water with a potential greater than this. Water at a depth of greater than 4.0 m meets this condition.

In these Red Earths large changes in water potential are associated with only small changes in water content (Williams *et al.* 1980) and therefore this decrease in potential below −1.5 MPa is not associated with large quantities of water. However, these quantities are apparently sufficient for plant survival, if not for growth.

The Chemical Environment

We have shown above how relatively simple concepts can lead to an understanding of the way in which climatic constraints affect plant growth. In such studies nutrients are not limiting. Thus the real challenge for the nutritionist is to predict the shortfall from the potential yield (limited by climate alone) that will occur when nutrient disorders are also present. In Figure 2 some of our unpublished data on the effect of phosphorus on the growth of Verano on a Red Earth (Oxic Paleustalf) were illustrated; there will be a whole family of such curves corresponding to any given phosphorus input.

Similar to the manner in which the moisture and temperature effects were treated as indices, it seems logical that the same sort of approach might be useful in considering a nutrient constraint, and in fact many expressions that are used to describe nutrient responses can be viewed in precisely this fashion.

Consider the well known Mitscherlich equation

$$Y = A(1 - Be^{-cx}) \qquad \ldots (17)$$

where A is the asymptotic maximum yield or potential yield as determined by the physical environment, B is the relative response when the constraint caused by nutrient X is removed, and c determines how rapidly the curve approaches the asymptote. The expression within the parentheses is an index of the nutrient supply that is used in a multiplicative manner with the yield potential. However the parameters of equation (17) as they might be fitted to any given data set are site, crop, and season specific. To be more generally useful we must find some means of incorporating into such an index those soil characteristics that we know from our accumulated experience to be important.

The parameter B does not present any real problems since equation (17) is readily rearranged to

$$Y = A(1 - e^{-c(x+x_o)})$$

with $B = e^{-cx_o}$. Expressed so, we can associate x_0 with the amount of nutrient X initially present in the soil and measured in the same units as are used for that applied.

The parameter, c, is less easy to deal with; certainly it will depend upon the crop, and may depend upon soil and/or environmental factors also. Considering phosphorus as an example, it is now widely recognized that the phosphate sorption characteristics of the soil exert considerable influence on the effectiveness of freshly applied phosphorus. Some data for northern Queensland soils make this point (Figure 9).

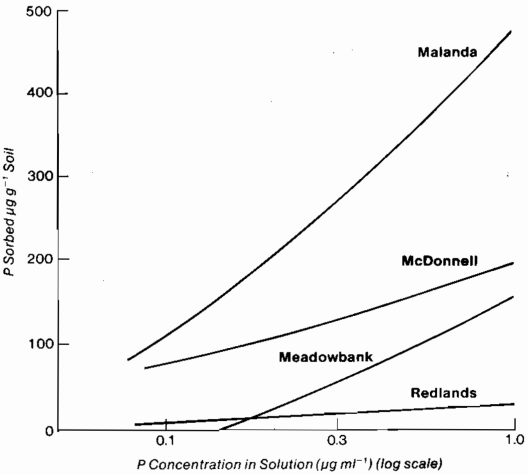

Figure 9. Phosphate sorption isotherms for some north Queensland soils. Experimental conditions: 1:10 soil: solution in 10^{-2}M $CaCl_2$; 24 hr continuous shaking. (Unpublished data of M.E. Probert).

Field experiments have shown that the initial phosphorus requirements for establishment of *Stylosanthes* species are approximately 15 kg ha^{-1} on the Redlands Red Earth (Alfisol), some 150 kg ha^{-1} on the McDonnell Yellow Earth (Ultisol) and over 500 kg ha^{-1} on Oxisols similar to the Malanda Krasnozem. In contrast on the Meadowbank Euchrozem (Inceptisol) responses to phosphorus are not obtained. Thus we see how a soil's sorption characteristic should be a unifying concept in understanding initial responses to phosphorus on different soils. The important aspects that need to be accounted for are the intercept on the concentration axis (conceptually this can be related to the soil solution concentration) and the slope of the isotherm that will govern how much phosphorus is required to raise the soil solution to a non-limiting concentration. The slope of the sorption isotherm is important in that it determines the rate at which phosphorus diffuses through soil either away from a source (e.g. a fertilizer granule) or towards a sink (e.g. a plant root).

In soil however, phosphorus continues to react over long periods of time causing the effectiveness of residual phosphorus to decline with time (Figure 10(a)). In Figure 10(b), the fitted values for the curvature parameter, c, are related to the time since phosphorus was applied, from which it can be calculated that the effectiveness of phosphorus in this soil declined to 0.57 of its initial value for each year of contact with soil. Deviations about the fitted line in Figure 10(b) must include any seasonal variations, but it would seem that such effects were relatively small compared with the overriding effect of time. For these data, an exponential loss in effectiveness of phosphorus described the process over the five year period, but others have found that the decline in effectiveness usually slows down with time and that alternative expressions may better describe the residual value function (e.g. Barrow 1980).

A further problem in modelling these systems is displayed in Figure 10(a), where it can be observed that the relative yield with zero application changes with time. Part of this may be due to the removal of phosphorus in the harvested crop (which has not been allowed for in Figure 10) but in some circumstances the relative yields seemingly increase with time!

A very simplistic model that we have used with some success to describe other data can be written as follows:

$$Pe_{i+1} = (Pe_i - Pu_i)\, f + k \qquad \ldots (18)$$

where Pe_i is the effective phosphorus in soil in year i, Pu_i is the phosphorus removed in the crop in year i, f is the residual effectiveness of phosphorus after one year, and k allows for other losses or gains by the system that might include for example, immobilization of phosphorus into organic forms. The treatment of k as an invariant flux is obviously an over-simplification since it would seem reasonable to expect it to depend upon the amount of effective phosphorus in soil.

When a source is applied that is not immediately fully effective, e.g. rock phosphate, it can be assumed that a proportion, r, is released into an effective form; this is then subject to loss of

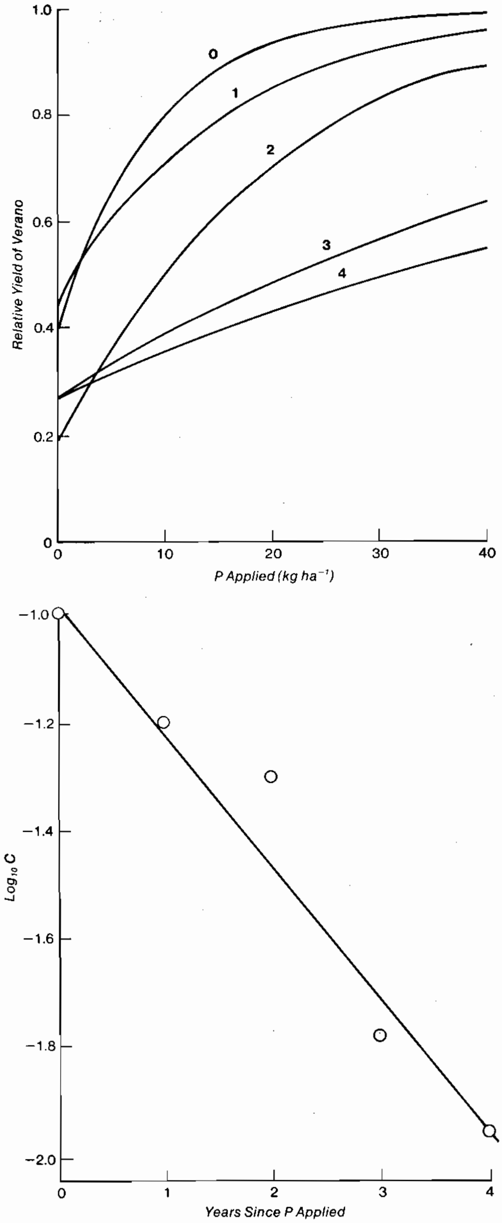

Figure 10. The response of S. hamata *cv Verano to a single application of phosphorus. (a) fitted Mitscherlich equations ($RY = 1-Be^{-cP}$) in each of five seasons. Phosphorus was applied in year 0. (b) relationship between fitted values of c and time since phosphorus was applied. (Unpublished data of authors).*

effectiveness as described above. It can now be expected however, that a further proportion, r, of the unreacted residue will be released in the second season. Again this might be an oversimplification of the 'dissolution' of a sparingly soluble source of phosphorus (would not its rate of dissolution depend upon its surface area, and P and Ca concentrations in solution?) but nonetheless it described very well the experimental data of Fisher and Campbell (1972) for the growth of *Stylosanthes humilis* over three seasons at Katherine (Figure 11). It is to be noted that the model accurately predicts the improving performance of the initially less effective source in contrast with the declining effectiveness with time obtained with superphosphate. Because the relative yields at zero application increased with time, a positive value of k was required in this instance. K.R. Helyar (pers. comm.) has similarly found when endeavouring to model the response of wheat that it is necessary to invoke an input of phosphorus into the system. Without such a term extractable P in soil and relative response at zero application should decline with time due to removal in the crop, but apparently this is not always borne out experimentally.

Nutrient Loss by Leaching

Phosphorus is an immobile nutrient in soil; we would like now to refer briefly to two situations where leaching is seemingly of major importance.

The first concerns nitrogen. Growing forage legumes in tropical regions not only provides a higher protein diet for the grazing animal but should also improve soil nitrogen levels, which may make a legume-ley agricultural system with a cropping phase feasible (McCown *et al.* 1983). However, the few data that are available show that total soil nitrogen does not build up to any great extent under tropical pastures, even when they contain a substantial legume component. Furthermore, efforts to utilize such nitrogen by

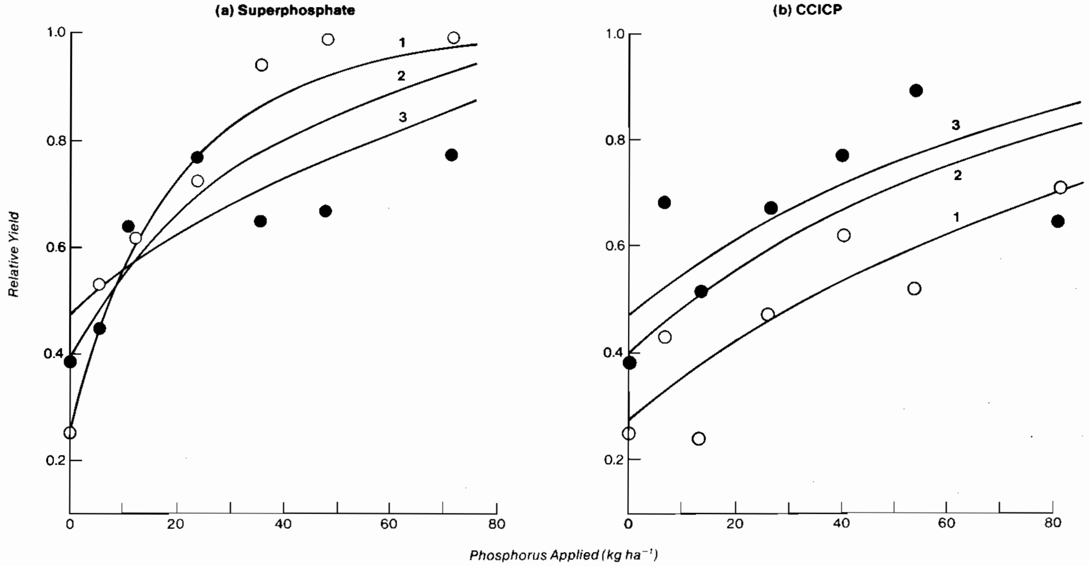

Figure 11. Response of Stylosanthes humilis *to initial applications of (a) superphosphate and (b) calcined Christmas Island C-grade phosphate (CCICP) at Katherine, Northern Territory on an Oxic Paleustalf. (Fisher and Campbell 1972.). Parameters of the fitted model (see text) are: initial effective P in soil = 6.8 kg/ha, relative effectiveness of 1 yr old P = 0.71, k = 6.9 kg/ha/yr, fraction of CCICP becoming effective each year = 0.23, asymptotic yields in years 1, 2, and 3 = 7 520, 5 420, and 3 890 kg/ha, and a common curvature parameter = 0.048 kg/ha. Observations are plotted for the first (○) and third (●) seasons only.*

cropping have found that its effect is short lived, being largely restricted to the first season after a ley (R.K. Jones, R.L. McCown, pers. comm.). Why should this be different to our temperate experience where organic matter and soil nitrogen continue to build up for long periods of time?

The amount of nitrogen fixed by tropical legumes compares quite favourably with temperate species (Vallis 1972). Thus it seems likely that any difference must result from higher rates of mineralization in the tropical environment and the subsequent removal of nitrogen from the profile. In semi-arid tropical regions water does move through the profile and frequently there is a substantial drainage component below the rooting zone (Williams *et al.* 1980). In Figure 12 the redistribution of applied nitrate- and ammonium-N that occurred in a Red Earth (Oxic Paleustalf) in 35 days, during which 518 mm of rain fell, is shown. Almost 60% of the applied ammonium-N had been nitrified and the peak nitrate concentration had leached to 75 cm. The recovery of applied-N in soil was 95% from which it is inferred that there had been little loss to the atmosphere. There are comparable studies from the Northern Territory on similar soils (Wetselaar 1962; Day 1977).

We also have data that show leaching of nitrate under legume pastures. However, to our knowledge no one has yet applied the theories of solute movement to such systems. The processes that are occurring are well known. By the appropriate choice of parameters it should be possible to describe the systems mathematically and thus use climatic data to drive a simulation model to evaluate losses of nitrogen by leaching. A good example of this type of modelling is afforded by the work of Watts and Hanks (1978) who examined on a 'macro' scale the interaction of the major processes affecting nitrogen uptake and leaching during growth of maize in a sandy soil environment.

Assuming that the downward movement of nitrogen is the main loss mechanism in such systems, there are important implications. Obviously a growing plant will have to trap its nitrogen before it is leached beyond the root zone. Furthermore, what is the ultimate fate of the nitrate moving down the profile? Would the widespread use of forage legumes in these environments result in increased nitrate concentrations in groundwater?

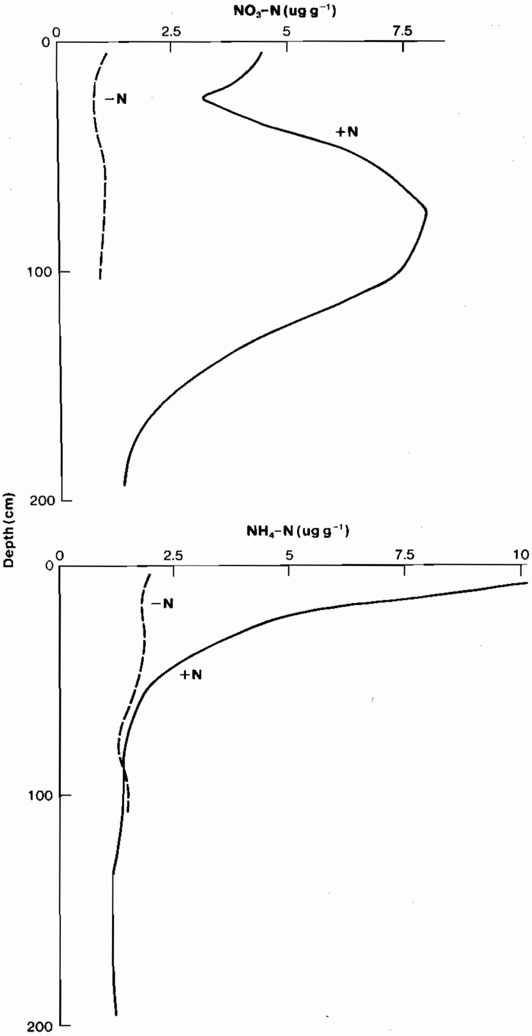

Figure 12. Distribution of nitrate- and ammonium-N in a Red Earth (Oxic Paleustalf) at Redlands 35 days after applying ammonium nitrate. The plus-N treatment is the mean of 150 and 200 kg/ha rates of application. (Unpublished data of authors).

Sulphate also leaches in soil, although as shown by Probert and Jones (1982) on a non-calcic brown soil (Rhodic Paleustalf) it may be retained in an adsorbed form in the subsoil. Such sulphur is available to plants. Whereas in the discussion above on phosphorus, it is implied that a nutrient growth index may be possible simply from consideration of the surface soil, this is not likely to be so for more mobile nutrients (the distributions of which will change during the growing season) or for nutrients that may be taken up from different depths in a profile. Thus the description of the sulphur responsiveness of tropical legumes in a range of northern Australian soils was considerably improved when a weighting function was used to obtain an index of extractable sulphur over the whole soil profile than when only surface soils were considered (Probert and Jones 1977).

Discussion

The purpose behind the characterization of soil and climate constraints to plant production is to provide a quantitative means of predicting the expected production for a given set of technologies in another set of soil and climate situations. The philosophy we are expounding is that the most effective and efficient means of doing this is to integrate in the form of predictive models the accumulated knowledge of soil scientists and agronomists. We know that the processes are exceedingly complex, but submit that the challenge is to distil from these the simplest, essentially sound, relationships that give useful predictions of production.

In this paper we have tried to show how this can be achieved for the pasture situation we have studied in the Australian semi-arid tropics. We think that application of the principles of soil science and plant nutrition, the expertise of chemists and physicists, does result in an understanding of the system. In particular the application of the theories of agricultural physics enables an assessment of the potential for agricultural production in these areas and the likely risks involved for its practitioner. The season-to-season variation in productivity is large in the semi-arid tropics. A static analysis does not provide any measure of the risks involved either in terms of yield or response to fertilizer application. However, dynamic analysis, utilizing established principles of soil science and agricultural climatology, can provide such measures as we have demonstrated here, and similarly by Stewart and Hash (1982) for maize production in the semi-arid areas of Kenya.

Our work demonstrates that simple models can describe phosphorus response provided the models take account of the principles that describe phosphorus behaviour in soil. Results published in the Final Report of the Puerto Rico Benchmark Soils Project (Beinroth 1982) suggest to us that these workers demonstrated that the response of maize to phosphorus could have been predicted from a knowledge of the phosphate sorption characteristics of the soils and the Truog extractable P, although this finding does not appear amongst their conclusions. It would be somewhat heretical (from the Benchmark Project point of view) to suggest that this has precious little to do with agrotechnology transfer within a soil family. In fact we would assert that if the models reflect sound principles of soil science, they should work across all soils.

Acknowledgement

It is a pleasure to acknowledge Dr R.L McCown for assistance in the provision of long-term water balance data and for helpful discussion during the preparation of this paper, and Mr G. Rollinson for permitting us to conduct our experiments on his property.

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S.M. Virmani* **Discussant — 1**

Farming Systems Research: A Framework for Alleviating Soil-Climatic Constraints for Improved Management Systems for Alfisols in the Semi-Arid Tropics

The keynote paper entitled 'Characterization of the soil-climate constraints for predicting pasture production in the semi-arid tropics' concerns the application of the principles of soil science to the estimation of water, nutrient, and environmental stresses for prediction of plant production. The authors have utilized a generalized nutrient stress model with particular reference to P nutrition of crops to explain plant responses to applied P. It is noted that modeling could help in elucidating quantitatively the key processes of plant production.

The paper covers several areas that appear somewhat speculative. It is not clear if the proposed model adequately covers some of the major soil orders of the SAT (e.g. Alfisols, Vertisols, Oxisols, and Entisols). Some explanations on the leaching of P in SAT (semi-arid tropics) soils may be necessary. Further, responses to P are normally much less sensitive to variations in the seasonal moisture regime than responses to N. Since there is a strong interaction between N and P, it is pertinent that any model on nutrient stress analysis should be developed with a description of the N in the soil. In some ways the approach proposed by Williams and Probert tends to comply with the norms of soil science as a discipline. I believe, that to be useful, research on the optimization of crop production in the SAT should be holistic and multi- and inter-disciplinary. Such research must draw upon expertise from an array of sciences.

In the following comments, I propose a farming systems research framework for developing production strategies for increased crop production in the SAT. These regions are characterized by low agricultural productivity because the soils of these regions are often low in fertility, difficult to cultivate, and the rainfall is low, erratic, and highly seasonal. In the SAT regions of the developing world, the economic resources are also limited. The current levels of crop production, under traditional agriculture in these harsh environments, are normally inadequate to meet the needs of the rapidly increasing populations in many developing countries. Increased food production in the SAT, in the recent past, has been achieved through expansion of the cultivated area. A major danger of short-term increases in cropping intensities, and of extending cultivation to areas marginally suited for arable agriculture, is that these activities tend to accelerate soil erosion, to increase pest and disease problems, and to reduce soil fertility if adequate attention is not given to all aspects of agricultural development.

ICRISAT now considers that a multidisciplinary framework for conducting resource-centered, holistic farming systems research in SAT countries is urgently required. Without such research, technological development in the SAT would either be delayed or impaired, and erosion of the remaining resource base would be accentuated (ICRISAT 1983).

Farming Systems Research: Objectives and Strategy

The main objective of ICRISAT's farming systems research is to develop technologies for increasing and stabilizing agricultural production through the efficient use of natural and human resources in the seasonally dry SAT. Farming systems research (FSR) starts on-farm and finally ends on-farm, too. By understanding the farmers' environment and the constraints influencing their decisions, a resource-centered farming systems approach complements the seed and commodity-oriented programs by sharpening the problem identification, shortening the gestation period for agricultural research, and improving the chances for the adoption of recommended technologies.

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The particular objectives of FSR that evolve from the above broad objectives are the following:

1. To understand the physical, biological, and socio-economic environments with which agricultural production takes place in the SAT.
2. To evaluate existing farming systems in representative or benchmark environments to improve our understanding of the farmers, their problems, skills, and constraints. Such information is used to help design crop improvement research and strategies, thus increasing the efficiency of agricultural research.
3. To consider research on new practices, principles, systems, components and subsystems at benchmark and on-farm locations.
4. To evaluate prospective technologies on farms in identified priority regions.
5. To monitor the adoption of new technologies emanating from FSR, assess their consequences, and derive implications for future farming systems and related research priorities and strategies.
6. To develop suitable methodologies to achieve these objectives and to use them as a basis for training in the concept and practice of FSR.

Strategy

FSR at ICRISAT comprises four broad activities: base-data analyses; on-station research; on-farm research; and simulation, modelling and systems analyses.

Base-data analyses involve the compilation of primary and secondary data on the SAT, aimed at delineating relatively homogenous areas for regionally focused research, and providing factual background for determining research priorities and strategies. This work should be considered as a continuing part of any FSR.

On-station studies are carried out at benchmark sites, and cooperative research locations primarily involving single- and multi-component research. A 'major operational research' phase is not to be part of on-station studies but is to be included in on-farm research. However, multi- and inter-disciplinary research is strongly encouraged in on-station activities.

On-farm research is an important function of FSR. Without this, the efficacy of base-data analyses and on-station research would be in question. On-farm research involves a combination of reconnaissance or exploratory surveys, diagnostic experiments, evaluative experiments, monitoring of technology adoption and constraints thereto, and evaluation of the consequences of adoption, including yield-gap analysis.

Modelling and simulation studies are useful in evaluating the impact of environmental factors on the biological processes, and determine much of the strategy and tactics of crop production. In the systems approach, climate and soil occupy a primary position in the whole hierarchy of data acquisition, processing, and analysis, and they become an integral part of the whole system.

FSR explicitly considers the natural resources of land, climate, people, and animals, and how they interact with cropping systems and crop cultivars to produce food. A more pragmatic research focus is oriented towards several well-defined, yet broad, research topics at the subsystem level. Specific research thrusts are identified for concentrated research efforts from time to time, based on accumulated experience, emerging problems, and constraints.

Priority Research Areas

Widely different management systems are required to evolve improved farming systems for the major soil orders of the SAT. Four major soil orders — Alfisols, Entisols, Oxisols, and Vertisols — encompass approximately 85% of the SAT. In the developing world, Alfisols and Entisols predominate in West Africa, and Alfisols and Vertisols in Asia; thus climatic and soil interactions research should concentrate on these soils (ICRISAT 1982).

Some of the priority research areas requiring further research are the following:

1. Characterization of Resources and Identification of Benchmark Sites

   Compilation of information on the agroclimatic and soil resources of the SAT should receive high priority in the selection of benchmark sites for developing and evaluating new technologies for a wide range of environments encompassing the major soil orders of the SAT. Such base-data analysis should help quantify risks to dependable agriculture associated with different types of land-use systems.

2. Development of Alternative Land and Water Management Techniques for Alfisols and Entisols

   Because surface sealing and crust formations in Alfisols are effective inhibitors to intake of water and seedling emergence, and inducers of runoff of rainwater, alternative land configuration and surface management techniques for increasing infiltration, minimizing erosion, and enhancing the potential for life-saving irrigation are needed. A substantial research effort should be made to develop land-and-water-management systems for light-textured Entisols and Alfisols with particularly low waterholding capacity, susceptibility to leaching, and consequently greater likelihood of moisture and nutrient stress.

3. Rainwater Management in Drylands

   Rainwater management should receive critical evaluation in a watershed-catchment context in operational research. On-farm research for evaluation and transfer of technology in this context is crucial.

4. Nutrient Management for Improved Productivity

   The soils found in the SAT are low in organic matter. Alfisols and Entisols generally have low clay contents. The clay is usually illitic and kaolinitic. Therefore, special attention will have to be given to improving nutrient efficiency under diverse cropping/land-use systems. Improvements in the efficiency of N and P fertilizers are urgently needed. Long-term studies on the dynamics of soil and applied nutrients should receive greater attention.

5. Machinery and Tool Development

   Improvements in the efficiency of farm inputs and operations as affected by the use of the machinery appropriate to the farmers' conditions and resources need emphasis. In the SAT regions, special attention should be given to sand-fighting equipment (in areas where wind erosion occurs) and crust breakers for effective and uniform seedling establishment.

6. Conservation-effective Farming Systems

   Soil losses by erosion and water losses as uncontrolled runoff are common in the SAT Alfisols. The erosional losses have a clear and immediate impact on farm productivity. The management practice evolved for the improved utilization of Alfisols in the SAT must be effective in respect of soil and water conservation, so that the resource base is conserved. At the same time the improved systems should be productive and economically attractive so that farmers become keen to adopt them.

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R. Fauck* Discussant — 2

Interactions of Soil Characteristics and Environmental Evolutions in the Sahel

The Sahel is situated in western Africa and is represented by an homogeneous belt limited by the 200 and 600 mm mean annual isohyets. The period of summer rainfall does not exceed three months and the development of agriculture and stock farming is constrained mainly by aridity. The main geomorphological units are sand dunes, long slopes with very gentle gradients, strong relief over hard rocks, and a rather non-functional, fossil and usually sand-filled hydrographical network.

The soils are varied, but at small scale the deep sandy soils (semi-arid and tropical ferruginous according to the French classification) and the clay loam soils (semi-arid, Vertisols and hydromorphic) are dominant. Saline or halomorphic soils are not commonly observed. Most of these soils are included in the Aridisols and Alfisols of Soil Taxonomy.

The vegetation is composed of an annual grass cover and shrubs, which are generally thorny, scattered over the landscape or concentrated within depressions with intermittent flow.

This homogeneity appears only in small scale studies. In fact, a number of large-scale interdisciplinary studies conducted over five years in Senegal, Mali, Upper Volta, and Niger have revealed great variety in the ecological situations of the Sahel. However, each of them shows a close relation between the landform, soils, and the vegetation cover. The evolution of the latter is rapid due to climatic changes and the exploitation or over-exploitation of the environment by men and their herds. Soil evolution follows upon vegetational changes.

Climate is the primary factor in evolution because it varies greatly between years. For instance, the total annual rainfall at Tahoua (Niger) ranged from 206-565 mm between 1969 and 1982. In fact, the regular decrease in rainfall is alarming. The mean annual rainfall at Agades (Niger) amounted to 165 mm over the period 1922 to 1960. It has fallen to 138 mm between 1970 and 1980. One cannot conclude that deterioration of the climate is permanent but only a temporary period of deficiency of this duration is enough to account for the difficult economic situation observed in the Sahelian zones.

But the consideration of the mean is only one approach to the problem. In reality, the closer one gets to the edges of the Sahara the more heterogeneous is the spatial distribution of the rainfall. This results in big differences in the growth of the annual grass cover with attendant consequences for pastoral policy, nomadism, and the over-exploitation of ecosystems.

Soils

In large scale studies there is a great variety of soils. However, in selecting classification criteria, it is observed that only a restricted number of characteristics are really significant. These are the real constraints upon soil use. These are:

1. The Profile Depth

   The shallow, skeletal soils are widespread on hard rocks or on outcrops of ferruginous hardpans inherited from more humid Quaternary periods. These soils are of little interest for development but they are of great practical importance for their occurrence on long slopes leads to immediate runoff after showers. Generally, these water resources are lost, for they are not used as in North Africa where water spreading is the practice.

   There are two types of deep soils, on aeolian sands or on clay loam materials derived from ancient weathering profiles or sedimentary rocks. There is a big variability in their distribution.

2. Profile Differentiation

   A sandy cover overlying clay layers is commonly observed. Although controversial as far as soil classification is concerned, a cover less than 20 cm thick completely changes the possible uses of the soils.

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Rainwater is trapped by sand and accumulates in chemically rich vertic clay horizons, which allows for development of excellent pasture lands for camels. Similar soils situated under more humid climatic conditions, may lack the aeolian sand.

3. Water and Temperature Regimes
These are little known. However, one can say that sandy soils have good porosity and are excellent reservoirs for available water. On the contrary, many vertic or hydromorphic soils with 2/1 clays provide an arid pedoclimate for vegetation.
4. The Structure of the Surface Horizon
Surface crusting is observed in all types of soil. This is probably the result of splash followed by the rapid and very pronounced drying under semi-arid climatic conditions. Although the crust is very thin, it completely changes the permeability of the surface soil. Deep sandy soils without such a surface crust could theoretically accumulate the whole rainwater and runoff and then provide a less arid medium for plants than that defined by local climatic data. Conversely, a crust leads to considerable runoff from early rains and to reduced water storage. Therefore, the latter cannot be assessed from meteorological data alone.
5. Erodibility
This depends above all on the detachability of exposed soil particles to transportation by wind or runoff waters. This is not well understood, but it seems to depend on texture and thickness of surface crusting.

The Environmental Evolution

The evolution of the grass cover is rapid depending on the climatic variability and on cropping and grazing conditions. The evolution of the woody vegetation is less rapid. After 5 years of exceptional drought, a number of woody species have disappeared from some zones. Such a situation has resulted from a shortage of water resources for several consecutive years due, on the one hand, to a decrease in rainfall and, on the other hand, to the increase in runoff coefficients. Therefore, the term 'desertification' has been used. In a true sense it is not an advance of the Sahara desert, but rather the local appearance of desert conditions, i.e. the disappearance of all vegetation.

The consequences of the rapid degradation of vegetation on the soil cover are obvious. New deflation is observed in the dry season and, elsewhere, there are deposits of transported sand. An increase in runoff is also observed on bare soils and subsequently, sheet erosion occurs. Runoffs amounting to nearly 50% of rainfall have been recorded in Upper Volta. This has resulted in gully erosion on dune landforms. Finally, some alluvial plains have been flooded, with erosion of the banks and irrigation canals.

The successive effects of aeolian and water erosion cause the sandy A horizons to be reworked and sometimes, the more compact red B horizons to be exposed. In practice one sees that, in all profiles, the A horizon has been reworked more or less recently — sometimes with a clear discontinuity with the underlying B horizons. The existence of this horizon, a particular type of Ap, changes the water regime of the soils in the toposequence.

However, the vegetation shows extraordinary powers of colonization and regeneration. When the environment is protected or when climatic conditions improve, pioneer plants establish themselves again in a well-ordered succession. However, some other conditions are necessary for good regeneration. The first requirement is the presence of seeds. Aeolian and water erosion carry away not only soil particles but also seeds, which may be their most serious consequences. The stock of seeds, which have been carried by wind, must be replenished over time. Then plants must search for water supplies in the soils. Infiltration is blocked mainly by the surface crust and it is on this which one should act. Numerous authors consider that animal herds lead to soil compaction but they sometimes provide a means for improving permeability and make subsequent regeneration possible. Exploiting the environment does not mean degrading it, as is sometimes said. The same does not hold true for overexploitation. Moreover, it is observed that some microdunes heaped up by the wind serve as traps for rainwater, runoffs, and equally for seeds. These piles of sand are the sites of the most rapid regeneration of grass cover and of the progressive accumulation of organic matter. Then, woody shrubs establish themselves, leading to an increase in aeolian accumulations. In contrast, the clay loam soils take much longer to recover with vegetation following a period of desertification.

Conclusions: The Evolutionary Cycles

In the semi-arid Sahel, there is continuous evolution of the grass cover and of the characteristics of soil upper horizons. The evolutions differ in intensity with ecosystems, but generally they are rather rapid. There is superimposition of a series of evolutions, the oldest of which are inherited from various pedoclimates from late and recent Quaternary periods. Small variations in the existence of a sandy soil cover and destruction of the surface crusts bring about great changes in vegetative regrowth. Water erosion is a hazard even under semi-arid climatic conditions. In contrast, aeolian erosion can have favourable effects, which should be controlled.

In any case, the possibility of accumulating available water is the main factor in land use. A deep profile is not sufficent since good infiltration is critically important. Research must be carried out in order to get a better knowledge of the processes affecting water dynamics in soils. The development of the Sahel, where the climate fluctuates so much calls for a more efficient use of water resources along with a better spatial distribution of the water by spreading it from skeletal soils to soils where it can be used by plants.

Desertification is a real danger, for it becomes permanent and quickens of its own accord once the soils attain a certain level of degradation. But the observed cases of rapid regeneration and the analysis of close correlations between the evolution of vegetation and that of soil characteristics shows that simple methods of development can be found. First of all, it is necessary to study soil constraints.

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Session 4
Soil/Environment Interactions in the Semi-Arid Tropics

Summary of Discussion

J.S. Russell*

A major factor affecting the prediction of plant production in the semi-arid tropics is the dominance of the water constraint in such areas. The term semi-arid implies both low potential, due to overall water limitation, and year to year variability. The effect of both of these factors increases as the semi-arid/arid frontier is approached.

The dominance of the water constraint also means that nutrient deficiencies such as nitrogen and phosphorus have to be considered as interactions, e.g. water-phosphorus, water-nitrogen etc. Interactions are much more difficult to study than main effects and this combined with year to year variability has limited understanding in this area.

An additional limitation is that in the past, research into aridity in general and semi-arid areas in particular has not received the attention it deserves. There has been a tendency to assume that deficiencies of water in dry areas can best be overcome by the use of irrigation and of water from outside sources.

It is being increasingly recognized that the irrigation option is applicable to a very small part of the semi-arid areas only and where this option was available, it has usually been exercised. Increased emphasis is now being given to understanding water dynamics in soils and plants and to finding ways of making best use of the water available.

Like the Sahara, the Australian semi-arid areas have a long frontier with the arid and desert regions, extending over temperate, subtropical, and tropical climatic zones. The amount of experimental and practical experience on nutrient and water constraints varies with the climatic region. It is most extensive in the southern and temperate regions where crops are grown with winter rainfall and where there is more than 120 years of intensive land-use experience in frontier situations. In these areas, the use of phosphate fertilizers extends to the limit of crop cultivation of cereal crops such as wheat and barley in spite of the low rainfall and year to year variability. On the other hand, use of nitrogen fertilizers for wheat, in particular, is restricted to areas of higher and less variable rainfall.

In the subtropical, semi-arid areas, the pattern of phosphorus and nitrogen interactions appears similar, particularly with cool season crops such as wheat grown on soils with moderate to high levels of stored water. Water-holding capacity of the soil is an important factor in affecting the continuity of growth of summer crops in the subtropics, especially where rainfall variability is high. This is of lesser importance in crops grown on winter rainfall in the temperate semi-arid areas.

Less information is available concerning nutrient-water interactions in the Australian semi-arid tropics, especially towards the limits of cultivation. It is believed that a greater scientific understanding of this area and the application of the principles of soil science and plant nutrition will avoid the slow and painful trial and error process that has characterized the establishment of the limits to permanent cultivation in other semi-arid areas.

Soil properties have an influence on the effectiveness of water use in semi-arid areas and some management options are available. However, large areas of soils in semi-arid areas are of low fertility such as Entisols and Alfisols. On many of these soils, pastures rather than crops are the preferred form of land use. Pasture plants that are adapted to semi-arid areas have

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the ability to integrate the intermittent available water periods better than crop plants.

In attempting to improve the prediction of plant production in the semi-arid tropics, more attention needs to be paid to obtaining greater scientific understanding of the climate-soil-plant system. Both the keynote and the discussion papers emphasized the importance of understanding water dynamics in semi-arid soils. In terms of understanding the operative processes, there is little question that water-balance models are an important tool. Because of the critical importance of water balance in semi-arid areas, variations in amount of water available can greatly affect plant growth. Thus explanation of water availability can frequently explain a high proportion of the water variability of plant yield.

Water-balance models are a key component of crop production models in semi-arid areas. Use of these models is of value in transferring results from experimental stations, in identifying risks to levels of crop production, in shortening the time for evolving production systems, in identifying gaps in knowledge, and in predicting production.

Most of the available water-balance models are robust when applied to semi-arid areas. One reason is that most models are self correcting in that water that is not lost today is lost tomorrow. Greater difficulties have been experienced of using water-balance models in humid areas and wetland rice was cited as an example.

Good models characterize the soil the way a plant sees it and it is important that models be mechanistic rather than empirical. There is a tendency in modelling generally to move from the simple to the complex. If models become too complex there is difficulty in obtaining inputs and parameters for all but a few sites. Thus simplicity has definite advantages for models being used in field situations. There is also a difficulty in establishing data bases in countries in tropical regions to provide the necessary input data.

In contrast to the wide range of simple to complex water-balance models available for use in semi-arid areas, little work has been done in modelling nutrient entry into plants. Partly this reflects the lack of information in this area.

Another area where quantitative information is lacking is on runoff in semi-arid areas and in the development of useful runoff functions. This compares with the much greater information available for the humid tropics. The runoff function is clearly a key component of precise water balance models and this area needs to be given further attention particularly as surface soil management techniques are being studied in more detail.

Water balance models are useful in indicating the range of variability of soil water over time. The question of whether rainfall variability was more significant in semi-arid environments than in other more humid environments was raised. In reply, it was noted that the relation between rainfall and evapotranspiration was more critical in the semi-arid tropics than in the humid tropics. Also, a major problem in the semi-arid tropics were years in which the rainfall was very low. The high interannual variability was seen as a major factor dominating evolutionary vegetation changes in the Sahel.

A second area of study in the semi-arid areas that needs more attention is in the effects of land management practices. There is a need for increased understanding on the effects of land and surface management practices on the efficiency of water use and of plant productivity.

Soil cover is important in ameliorating the harsh environment that can exist at the surface of the soil. In the semi-arid tropics this cover can reduce the surface soil temperature and can improve plant germination and establishment. It can also reduce the erosivity of the surface soil.

The role of pastures in the semi-arid tropics needs to be studied in more detail. Pasture plants can increase the amount of ground cover available and could be useful in parts of the Sahel, expecially as grazing animals are an important component of the ecosystem. Pastures are particularly useful on soils of low fertility in marginal lands. A wide range of tropical forage legumes is held in Australia by the CSIRO Division of Tropical Crops and Pastures. This genetic-resource bank comprises more than 14 000 accessions. Some of these legumes could be useful in semi-arid, tropical environments and further research in this area was suggested.

The question of the balance of crops and pastures was raised. Crops are major components of agro-ecosystems with a high human population density such as areas of the semi-arid tropics that have moderate annual rainfall.

In such areas, the role of pastures is restricted to the low fertility soils. However, as aridity increases, the role of pastures increases.

As with the use of minimum tillage, a key factor in the usefulness of pasture legumes as components of cropping systems is the proportion of available water that such plants use. The development of herbicides does allow pasture growth to be terminated as a management practice to provide soil cover.

The point was made that whilst in semi-arid areas it was desirable to prevent runoff as aridity increased, there was scope for directing runoff into mini dams and concentrating the limited water into areas where cultivation could then occur.

Session 5

Physical Problems of Vertisols

Chairman: C.F. Bentley
Discussion Leader: J.P. Quirk

Soil Physical Factors in Crop Production on Vertisols in Queensland, Australia

G.D. Smith, D.F. Yule and K.J. Coughlan*

Vertisols are minor soils in the traditional agricultural areas of temperate regions but large areas occur in the Australian subtropics. The estimated area of Vertisols in Queensland is 50 M ha (Weston *et al.* 1981), which is about two-thirds of the Australian total and about one-fifth of the world total area (Hubble 1972). At present 1.2 M ha are cropped and a further 6 M ha have potential.

The physical properties of Vertisols can cause problems in crop production; this paper outlines the soil physical problems encountered, and research approaches adopted in Queensland.

Climate

The area cropped lies between 20° and 29° S latitude and within the 500–800 mm rainfall isohyets (Figure 1). Mean daily maximum temperature ranges from 25–30°C and mean daily minimum from 11–19°C. Summer rainfall predominates (Table 1). Mean daily minimum evaporation usually exceeds rainfall throughout the year (Table 1). The erosion index of rainfall is highest in summer months (Table 1). Variability in rainfall is a major problem for farming (Hammer 1983). Rain commonly falls on a group of 2–3 rain-days with several days or weeks of dry weather intervening, even in the wet season.

Role in Crop Production

Vertisols are used extensively for winter grain cropping. Farm size ranges from 250 ha in reliable rainfall regions to 5 000 ha in marginal areas. Wheat is the main winter crop; barley, oats for grain and grazing, canary seed, linseed and safflower are also grown. Grain sorghum and sunflower are the main summer crops, with lesser areas of cotton, millets, panicums, forage sorghum and, in the higher rainfall areas, maize and soybean.

Irrigated Vertisols (approx. 50 000 ha) produce cotton, maize, soybean, wheat, sorghum, vegetables and lucerne. Groundwaters are used extensively in the Lockyer and Callide Valleys and on the Darling Downs. Major areas are irrigated with surface water at Emerald, St. George, Theodore and on the Darling Downs. Large farm dams to store surface runoff for irrigation, are becoming more common.

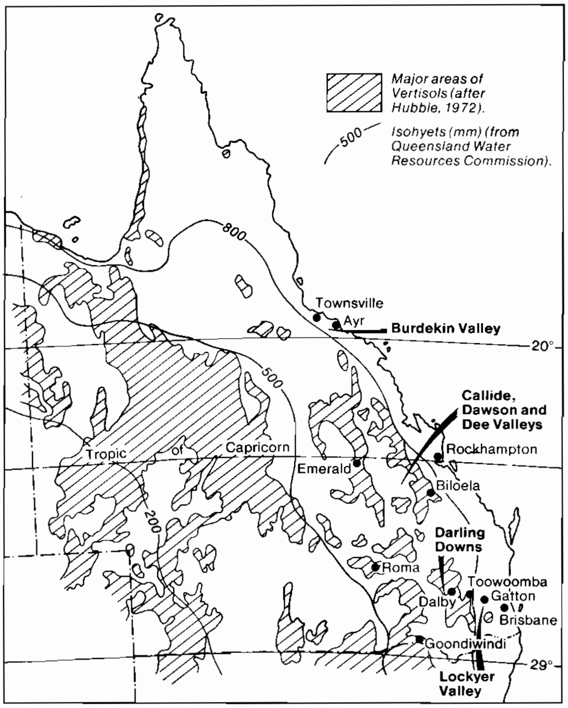

Figure 1. Map of Queensland showing the distribution of Vertisols in relation to mean annual rainfall, towns, and locations.

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Table 1. Climatic indices for selected Queensland towns.

Town	Index	Mean Quarterly			
		Jan–Mar	Apr–Jun	Jul–Sep	Oct–Dec
Ayr	R	8.2	1.3	0.6	1.9
	E	5.7	4.2	4.7	6.7
	EI	366	6	11	187
Emerald	R	3.1	1.1	0.8	2.0
	E	6.7	4.1	4.7	8.0
	EI	172	16	11	106
Gatton	R	3.4	1.5	1.1	2.7
	E	6.0	3.7	4.0	6.7
	EI	157	11	15	102
Roma	R	2.5	1.1	1.1	1.9
	E	6.9	3.3	3.4	7.1
	EI	122	16	11	71

R = mean daily rainfall (mm).
E = mean daily pan evaporation (mm).
EI = mean erosion index calculated from total rainfall energy and maximum 30 min intensity (Rosenthal and White 1980).

Traditionally, dryland farmers try to grow one crop each year with fallow in the alternate season. Either a winter or a summer crop can be grown. However, there is an increasing tendency towards opportunity cropping (planting when the soil water store is substantially replenished irrespective of season) (Berndt and White 1976). Waring *et al.* (1958) found wheat yield was significantly linked with the amount of water held in the soil at sowing.

Livestock production (for beef and wool) in association with cropping is usually found only where grain production is less reliable. Native or sown pastures, crop residues, and fodder crops are used for grazing. Regular crop-pasture rotations are uncommon, but might be used more widely if a suitable legume species were available.

Soil Characteristics

Classification

The Queensland Vertisols have generally been classed into two broad groups. The darker forms are black earths (approximately coinciding with the Pellustert great group) and are usually formed on basic rocks (particularly basalt) or alluvium derived therefrom. They are most common in the eastern part of the State. The other more widespread group comprises grey, brown or red clays (Chromusterts and Torrerts) and occur throughout the State on a range of parent materials. This group is more diverse than black earths in depth of solum, cracking pattern, structure in the upper profile, gilgai development, soil reaction profile, salinity and sodicity, and clay mineralogy (pers. comm. R. Isbell, CSIRO, Townsville). The occurrence of gilgai microrelief varies greatly. It may be absent or range up to giant forms in which the vertical interval between mound and depression can be as much as 2 m (Hubble *et al.* 1983).

Analytical Data

Some analytical data for the upper horizon of selected soils are given in Table 2.

Management

Properties of Vertisols can be either an advantage or a disadvantage for farming. Characteristics that, when present, are an advantage include: high natural fertility, high plant available water capacity, high potential infiltration rates (via cracks) when dry, self mulching (aids seed bed preparation), lack of specific restrictions to root penetration, ability to rejuvenate structure, and occurrence in large areas on gentle slopes.

Characteristics that, when present, are a

Table 2. Some properties[a] of the 0–10 cm layer of selected Queensland Vertisols.

Soil[b]	pH	EC	OC	CS	FS	S	C	CEC	Ca	Mg	Na	K	$WC_{0.33}$	WC_{15}
1	8.3	0.10	1.2	11	47	8	32	28	22.6	6.6	0.3	0.5	24	12
2	8.1	0.11	1.9	24	27	10	36	27	19.6	7.9	0.5	1.0	26	14
3	7.5	0.06	1.6	12	32	17	36	29	18.6	7.1	0.8	0.9	26	13
4	8.5	0.11	1.4	15	28	11	42	28	23.9	7.0	1.1	0.6	30	15
5	8.0	0.16	1.8	12	23	20	43	37	27.2	7.4	0.7	1.0	35	18
6	7.0	0.06	1.2	7	24	20	47	29	17.5	9.6	0.3	0.7	30	16
7	7.6	0.07	1.2	6	18	17	58	46	13.6	26.1	1.8	1.5	40	20
8	8.2	0.17	1.7	3	11	22	63	52	38.3	9.4	1.6	1.9	47	25
9	8.2	0.15	1.3	2	17	15	65	66	39.5	23.5	3.1	1.7	54	29
10	8.0	0.05	1.0	4	16	12	67	84	53.5	26.2	0.3	0.8	52	33
11	8.3	0.19	1.3	3	8	10	78	74	42.9	28.2	2.8	3.1	66	37
12	6.8	0.12	1.5	2	3	12	80	60	28.7	28.7	1.6	0.8	49	30

a. pH = glass electrode 1:5 soil: water suspension.
EC = electrical conductivity (mS/cm) 1:5 soil: water suspension.
OC = organic carbon (%), Walkley-Black method.
CS = coarse sand (%); FS = fine sand (%); S = silt (%), C = Clay (%).
CEC = cation exchange capacity (m equiv./100 g) at pH 8.5.
Ca, Mg, Na, K = exchangeable cations (m equiv./100 g).
$WC_{0.33}$ = water content at −0.33 bar. WC_{15} = water content at −15 bar.

b. Soils arranged in order of increasing clay content. Soils 1 to 10 are from the Emerald Irrigation Area; 2, 3, 4, 5 and 8 are from the Dawson Valley; 6 and 12 are from the Burdekin Valley; 7, 9 and 11 are from the Darling Downs. For further details on these soils see Coughlan (1979).

disadvantage include:

1. Soil water relations — the relatively large amount of rain required to initiate effective water storage; slow infiltration when cracks are closed and hence high runoff; slow internal drainage and hence waterlogging and denitrification (e.g. Craswell and Strong 1976).
2. Soil structure — the narrow range of optimum water content for tillage causing difficulties in timing of operations (especially over large areas); instability to wetting or rain, resulting in surface seals and crusts; high implement draft when dry; large, strong clods in seedbeds obstruct seedlings; high soil erodibility.
3. Geomorphology — uneven microrelief (gilgai — Thompson and Beckmann 1982); slopes either inadequate (drainage) or excessive (erosion); high subsoil salinity; shallow water tables; shallow soil depth over rock.

In summary, some attributes make management difficult and cushion against mistakes; other attributes make management difficult and multiply the costs of slight mistakes. An understanding of the physical processes of Vertisols is a prerequisite for wise decisions in crop and soil management.

Physical Processes in Queensland Vertisols

Soil Structure

Of primary interest are the size and stability of aggregates in the surface layer; these influence seedbed properties, water intake, and soil erosion.

Dry Aggregate Size Distribution

The optimum dry aggregate size distribution for seedbeds has not been established. Yule *et al.* (1976) found that Darling Downs soils that commonly show seedling establishment problems have > 40% of seedbed aggregates greater than 5 mm. Coughlan and Loch (1984) studied the soil properties affecting dry aggregate size distribution for a range of cultivated Vertisols having clay contents varying between

38 and 84%. They found that:

$$\text{dry aggs.} > 5\ \text{mm}\ (\%) = 14.2 + 6.9\ \text{ESP} + 1.5\ \text{clay} - 1.39\ \text{CEC} \quad \ldots (1)$$

$(n = 26,\ R^2 = 0.76,\ P < 0.01)$

where

ESP = exchangeable sodium as percentage of the cation exchange capacity.
clay = clay (%)
CEC = soil cation exchange capacity (m equiv./100 g)

Although organic matter content was significantly correlated with aggregate porosity, it was not linked with aggregate size. Likewise Smith (1984, and unpub. data) found no significant correlation between aggregate size and organic matter after wetting and drying. Apparently the physico-chemical properties of the clay present in the soil override any effect of organic matter in determining aggregate size distribution. This conclusion is in accord with Warkentin (1982) who suggested that in clay soils organic matter is important on a microstructural rather than a macrostructural scale.

Two conclusions can be drawn from equation (1):

1. Fine seedbed conditions are favoured in soils with high CEC in relation to clay content, i.e. containing highly active clay minerals.
2. Management to mitigate cloddiness in seedbeds should reduce ESP or counteract clay dispersion, e.g. apply amendments such as gypsum, or protect the surface from the dispersive action of rain.

Aggregate Breakdown

RAPID WETTING

Stresses induced by rapid wetting of dry soil have been attributed to differential swelling (Quirk and Panabokke 1962), trapped air effects (Emerson 1964) and heat of wetting (Collis-George and Lal 1973). We have found trapped air effects to be negligible in Queensland Vertisols. Breakdown is strongly dependent on initial moisture content. Slaking has been shown by Collis-George and Lal (1970) to reduce infiltration in laboratory columns but it would not be expected to interfere with water entry in the field if recharge is mainly via cracks. However, water flowing down cracks may degrade subsoil structure by slaking (pers. comm. T. Abbott, Department of Agriculture, Rydalmere, New South Wales). Coughlan and Loch (1984) found that slaking alone, if unaccompanied by clay dispersion, did not appear to increase dry aggregate size. Smith and McShane (1981) found that, when seed was sown into dry soil, which was then irrigated, partial slaking of large clods produced a satisfactory seedbed. The consequences of breakdown probably depend on the size of the products. If breakdown produces material that acts as a filling and a binding agent between aggregates, then agronomically important processes could be adversely affected.

SLOW WETTING

Coughlan (1979) wet aggregates slowly by varying the suction on a sintered glass plate. He found, for the soils in Table 2, that the size of aggregates stable to wet sieving after slow wetting was a function of wetting rate and that water stability differences between soils, at similar wetting rates, were only small (Figure 2). Wetting rate at low tensions increased with CEC. When aggregates were wet under tension with gypsum solution (19 m equiv./L) the wetting rate, and breakdown, increased (Smith unpublished data). Soils that take in water rapidly are usually thought to have good structure but this evidence suggests breakdown would be greater in these soils. This highlights problems in using slaking tests to assess soil structural stability.

EFFECT OF RAIN

Rainfall energy plays a critical role in dispersion of aggregates. Coughlan *et al.* (1973) found a critical water content above which clay is readily dispersed by applied energy. They called it the Disruptive Moisture Content (DMC); it is related to the Liquid Limit and is close to saturation. Thus if constant rainfall is assumed, the amount of dispersed clay in field soils would depend on how often the DMC is reached and the wet strength of aggregates. The frequency with which the DMC is reached depends on the value of the DMC and the wetting rate of surface aggregates. Both DMC and wetting rate usually

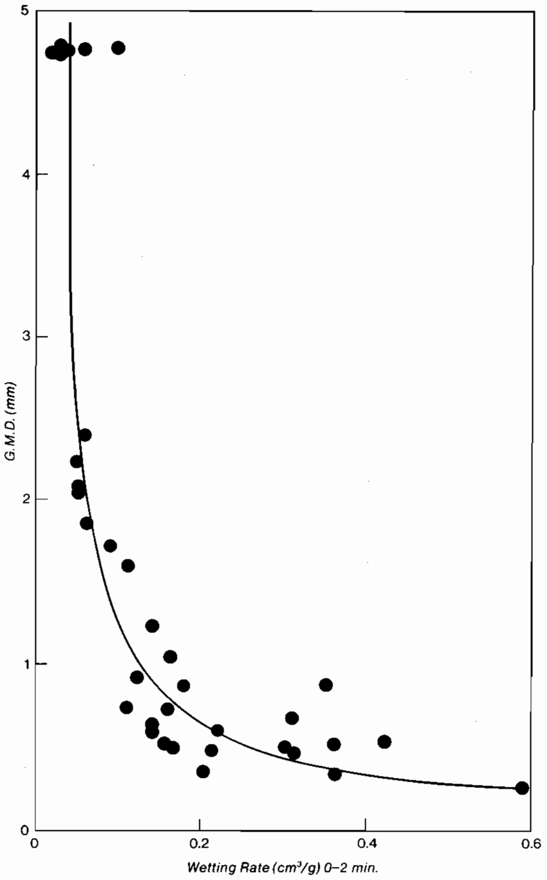

Figure 2. The effect of wetting rate on geometric mean diameter (G.M.D.) of water stable aggregates.

increase with CEC, so that soils with high CEC should have better structural properties and disperse less frequently. This expectation is generally supported by field observation.

Loch and Smith (unpublished) compared water stable aggregate sizes after simulated rain in a field rainulator and after immersion wetting. Immersion wetting produced a bimodal size distribution (Table 3). Simulated rain virtually destroyed the peak in the > 1 mm size range and caused breakdown to 0.5–0.125 mm and < 0.02 mm sizes. The importance of rainfall energy in producing breakdown to the very small sizes that influence field structure and erosion processes is clearly evident from these results.

Self Mulching Soils

Self mulching is defined as 'the tendency to form a loose, granular (dry) surface mulch as the result of freezing and thawing, or wetting and drying' (De Vos and Virgo 1969). Self mulching depends strongly upon environmental conditions, and is favoured by two processes:

1. Aggregate failure (but not dispersion) by rainfall or wetting.
2. Aggregate failure during drying.

Self mulching characteristics can be examined in the laboratory by measuring aggregate breakdown or porosity increase with gentle wetting and drying. Coughlan (1979) found that aggregate breakdown increased with increasing volume change on wetting and with increasing macroporosity of dry aggregates. Smith *et al.* (1978) found for a range of soils with more than 50% clay that the porosity of wet and dried aggregates increased with increasing clay content. Porosity increase on wetting and drying was significantly correlated (positively) with organic matter content only in soils with a CEC-clay ratio < 50 m equiv./g.

Coughlan (1984) found that, for a given Vertisol, self mulching was greater at a lower applied wetting rate. Therefore low intensity

Table 3. The effect of simulated rain and of immersion wetting on size of aggregates (weight %) found by wet sieving for two Vertisols from south Queensland.

Soil	Energy Source	Size ranges (mm)						
		> 1	1–0.5	0.5–0.25	0.25–0.125	0.125–0.02	0.02–0.002	< 0.002
Black earth	R	10	17	16	6	4	23	13
(Irving Series)	I	63	2	1	1	25	6	2
Grey clay	R	7	14	13	10	23	22	10
(Moola Series)	I	61	3	1	1	28	4	2

R = Rainulator (Meyer and McCune (1958) modified as per Loch and Donnollan (1983a)).
I = Immersion wetting of air dry soils.

rainfall or sprinkler irrigation should favour self mulching. Rapid, intense drying also favours self mulching (Coughlan 1984). Thus stubble retention on the surface could increase cloddiness by reducing the evaporation rate. This was confirmed by Loch and Coughlan (1984).

In summary, aggregation in the surface is largely due to differential swelling on wetting and shrinkage on drying. The breakdown of aggregates is generally beneficial if clay does not disperse either spontaneously or under rain. Mechanisms important in aggregation are mainly pre-determined by fundamental soil properties but management can have some influence. Retention of stubble will minimize breakdown under rain and hence reduce runoff and erosion, but may reduce self mulching that assists seedbed preparation. Amendments such as gypsum counteract dispersive influences and will reduce dry aggregate size in seedbeds. In general there is a lack of sufficiently sensitive tests to predict behaviour of Vertisols under field conditions, and the likely effects of management practices. However, Coughlan (1984) considered that aggregate wetting rate, dispersion ratio and aggregate wet strength offer some promise for predictive tests.

Bulk Density—Water Content Characteristic

The study of field bulk density in Vertisols is complicated by cracks (Berndt and Coughlan 1977). It can be simplified by using the Swelling Limit concept proposed by Yule and Ritchie (1980). The swelling limit, i.e. point L in Figure 3, is the moisture content at the break point between Structural and Normal shrinkage. In Vertisols the Normal phase usually extends to water contents much drier than the −15 bar water content (Figure 3).

The bulk density at L is the minimum the soil can attain. As the soil dries further, cracks begin to form. The drained void system (existing at L) in the soil between cracks remains constant throughout the Normal shrinkage phase. Thus the continuity and size distribution of voids present at L have important implications for agronomy. Agronomic processes influenced by these voids would include drainage in the very wet state (Greenland 1981; Bouma 1981), aeration of the soil mass between cracks, and root penetration (Greacen and Gardner 1982). Because of their agronomic importance the nature of these stable voids needs to be better understood.

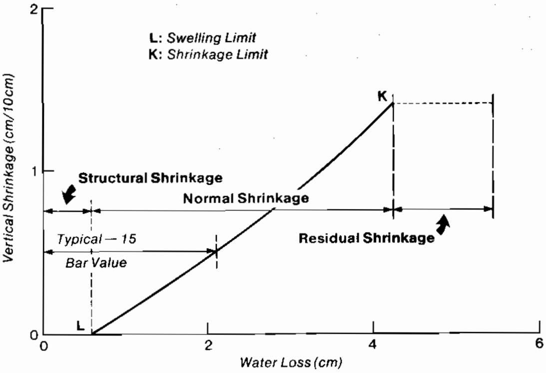

Figure 3. An idealized model of soil water loss and vertical shrinkage (adapted from Yule, 1983b).

In field bulk density studies it is virtually impossible to sample cracks representatively. However for depths beyond 20 cm the air content at L seldom falls outside the range 0.03 – 0.08 cm^3/cm^3. With two assumptions, viz. an air content of 0.05 cm^3/cm^3 and a particle density of 2.65 g/cm^3, the minimum bulk density can be calculated from the water content at L by:

$$\text{B.D.min} = \frac{0.95}{0.3774 + \theta_{gL}} \quad \ldots (2)$$

where B.D.min = minimum bulk density at the Swelling Limit (g/cm^3) and θ_{gL} = gravimetric water content at the Swelling Limit (g/g).

Thus bulk density can be calculated if the gravimetric water content at the Swelling Limit is known. The field approach, developed by Shaw and Yule (1978), is to measure gravimetric water content before any cracks open. Results using equation (2) will be sufficiently accurate for many purposes. However, errors will arise if the soil has not been adequately wet or if the assumed air content is wrong.

The bulk density-water content characteristic can be utilized in two ways. Firstly, the change in soil height in the field can be used to show water depletion by crops and hence for irrigation scheduling (Yule 1984a). Second, it can be used to characterize field bulk density without measurements over a range of water contents (Bridge and Ross 1984; Yule 1984b).

Soil Water Relations

Soil water storage capacity influences yield and the risk of failure in rainfed cropping; in irrigated cropping it influences frequency and efficiency of irrigation. Two aspects are vitally important, viz. water entry to the soil, and the plant available water capacity within the soil.

Water Entry

FLOOD IRRIGATION

Water entry during flood irrigation was studied for 10 Vertisols (ranging in clay content from 36–71%) under a wide range of antecedent water conditions at Emerald (Shaw and Yule 1978). They used isolated 25 m bays, sealed to a depth of 100 cm. Standard irrigation time was 5 hours and one irrigation was extended to 3 days. Water flooded into cracks and filled the soil 'from the bottom' before pondage was achieved. Very high initial water entry rates rapidly decreased as the cracks filled and the soil swelled.

The 5 hour infiltration data was fitted to an equation of Collis-George (1980):

$$I = i_{i^*} + S^* t^{0.5} \qquad \ldots (3)$$

where I = cummulative infiltration (cm)
i_{i^*} = an instantaneous infiltration (cm)
S^* = field measured term related to sorptivity
t = time.

For 50 infiltration events, equation (3) was significant at $P < 0.01$ at 27 events and at $P < 0.05$ at 18 events. The parameter i_{i^*} comprised 60–75% of the soil water deficit. S^* was independent of antecedent soil water content but varied across sites.

Collis-George (1980) suggested that i_{i^*} should be related to crack volume. Three dimensional, normal shrinkage theory implies that crack volume should be about two thirds of the total water content change (soil water deficit). Clearly, i_{i^*} found for these soils agrees with this suggestion.

A steady water intake was not reached after 3 days ponding in the above experiment. Gardner and Coughlan (1982) found infiltration rate after 7 days ponding declined by up to an order of magnitude from the rate at 5–24 hours on Burdekin Valley soils.

INFILTRATION UNDER RAIN

Soil water recharge via cracks is a function of rainfall rate and soil properties. If rainfall rate exceeds the infiltration rate of the soil between cracks, runoff flows into cracks (Ross and Bridge 1984). Thus soil properties influencing the rate of crack closure and factors such as the degree of self mulching, tillage, and surface cover are important. Loch and Coughlan (1984) found indirect evidence from chloride profiles that tillage reduced water entry via cracks. Further work is underway on infiltration under rain in Vertisols.

Plant Available Water Capacity

THE PAWC CONCEPT

Available water capacity (AWC) is an estimate of the soils water supplying capability. AWC is defined as the difference in volumetric water content between −0.33 bar (or −0.1 bar) and −15 bar soil matric potential. A rooting depth may be assumed or measured to provide an estimate of total AWC in the profile.

However several limitations have been found when applying this concept to field situations, e.g. field soils may not wet to −0.1 bar throughout the profile, root water extraction might not reach or may exceed −15 bar; and the laboratory procedures of grinding and wetting affect the result (Gardner and Coughlan 1982; pers.comm., P. Thorburn, Department of Primary Industries, Indooroopilly). Consequently Gardner *et al.* (1984) defined Plant Available Water Capacity (PAWC) as the difference between the upper storage limit and the lower storage limit measured in the field and summed over the plant-rooting depth. PAWC may vary with crop, stage of growth, level of plant stress, etc. but when it has been measured using appropriate management for the intended application, it has proved an extremely useful concept for comparisons among soils (Shaw and Yule 1978; Gardner and Coughlan 1982).

Comparison of PAWC and AWC can be used to indicate constraints on PAWC. Such constraints might be poor water entry resulting in incomplete subsoil wetting, or limited root depth and activity resulting in incomplete subsoil drying (Gardner et al. 1984). This information is fundamental to the development of appropriate management of amelioration techniques.

MEASURED PAWC VALUES

The upper storage limit has been measured following crop irrigation in isolated mini-bays (Shaw and Yule 1978; Gardner and Coughlan 1982) or after prolonged ponding in infiltration rings (Mullins 1981). The lower storage limit has been measured after an appropriate crop drying period or taken as the permanent wilting point (Mullins 1981). Shaw and Yule (1978) found grey clays in the Emerald area ranged in PAWC from 7.4–9.0 cm (mean 8.2 cm) with a rooting depth range of 40–60 cm (mean 50 cm). The PAWC of black earths in their study ranged from 9.6–13.8 cm (mean 11.8 cm) with a rooting depth range of 70–80 cm. Using similar techniques, Gardner and Coughlan (1982) found grey clays and black earths in the Burdekin Valley had a PAWC range of 10.4–12.4 cm (mean 12.0 cm) with a rooting depth range of 85–120 cm (mean 100 cm). The grey clays studied in southern Queensland by Mullins (1981) had a greater range in PAWC, viz. 8.6–18.0 cm (mean 12.6 cm) for a rooting depth range of 75–150 cm (mean 110 cm). The black earths in this study had a considerably higher range of PAWC values, viz. 11.4–25.8 cm (mean 20.0 cm) with a wetting depth of 75–150 cm (mean 120 cm). The higher values obtained by Mullins may reflect longer ponding times and the use of permanent wilting percentages derived by the sunflower technique (in which field restrictions to root growth would not operate).

PREDICTION OF PAWC

Since field measurements of PAWC are slow, inconvenient and expensive (extensive replication is necessary), there is interest in prediction from other soil properties. Shaw and Yule (1978) found the maximum and minimum soil water contents in the field were highly significantly related to CEC and −15 bar water content. Below 70 cm, the prediction was improved by including a salinity index. The equations based on −15 bar water contents have been successfully used in other regions (Gardner and Coughlan 1982; Reid *et al.* 1979).

An estimate of the depth of active root zone is also necessary to predict PAWC. Shaw and Yule (1978) found the maximum rate of increase of chloride with depth was a useful predictor; Reid *et al.* (1979) and Gardner and Coughlan (1982) found the depth of peak chloride was a better estimate. McCown *et al.* (1976) predicted PAWC using a triangular distribution derived from measured maximum and minimum water contents in the surface and depth to the peak salt concentration. This approach was successful on Burdekin soils (Gardner and Coughlan 1982). However soluble salts may be substantially leached by deeper wetting after a change in moisture regime (Smith and McShane 1981; Yule *et al.* 1980; Gardner and Coughlan 1982). Root growth models for individual crops on particular soils would be the best way to estimate root depth in PAWC calculation where fallows or irrigation are used.

Mullins (1981) predicted PAWC for five Great Soil Groups (Stace *et al.* 1968) from wetting depth estimated from either the electrical conductivity profile or soil profile features. Williams *et al.* (1983) developed equations for the soil moisture characteristic for groups of soils with similar soil moisture characteristics. These equations may be used to predict AWC if new soils can be allocated to groups.

The work of Mullins (1981) indicates that it may be possible to derive a simple equation to predict PAWC (and distribution in the profile) for groups of soils, based on some easily measured property or morphological feature. Such groupings could be useful for an edaphological soil classification.

In summary, PAWC is an important soil property that should be determined in the field under conditions appropriate to the intended application. Predictions that are satisfactory for some planning purposes are available.

Management Studies

Soil Erosion

EFFECT OF SURFACE MANAGEMENT ON HYDROLOGY AND SOIL LOSS

The effect of crop or stubble cover and tillage is being monitored with automatic instruments at four sites — two on the Darling Downs (Freebairn and Boughton 1981) and one site each at Emerald (Sallaway *et al.* 1983) and Roma.

Catchments are contour bays of 1–15 ha — the basic farm management unit. Hydrological characteristics of runoff events in the Darling Downs experiment (slope 6–7%) are reported by Boughton and Freebairn (1981). A multiple linear regression (R = 0.63) linked runoff coefficient (runoff rate — rainfall intensity ratio) to percentage surface cover (negative) and 15 min rainfall intensity (positive).

Surface management can reduce runoff and soil movement to 'acceptable' levels (Table 4). The stubble mulched treatment (tilled with stubble left on the surface) had the highest fallow efficiency (% of fallow rain stored at planting), and small soil loss. Although the zero tillage treatment (stubble retained) almost eliminated soil loss, the fallow efficiency was low.

A simple water balance from runoff and soil water content measurements suggests that evaporation is the major loss mechanism contributing to the generally low-fallow efficiencies. Shallow weighing lysimeters showed that stubble retention reduced the rate of evaporation after rain, but resulted in only minor differences in total evaporation over long dry periods. Therefore frequency of rain would affect fallow efficiency if evaporation were the main process influenced by surface management. However the runoff data suggest that the main effects on fallow efficiency are due to increased infiltration and less runoff during rain. Similarly Yule (1981) reported that stubble-retained zero-till plots at Hermitage Research Station had additional water accumulation at depth in the profile and earlier in the fallow compared with tilled bare-fallow plots.

The Emerald experiment (started in 1982) has nine contour bays (9–15 ha in area) with bank length up to 1300 m on slopes of about 2%. Wheat, sorghum and sunflower are grown and different tillage implements are used to impose various surface soil conditions, soil water contents and stubble cover at any time. In the initial four runoff events (in early 1983) trends in total runoff were bare fallow > sunflower stubble > sorghum stubble, and disc plough > blade plough > zero till. The combination of zero till and sorghum stubble eliminated runoff. Maximum soil loss (13.3 t/ha) was recorded under bare fallow conditions (Sallaway *et al.* 1983). These long-term commercial scale trials also allow testing of contour bank and waterway design criteria.

The effect of tillage implements on hydrologic processes has not been studied in detail. The results that are available suggest that tillage implements that leave the greatest amount of residue on the surface are the most effective in reducing erosion (Freebairn and Wockner 1982; Sallaway *et al.* 1983).

Research is underway to quantify further the effects of management practices, particularly on soil evaporation and infiltration. Modelling will then be used to evaluate management systems.

EROSION PROCESS STUDIES WITH A RAINULATOR

Erosion processes are being studied with a large (22.5 ×4 m) rainfall simulator or rainulator (Meyer and McCune 1958). Aspects being studied include effects of rainfall, soil and sediment properties, surface tilth, stubble cover and plot size on runoff, and erosion processes.

Table 4. The effect of fallow management practices on runoff, water accumulation, soil movement, and yield on a black earth at Greenmount on the Darling Downs (mean 1978–1982).

Management Practice	Bare Fallow[a]	Stubble Incorporated[b]	Stubble Mulched[c]	Zero Tillage[d]
Runoff (mm)	81.8	53.3	39.7	53.6
Fallow efficiency (%)	16	17.5	23.0	17.0
Soil movement (t/ha)	70	20	4	1
Yield (t/ha)	2.81	2.88	3.11	2.85

a. Bare fallow — stubble burnt at harvest, tine cultivation.
b. Stubble incorporated — disc cultivation to incorporate stubble, then tine cultivation.
c. Stubble mulched — cultivation with wide spaced sweep tines to maintain stubble on the surface.
d. Zero tillage — stubble retained, weed control by herbicides.

(Source: D.M. Freebairn, Queensland Wheat Research Institute, Toowoomba).

The rainfall intensity and individual drop energy needed to form a surface seal varies from soil to soil (Loch 1982) due to variations in infiltration capacity and saturated aggregate strength.

Loch and Donnollan (1983a) found that:

1. Tillage across the slope delayed runoff and increased total infiltration by up to 13 mm compared with tillage up and down the slope.
2. Rain-flow occurred on all plots, but rilling occurred only on plots with discharges > 0.6 L/sec.
3. Sediment was moved, mainly as bed-load, by both rain-flow and rilling but rills carried 4.8 times more bedload.

Also, selective transport did not affect sediment size (Loch and Donnollan 1983b). Hence sediment size can be used as a measure of aggregate breakdown by rain and runoff. Erodibility was related to differences in sediment (aggregate) density rather than to differences in sediment size.

Loch and Donnollan (in press) found that stubble mulch greatly increased rates of interflow (lateral flow) in a roughly-tilled Vertisol. The peak rates of interflow (53 mm/hr under 3 t/ha wheat stubble) could have large effects on catchment stability.

CHARACTERIZATION OF INFILTRATION USING SIMULATED RAIN

Management systems must be assessed under a range of conditions so that models such as CREAMS (Knisel 1980) can be evaluated. An important requirement is the infiltration characteristic. In Queensland, intense rains commonly cause sealing of bare soil surfaces, reducing time to ponding and the effective saturated hydraulic conductivity. A rainfall simulator is used to provide infiltration characteristics under a variety of soil surface and profile conditions in the instrumented catchments described previously (pers. comm. S. Glanville, Department of Primary Industries, Toowoomba).

The machine is a modified version of the Grierson and Oades (1977) rotating disc simulator. Drop sizes and energies are similar to those in natural rain above 50 mm/hour (Marston 1980). Freebairn *et al.* (1984) found good agreement between final infiltration rates derived from runoff under natural rain and those derived using the rainulator and this rotating disc simulator.

CONSERVATION CROPPING DEVELOPMENTAL RESEARCH

Erosion control measures must be in harmony with farming systems and socio-economic considerations if they are to be accepted by the community (Lal 1982). Acceptance of conservation measures by farmers in Queensland has been studied (Chamala *et al.* 1983). Developmental research aims to span the gap between research findings and commercial farming systems (pers. comm. G. Bourne, Department of Primary Industries, Emerald). Demonstration areas and trials are monitored on farms so that difficulties with machines, soils, and crops in commercial applications can be encountered and remedied. Farmers can compare performance with established methods over a number of seasons, which gives confidence and experience with a modified system. Economics also test the worth of experimental systems.

MODELLING OF PRODUCTION AND SOIL EROSION IN CROPPING SYSTEMS

A model is being developed to evaluate crop system options in terms of crop production and soil erosion. Growth and yield sub-models are being developed for a range of crops. Models for sunflowers (Goyne *et al.* 1979) and wheat (Woodruff and Tonks 1983) have been used to estimate probabilities for success of cropping in marginal areas (Hammer and Woodruff 1983). Sub-models for runoff and soil loss will interact through a soil water balance sub-model.

The model will integrate research results from several disciplines and will indicate gaps in knowledge for future research. Work to date has shown the need for improved knowledge of evaporation and infiltration. Other models, such as CREAMS (Knisel 1980) are also being evaluated and will be used where applicable.

Crop Establishment

Crop establishment problems are usually due to crusting, cloddiness, or drying of the seed bed. Crusting can be a serious problem if rain falls soon after planting. Cloddiness results in poor seed soil contact (particularly with small seeds), low hydraulic conductivity, drying of the soil around the seed and premature exposure of the emerging seedling to light (Leslie 1965). Soil amendments such as gypsum can be used to modify soil properties but are expensive.

Planting techniques can mitigate cloddiness problems. Research into crop establishment has used experimental planter units fitted to commercial equipment. A range of planter options has been examined across a range of antecedent conditions. Typically the largest response is to presswheels (Table 5). Satisfactory wheat establishment has been obtained up to 8 weeks after rainfall (pers. comm. B.J. Radford, Queensland Wheat Research Institute, Toowoomba).

Rapid drying of the seedbed can be counteracted by moisture seeking techniques using narrow, rigid planting tines with wings to remove excess dry soil, and presswheels. Similar equipment with addition of a coulter has produced satisfactory establishment under no-till conditions.

Tillage and Stubble Management

Modern farming systems aim to minimize costs in terms of labour, fuel, and soil loss, and to maximize yield. Field trials have been set up to study the effects of tillage and stubble management. These trials provide a guide to effects on crop nutrition in the short term (White 1982) and to soil chemical (Dalal 1982), physical (Loch and Coughlan 1984), and biological changes (Thompson 1982) in the long term.

A trial comparing summer fallow systems (± cultivation × ± stubble) was started at Hermitage Research Station in 1968. In the period 1968–1979 the mean fallow efficiency was 27% for zero till and 20% for cultivated treatments. Over this period, the mean available water at planting was 26.6 cm in zero till and 22.6 cm under cultivation (Yule 1981). Runoff is not measured in this trial and it is not known if the differences are due to an effect on evaporation or infiltration. There is evidence from a similar trial at Biloela (pers. comm. G. Thomas, Department of Primary Industries Research Station, Biloela) that sweep tine implements increase water content in the surface after rain — possibily by creating a smeared layer that restricts water movement downward. A sweep tine implement was not used in the Hermitage trial but Loch and Coughlan (1984) found in 1974, that tillage was associated with higher subsoil soluble salts. They attributed this to a cumulative effect of decreased infiltration due to cracks being filled with soil by cultivation.

Considering long-term changes in soil properties, various workers (Martin and Cox 1956; Craswell and Waring 1972; Dalal 1984) have found that soil organic matter declines with length of history of cultivation. The rate of decline varies with soil type (Dalal 1984). This has important implications for soil fertility as organic matter is a key source of nutrients in traditional farming systems. The effect of organic matter on aggregation was discussed earlier. The loss of organic matter resulting from long-term cultivation has been accompanied by significant increases in soil bulk

Table 5. Effect of water injection, seed soaking and a presswheel on final establishment percentage of grain sorghum after planting at two times after rain on a black earth at Condamine, south Queensland.

Treatments	Days between last rain and planting	
	9	32
Control	32	20
W	48	21
S	46	18
P	77	55
LSD (P = 0.05)	15	18

W = water injection at 40 ml per m.
S = seed soaked in water for two hours.
P = rubber presswheel.

(Source: B.J. Radford, Queensland Wheat Research Institute, Toowoomba).

density (Dalal 1982). Further studies of physical changes are planned. Organic matter levels have been increased to a level approaching that in natural grassland by a combination of zero-till, stubble retention, and nitrogen fertilization (Dalal 1982).

Vertisols are usually considered to have capacity to regenerate structure with wetting and drying (e.g. Warkentin 1982). However, there has been concern that plow pans may be restricting root penetration of tap-rooted crops such as cotton and sunflower. Investigations have usually failed to find any visible changes in structure from the virgin state (McGarry and McDonald 1983). Farmers who are concerned about soil compaction sometimes practise deep tillage or deep ripping. On grey clays with naturally dense subsoils in the Burdekin Valley it was found effective in increasing stored water and yield under irrigation (Smith and McShane 1981). Implements that disrupted the subsoil as large clods (30–90 cm diam.) gave a response lasting several years — probably by creating more stable voids continuous deep into the profile. Gypsum prolonged the effect of deep ripping that had intensively shattered the subsoil into small clods (5–30 cm diam.). Without gypsum the effect of intensive shattering lasted only about one season. A similar effect of gypsum was obtained by McKenzie *et al.* (1983) in northern New South Wales. Expenditure of the additional energy required for deep ripping seems questionable for rainfed crops on extensively cracking soils. However, there are reports of crop response to improved water storage after deep tillage on Vertisols in the Goondiwindi area (pers. comm. F.G. Ghirardello, Goondiwindi).

Gypsum as a Soil Amendment

Gypsum from natural deposits has been used as an amendment to improve soil structure in southern Australia for many years (Loveday 1975). Farmers report various benefits from gypsum, e.g. better surface drainage, tillage earlier after rain, lower power requirements and less tillage for a seed-bed, improved emergence, easier weed control, and better crop growth and yield. There is also the possibility of a nutritional response to sulphur on some soils (White 1979). Gypsum use is expensive (because of freight) and can only be justified economically by a worthwhile yield response, usually over several seasons.

The quantities of gypsum applied, viz. 2–5 t/ha are relatively low when compared with the amount of exchangeable sodium present. The main response observed appears due to the electrolyte effect (Quirk and Schofield 1955; Loveday 1976) rather than to a substantial displacement of exchangeable sodium. Farmer management decisions, soil type, and seasonal weather influence the longevity of response. In dry seasons gypsum may increase water storage (e.g. Doyle *et al.* 1979). The soil water storage response appears to be due to improved infiltration and water movement deeper in the profile. For example, in a trial at Dalby in 1981, gypsum treated soil stored an additional 2 cm of water in the 90–150 cm depth interval during the fallow. Barley yield increased by 400 kg/ha (approx. 15%) and this increase was significantly correlated with water content in the 90–120 cm depth interval at the time of sowing. In wet seasons, gypsum improves drainage and allows earlier planting after rain.

At present the decision as to whether or not to apply gypsum is based mainly on field observations of sealing under rain, cloddiness, and emergence problems. Test strips are usually applied. A laboratory test for structural stability under rain would be useful for assessing gypsum responsiveness. Gypsum rate trials at present under way will provide samples for field calibration of such a test. They will also show the longevity of crop and soil process response to several rates of gypsum.

Soil Salinity

Extensive areas of Vertisols have appreciable subsoil salinity prior to development. The extent to which this subsoil salinity affects crop performance (e.g. Fisher 1981) is not known. However, there is serious production loss in some areas where soluble salts have concentrated in the surface because of shallow water tables. Usually the area is small, possibly part of one farm, and the source of water may be several km away (e.g. Thompson 1981). The approach has been to monitor groundwater behaviour and composition (using piezometers) and soil salinity. Techniques used include earth resistance (Shaw 1981), seismic hammer (limited use to map rock structure), and trilinear diagrams to classify water compositions (pers. comm. R.J. Shaw, Department of Primary Industries, Indooroopilly).

In most trouble spots the problem is linked to restriction in groundwater movement due to a change in rock or soil type. At Emerald, a high water table has developed in mid-slope positions near a soil type interface. Dowling *et al.* (1984) found that cotton yield was related to depth of water table, groundwater quality, or surface soil salinity depending on slope position and soil type. Claydon (1982) discussed the performance of subsurface drainage installations and gave preliminary guidelines for interceptor drain specifications. Yule *et al.* (1982) showed that drainage rapidly improved crop yields in slightly salinized areas but was ineffective after three years in areas with high secondary salinity and sodicity. Critical water table depth for salt accession to the surface was about 100 cm. Gypsum and deep ripping did not influence reclamation. These authors concluded that drainage, supply channel sealing, and appropriate farm management were necessary to overcome the problem.

Irrigation Water Quality

A high proportion of the irrigated Vertisols in Queensland are watered with groundwater (Shaw and Hughes 1981). Many of the waters used have electrical conductivity (EC) > 2.3 mS/cm and would be rated as highly saline on commonly accepted criteria (Richards 1954; Hart 1974). Approximately 34% of the waters being used in the Lockyer Valley, 20% in the Callide Valley, and over 50% of waters in the Dee Valley are in this high salinity category. On some farms in the Lockyer Valley, waters with EC of 4.5–6 mS/cm have been successfully used for irrigation for up to 40 years. On the Darling Downs, high bicarbonate waters have been used for several years on black earths (Cassidy 1971). Hence there is concern on the possible salinization of highly productive soils. There is also concern that groundwater quality in some areas is deteriorating as a result of tree clearing on elevated land.

Current research aims at a quantitative understanding of the interaction between water quality, condition of use, soil type, and climate in the Lockyer Valley. This will provide a basis for general purpose water quality assessment criteria. Preliminary results (pers. comm. R.J. Shaw, Department of Primary Industries, Indooroopilly) indicate that soil properties, particularly clay mineralogy and clay content have a greater effect on salt accumulation than irrigation management. Soils with highly active clays (CEC-clay ratio > 0.9) tend to be more permeable, and can tolerate higher salinities. Soils with 40–60% clay and a CEC-clay ratio < 0.6 have the greatest salt accumulation. Soils with 40–50% clay tend to have the highest density (Smith *et al.* 1978) and thus by implication, the lowest hydraulic conductivity and least leaching.

Irrigation Management

The high initial infiltration via cracks in dry soil and the low final infiltration rates in wet soil make Vertisols well suited to flood irrigation. Cracks tend to form along the interrow (Swartz 1966). Hence as water flows down the interrow furrow, the soil deficit will be rapidly replenished (the 'self-regulation' of Farbrother (1972)). The wet, relatively slowly permeable soil will provide efficient surface water transport to dry soil further down the furrow. Total infiltration should be uniform down the furrow and independent of time. However, the low saturated hydraulic conductivity values predispose these soils to waterlogging and aeration problems. Several aspects of irrigation management are currently being investigated at Emerald.

IRRIGATION SCHEDULING

A simple crop factor-pan evaporation model (Keefer *et al.* 1982) has been satisfactorily used to schedule cotton irrigation. Irrigation deficits have been set for soils based on 70–80% of the PAWC data of Shaw and Yule (1978). These values require some field calibration based on crop response and farmer management. In the 1982–83 season the model was compared with neutron moisture meter scheduling (pers. comm. W.D. Hamilton, Department of Primary Industries, Emerald). The two methods agreed within two days throughout the season.

IRRIGATION EFFICIENCY

The efficiency of a range of flood irrigation strategies for cotton is being studied from two aspects: (a) application efficiency, and (b) crop production efficiency. The 1982–83 season data show that tail drain flow increases rapidly once runoff starts (the net infiltration rate falls to less than 1 mm/hr within 3–4 hours). Extended periods of irrigation do not significantly increase irrigation increment. As tail drain flow is the main source of loss, application efficiency can be improved by precise timing of water application. Seasonal differences between irrigation strategies and the production efficiencies are currently being evaluated. A problem yet to be resolved is uneven flow down furrows with consequent uneven wetting across the paddock.

AERATION

Serious yield reduction from waterlogging and poor aeration following flood irrigation of Vertisols has been reported in New South Wales (Hodgson and Chan 1982). Good surface drainage and short times of ponding are essential (Smith and McShane 1981). Muchow and Yule (1983) suggest slopes should exceed 0.1%. At Emerald, with slopes of about 1%, no detrimental waterlogging has been observed.

Conclusions

Vertisols used for agriculture in Queensland vary widely in properties and because of this variation farmers face a range of problems. Short-term risks are related to variable rainfall and soil physical properties unfavourable for crop establishment and crop water supply. Long-term risks arise from soil erosion and fertility decline. Research aims to understand physical processes operating on these soils and apply this knowledge to reduce the risk of crop failure and to maximize efficiency in crop production while minimizing risks from erosion. Research has not been exhaustive and our understanding is by no means complete.

This general situation no doubt has parallels (with allowance for different environments and cultures) in other countries. We can learn from this overseas work and in turn some of our knowledge may be useful for problems in the many countries where Vertisols occur.

Acknowledgements

The authors are grateful to several officers of the Department of Primary Industries who gave freely of their results and their knowledge for the preparation of this paper.

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J. Venkateswarlu* **Discussant — 1**

Soil Problems with Vertisols with Particular Reference to Surface Soil Conditions and Water Relations

Drs G.D. Smith, D.F. Yule, and K.J. Coughlan, in their excellent key-note paper on 'Soil Physical Factors in Crop Production on Vertisols in Queensland, Australia' reviewed the inherent properties of Vertisols, giving emphasis to the problems encountered in managing these soils.

In the following paragraphs, the Indian experience on Vertisols is given.

Vertisols and Associated Soils in India

Vertisols and associated soils, viz. Inceptisols and Entisols occur in peninsular India covering an area of about 72.9 M ha (Figure 1). They are generally known as 'black soils'. They constitute about 22.2% of the total geographical area of the country. The distribution of these soils in nine states in India is given in Table 1.

At present, about 24 M ha are under arable farming and there is very little scope for increase of the area under cropping. The potential yields are very high in these black soils (Table 2).

The typical climatic water balance for the low, medium, and high rainfall regions in these black soils is given in Figure 2. Evaporation exceeds precipitation in the low rainfall region in all months while in the medium rainfall region, precipitation is in excess during August and September. In the high rainfall region it is in excess from July to September. When a ratio of actual evapotranspiration/potential evapotranspiration was calculated, the growing season (AE/PE > 50%) was below 20 weeks for low rainfall regions, 20–30 weeks for the medium rainfall zones, and above 30 weeks for the high rainfall regions.

In the low rainfall regions the shallow black soils are cropped during the monsoon whereas the deep black soils are sown with post-monsoon crops. In the medium rainfall regions intercropping is practised, and in the high rainfall regions sequence cropping is possible. Some 15 M ha of Vertisols exist in the last group, but almost 12 M ha are fallowed during the monsoon (Ryan and Sarin 1981).

About 10% of the black soils are irrigated in India of which Bhumbla (1981) estimates that 1.4 M ha are already salt affected.

Average size of holding varies from 3.7 to 7.5 ha in 2.0 to 3.6 ha fragments.

The important crops of the region are:

1. Monsoon period: Sorghum, corn, pearl millet, rice, mungbean, pigeonpea, soybean, sun-flower, peanuts.
2. Post-monsoon period: Wheat, sorghum, chickpea, safflower.

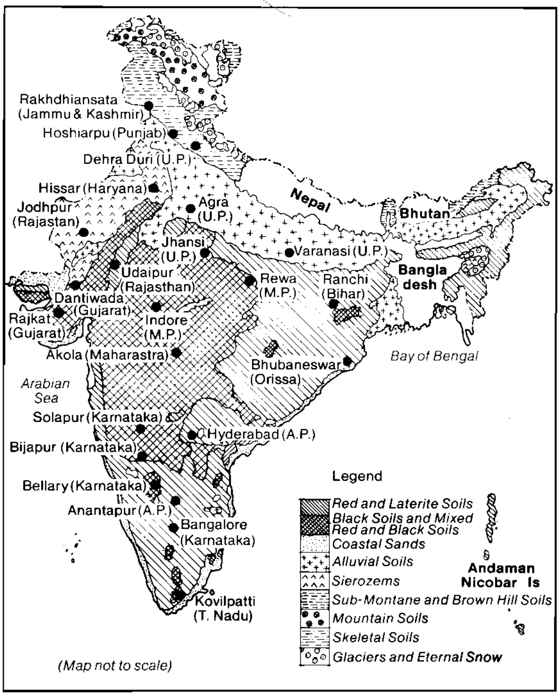

Figure 1. Soil Map of India.

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* Project Coordinator (Research), All India Coordinated Project for Dryland Agriculture, Saidabad, Hyderabad, India.

Table 1. Distribution of black soils in India.

State	Area (M ha)
Maharashtra	29.9
Madhya Pradesh	23.0
Gujarat	8.2
Andhra Pradesh	7.2
Karnataka	6.9
Tamil Nadu	3.2
Rajasthan	2.5
Orissa	1.3
Bihar	0.7

Source: R.S. Murthy (1981).

Table 2. Production potential of the Vertisols and associated soils.

Rainfall (mm)	Potential yield of crops (t/ha)					
	Cereals		Pulses		Oilseeds	
	Potential yield	Present yield	Potential yield	Present yield	Potential yield	Present yield
Low (< 700)	1.7	0.3	1.1	0.2	1.2	0.2
Medium (700–900)	2.1	0.5	1.4	0.3	1.3	0.4
High (> 900)	3.4	0.9	1.5	0.7	2.4	0.6

Characterization of the Black Soils in India

In their book on benchmark soils of India, Murthy *et al.* (1982) described 13 benchmark soils in the black soil region. Shankaranarayana and Sarma (1981) point out that the black soils characteristically have a clay content of 40–60% or more. The clay is dominated by montmorillonite, which is responsible for the problems and potentials of these soils. The soils swell, shrink, and crack and are also easily dispersed. They have a high moisture retention capacity and potential fertility.

Broadly speaking, the black soils in India are of two kinds, viz. *in situ* soils and 'transported' soils (Desai 1942).

The soils formed by *in situ* weathering consist of those derived from igneous and sedimentary rocks. The soils derived from basalts are heavier and more productive than those derived from the gneissic complex (Desai 1942). In catenary situations, such as those in the Deccan region, transported soils occur in the lower elements of the slope.

As rightly pointed out by Smith *et al.* (These Proceedings), for fuller exploitation of the Vertisols and associated soils, it is necessary to understand their physical properties and their significance in crop production.

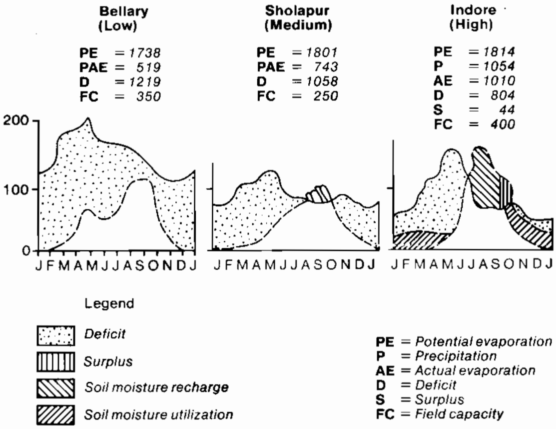

Figure 2. Climatic water balance for low, medium, and high rainfall zones in black soils. (Based on long-term meteorological monthly means. All measurements in mm.)

Research in India

Soil Structure

All the physical factors that affect plant growth can be grouped together and referred to as soil structure. The factors that have an impact on the development of soil structure are (a) the nature and extent to which the cations are saturated on the exchange complex; (b) the interaction of clay particles with moisture and temperature; (c) soil fauna and micro-organisms; and (d) clay-organic matter interaction and the vegetation.

In a majority of Vertisols, the surface 2–10 cm layer of soil is a loose mulch with medium to fine granular aggregates produced in the dry season by the process of self-mulching. Soil structure is most strongly developed when the soil is dry. Krishna and Perumal (1946) in the Deccan region described a specific structure that they named 'lentil' as it closely resembled the lentil seed (a double-convex lens). Lentils were found between 90–200 cm depth with dimensions of 10–20 cm. Sub-lentils could be dislodged from bigger peds. As the moisture decreases, the small lentils become more and more apparent.

1. Factors Promoting Soil Structure

The aggregation in Vertisols is significantly correlated with smectite, the dominant crystalline mineral in clay fractions (Krishnamurthi and Singh 1975).

The most favourable structure for plant growth is difficult to define. A well aggregated soil should contain surface crumbs in the range of 1–5 mm in dry and wet conditions respectively. Such soils do not crust and hence seedling emergence will be no problem. Similarly, they offer less mechanical impedance to root penetration.

Ley farming would help in improving soil aggregation but under Indian conditions, its scope would be limited. Application of FYM over years improved aggregation in black clay soils (Kibe and Basu 1952). Compost improved infiltration rate as did organic residues that were allowed to decompose *in situ*. The latter improved the soil aggregation as well (Table 3).

Rama Mohan Rao *et al.* (1983) grew peanuts for three seasons with different land configurations and chemical treatments and found improvement in soil aggregation as well as hydraulic conductivity (Table 4) in deep black soils of the Deccan region.

2. Bulk Density–Water Content

Root activity and bulk density are related. There is little or no root penetration into soil horizons having bulk density greater than 1.8. This is largely due to the increased soil strength that offers more mechanical impedance. In fact in the Vertisols of Nizamabad district of Andhra Pradesh the presence of these high bulk density layers in the subsoil restricted root growth of sugarcane. Chiselling to a depth of 20 cm along with mixing gypsum at 50 kg/ha increased sugarcane yield by 25 per cent (Gupta and Nagaraja Rao 1982).

Bulk density of Vertisols varies with water content. It was found to range from 1.3 to 1.8 depending on the swelling or desiccation in the Vertisols in the Deccan region. An increase in bulk density of the soil decreased the percentage of pores bigger than 0.05 m in diameter, but had no effect on the capillary pore space (Ghildyal

Table 3. Effect of *in situ* decomposition of different materials on soil aggregation (MWD in mm) and infiltration (cm/hr).

Treatment	Soil Aggregation (MWD)	Infiltration rate of disturbed sample
Control	0.11	2.59
Compost	0.11	4.39
Sorghum straw	0.16	4.75
Cassava leaves	0.38	8.10

Source: Ch. Krishnamoorthy *et al.* 1956–64. Annual Reports of the Soil Conservation Centre, Bellary.

MWD = Mean weight diameter (mm).

Table 4. Soil properties as influenced by land and soil treatments.

Treatment	MWD* (microns)	HC* (mm/hr)
Flat — Control	439	2.08
Bed	756	2.90
Gypsum to bring down ESP to 2.0		
a. Flat system	600	2.59
b. Bed system	670	2.81
Initial value	301	0.86

*Values at the end of three seasons of peanut.

HC = Hydraulic conductivity.

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

and Satyanarayana 1965). Similarly, the increase in bulk density decreased the hydraulic conductivity of the soils and water diffusivity in black clay loam (Sharda and Gupta 1978). The transmission characters were more seriously affected. The depth of infiltration was reduced by 30% and the upward capillary flow by one-half to two-thirds as bulk density increased by 0.1 g/cm^3 to over 1.2 g/cm^3.

3. Effects of Cations on Soil Structure

(1) Sodium

The ill-effect of sodium on soil productivity is well established. On wetting (either through rain or irrigation), the sodic soils disperse, and they shrink heavily upon drying. Both wetting and drying affect the moisture relationships adversely, and hydraulic conductivity is drastically affected (Figure 3). An ESP of 7.0 is critical for black soils (Rama Mohan Rao and Seshachalam 1976). Application of gypsum to reduce ESP to less than 7.0 improved the infiltration rate from 0.99 to 1.65 cm/hr. For economic considerations, then it is sufficient to apply gypsum to reduce the ESP to about 5.0 and only in the first 10 cm depth.

(2) Magnesium

There is seldom any indication of the possible influence of exchangeable Mg on the structure of Vertisols. For example, the plasticity indices of Ca-montmorillonite and a Mg-montmorillonite are very similar (Baver *et al.* 1977). However, Jayaraman (pers. comm. 1983) found synergistic effects of Mg and Na in determining the extent of dispersion in samples of Vertisols derived from a granitoid gneiss complex, basaltic trap, and limestone.

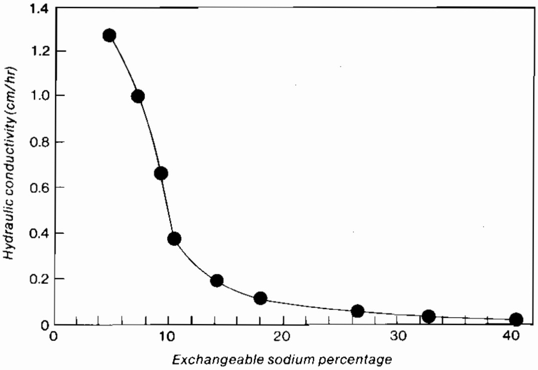

Figure 3. Hydraulic conductivity as influenced by exchangeable sodium percentage.

In the Australian context, the exchangeable Mg percentage also appears to be important in Queensland (Smith *et al.* These Proceedings) and needs further consideration.

Soil-water Relations

1. Entry of Rain-water

Movement of rainwater into the root zone is important for increasing crop production. The Vertisols of the Deccan are heavy with a tendency to become sodic (ESP: 8–30) and characterized by low infiltration (0.08 cm/hr). The initial intake rates in these soils may be very high as the rain-water enters through the deep cracks and fills the soil 'from the bottom' as noted by Smith *et al.* (These Proceedings). However, the intake rate falls to as low as 0.08 mm/hr once the soil is saturated at the surface and the cracks close. This results in a dry layer sandwiched between the wet layers

(Figure 4) leading to crop failures, particularly in low rainfall years.

Rama Mohan Rao *et al.* (1977) used vertical mulch to improve infiltration. Trenches of 15 cm width were made across the slope to a depth of 40 cm at intervals of 4 and 8 metres. Sorghum stubble was placed in these trenches protruding 10 cm above the ground level. Moisture recharge in the plots increased and showed a parabolic trend, particularly in the dry seasons. The soil water increased by 4–5 cm that led to a 400–500% increase in yield of sorghum in drought years and 40–50% in normal years over unmulched plots (Table 5).

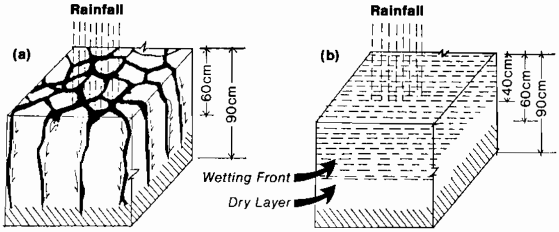

Figure 4. Movement of rain-water in black soils (a) kharif (b) rabi.

2. Soil Available Water and Crop Water Use

There is a lower limit of soil water content above which evapotranspiration from a cropped field is at potential rate. Below this threshold, water availability to the roots becomes limiting (Lahiri and Kharbanda 1966). The decrease in water use may or may not produce a corresponding decrease in crop yield. Singh *et al.* (1979) found that withholding irrigation to wheat in a highly water retentive soil decreased water use by 10 cm without any significant detrimental effect on yield. This is because certain crops may produce potential yield without evapotranspiring at potential rates (Prihar *et al.* 1978). That arable crops are capable of extracting soil water even beyond 15-bar values is now known. Prihar *et al.* (1978) found that wheat was able to deplete soil water well beyond 15-bar even to a depth of 2 metres. Similarly, gram removed substantial amounts of water from as deep as 150–180 cm and depleted soil water to below 15-bar value (Sandhu *et al.* 1978).

Thus, the plant available water capacity (PAWC) may vary with crop, stage of growth, level of plant stress etc. as pointed out by Smith *et al.* (These Proceedings). Gardner *et al.* (1983) well defined it as the difference between the field-measured upper storage limit and the lower storage limit, summed over the plant rooting depth. In fact, in the Vertisols of the Deccan (Bellary) crops like *Dolichos lablab* survived even at 4% soil moisture level while the PWC of those soils was 22–28%.

PAWC is an important soil property and needs field evaluation. Factors affecting PAWC for a given crop are the root profile, clay content, subsoil salinity, drainage characteristics, and rainwater entry into the profile. In India the soil depth is currently considered as the first approximation to assess PAWC in Vertisols. In a metre deep profile it is taken as 35–40 cm depending on the clay content.

Management Studies

1. Runoff and Soil Erosion

The magnitude of runoff and soil erosion depends upon the slope of the land and the condition of the land (cropped or fallow). Further, it is an interplay of the factors such as erosivity of the eroding agent (rainfall), erodibility of the soil, and the land form.

Sheet erosion is common on flat lands (slope

Table 5. Influence of vertical mulch on yield of sorghum (t/ha).

Treatment	Bellary (1973–74)	Solapur (1974–75)	Bijapur* (1973–74)
Control	0.84	0.84	1.66
Vertical mulch at 4 m interval	1.28	1.27	2.05
Vertical mulch at 8 m interval	1.19	1.12	1.82

*Tested for 5 m and 10 m spacing.

Source: Randhawa, N.S., and Rama Mohan Rao, M.S. (1981).

less than 0.8%); rills, washes and gullies of varying sizes are formed on sloping lands and more so in monsoon fallows. In such lands (slope more than 0.8%) under clean cultivation, there is severe erosion and runoff by high intensity rains, particularly where there is a layer of loose soil on the surface created by frequent ploughing and almost saturated and impervious soil below the surface.

The runoff in low, medium, and high rainfall Vertisols ranges from about 10% to 25% to 40% respectively (Tables 6 and 7).

Runoff and soil erosion is considered as a serious problem in reducing the root profile by loss of the top fertile soil. An important associated problem is siltation of a number of reservoirs.

2. Models for Management of Runoff and Soil Erosion

(1) Graded Bunds

In India, work on soil and moisture conservation was initiated in the mid-fifties with the start of eight soil conservation research centres. Contour bunding was the primary method adopted in the earlier days to contain the problem. But instead of solving the problem, the contour bunds led to problems of waterlogging, breaching and further serious loss of soil. Then, graded bunds were adopted with a cross-section of 0.84 m^2 at vertical intervals of 0.7 m with a channel (grade of 0.10–0.25%) on the upstream side connected to a grassed waterway. Chittaranjan *et al.* (1980) found these bunds more efficient than contour bunds. The advantage of this system is the scope for harvesting runoff into dugouts wherever it might be possible.

In fact in Bellary where the runoff is estimated to be about 10% of the annual rainfall, a farm pond of 3–5 m depth (1.5: 1 side slope) having a capacity of 0.25–0.3 ha m so harvested can be recycled to about three quarters of the catchment for one life-saving irrigation (Chittaranjan and Rama Mohan Rao, in press). The payoff for this critical irrigation is up to 2 q/ha/cm.

(2) Surface Drainage

At Indore, through an Indo-UK Operational

Table 6. Estimated water-balance components in Vertisols.

Water balance component	As % of rainfall (1973–78)
Runoff	25.3
Deep percolation	9.2
ET (Monsoon)	24.9
ET (Post-monsoon)	40.6

Source: ICRISAT Annual Reports, 1973-78.

ET = Evapotranspiration.

Table 7. Rainfall and runoff from small agricultural watersheds.

	Indore (990 mm)		Bellary (508 mm)	
Serial No.	Rain during the year (mm)	Runoff* (%)	Rain during the year (mm)	Runoff* (%)
1	975	53.6	559	12.7
2	645	34.2	481	10.3
3	1911	49.0	588	8.4
4	865	21.0	533	8.7
5	1376	28.8	542	8.4
6	1241	42.2	540	9.7
7	1131	36.9	—	—
8	985	39.5	—	—
Average	1141	38.1	540	9.7

Source: Anonymous. (1980).

*Expressed as a percentage of rainfall.

Research Project a 2 000 ha area was selected on a watershed basis for developing efficient rain-water management systems. The average rainfall in the region is 990 mm and is mostly confined to the monsoon season. The rainfall is highly variable, both spatially and temporally. A number of monsoon showers have an erosive intensity greater than 25 mm/hr. During parts of the year there can be either excess water and/or an acute deficiency. Excess water leads to stagnation and consequent drainage problems in these low permeable soils. It might finally lead to severe soil erosion problems.

To contain these problems, the model developed at Indore included the following steps (Verma 1982): (a) water diversion bunds, (b) grassed waterways, (c) stabilization of washes, and (d) provision of drainage areas between waterways.

The water diversion bunds are primarily meant for preventing rain-water from non-arable lands flowing on to the arable lands. To lead the water diverted by the water diversion bunds to natural streams, grassed waterways have to be developed at suitable sites. The cross-section of the waterway is calculated on the basis of the runoff rate, the total catchment area, and the value of permissible velocity of flow water, which depends on the nature of the bed. If the bed of the waterway is too steep, appropriate gabion structures are needed for stabilizing the waters.

By stabilizing the washes using strips of unploughed land and providing drainage areas between waterways, the area cropped during the monsoon can be greatly increased; at Indore, the area increased from 35% in 1974 to 65% today.

(3) Inter-terrace Treatment

The graded bunds are by and large the mechanical structure meant for arresting the problem of soil loss. But between the bunds (terraces), rainwater management was not seriously considered until recently in India. In the recent past, different land configurations were tested by ICRISAT (Kanwar *et al.* 1982). They found the broadbed and furrow system an efficient land configuration. The 150 cm wide beds are graded across the contour to a 0.6 per cent slope and are separated by furrows that drain into grassed waterways. Each bed is slightly raised, acting as an *in situ* 'bund' for good moisture conservation and erosion control. The furrow (50 cm wide) is shallow (15 cm) but provides good drainage to prevent waterlogging of crops on the beds. Excess water is led off through a system of field drains and grassed waterways.

The same result can also be achieved through open furrows, with a cross-section of 0.15 m^2, opened on a grade (0.2–0.3%) at 8–10 metres interval.

The net benefit accruing out of this model is a 15% increase in yield at any given level of fertility/productivity. But the implicit advantage in the system is drainage and thus it could be one of the approaches in high-rainfall areas of Vertisols to resolve the surface drainage problem.

3. Tillage

Tillage is necessary for preparing the land; but excessive tillage leads to soil compaction and structural deterioration. Neither shallow nor deep tillage conferred any increase in yield of crops and total moisture intake, when compared with traditional harrowing of three to four times to check weeds and create a soil mulch (Randhawa and Rama Mohan Rao 1981). In fact, deep tillage might lead to newer problems in cases where subsoil salinity is high or when subsoils tend to be more sodic. However, in the calcareous soils deep tillage might help in eventual reclamation of sodic soils.

A good seedbed is necessary for obtaining good plant stands in the drylands. Cloddiness in a seedbed is a problem (Smith *et al.* These Proceedings). Hayavadana Rao *et al.* (1975) found that pressing the seed rows would improve crop stands (Table 8). The seedling emergence was greater at 28% soil moisture compared with 32%, and it improved further with compaction in the case of sorghum, chickpea, cotton, and safflower.

Crusting can be an occasional problem that might occur due to a beating rain immediately after sowing. This is due to a breakdown in structure. The dispersed soil particles of silt and clay reorient themselves to form strong bonds and lead to crusting. In sodic soils, on the other hand, deflocculation takes place resulting in crust formation. The crust formation, in either case, inhibits water movement into the soil as well as seedling emergence.

If crusting is due to a beating rain soon after seeding and is a frequent problem, it is best

Table 8. Seedling emergence of different crops with and without compaction at two levels of soil moisture in a Vertisol.

	32%		28%	
Crop/Soil Moisture	Compaction	No compaction	Compaction	No compaction
Sorghum	50	34	96	71
Chickpea	67	27	89	76
Cotton	10	12	31	Nil
Safflower	8	5	52	50

Source: Hayavadana Rao, D. *et al.* (1975).

managed by 'set-line' cultivation adopted by the farmers of the black soils of Saurashtra region of India. Here the farmers grow crops in set-lines, 45–90 cm apart. They apply manure in these rows and cultivate only the lines, blading the inter-row spacing. Over time, the crusting problems are minimized.

On the other hand, if crusting is due to sodicity it can be easily overcome by the application of gypsum to reduce the ESP at least to values below 5.0.

4. Soil Salinity

Salinity and sodicity are twin problems of the black soils in India. About 1.4 M ha are said to be affected by these problems under irrigation agriculture. Varade (1982) summarized the formation of salt-affected Vertisols particularly under canal command as: (a) over and unscientific irrigation, (b) topographic situation, (c) aridity of the climate, (d) rise of groundwater due to canal seepage and leakage, (e) poor permeability/drainability, and (f) continuous use of saline groundwater as supplementary irrigation to canal irrigation from wells in command areas.

Reclamation of Saline Soils

The saline soils occur mostly near the streams. They are easily reclaimed by flushing alone and putting them under rice. Krishnamoorthy and Nayar (1960) found that the leaching of salts from the root profile is exponential in nature and with leaching 50% of the salts and 25% of boron initially present are removed (Figure 5). This suggests that extra leachings are needed for bringing down the boron content to a non-toxic level of 0.75 ppm and less.

Reclamation of Alkali Soils

Gypsum is the best amendment for reclaiming the alkali soils (Table 9). Gypsum application even at the rate of one-sixth of gypsum requirements was found to be adequate to get satisfactory yields of rice, wheat, cotton, and sorghum (Varade 1982).

Table 9. Effect of ESP and gypsum treatments on hydraulic conductivity of black soils in India.

Location	Clay (%)	ESP	Hydraulic conductivity (X 10 cm^{-3}/min)	% increase in hyd. cond. due to gypsum treatment
Sindamor	44.4	21.2	2.0	225
Adoni	41.8	15.4	1.8	206
Nandyal	42.2	14.8	1.8	228
Anatapur	39.0	14.7	1.2	375
Bellary	36.0	14.1	3.5	137
Kurnool	40.6	9.7	2.9	145
Dardoli	41.0	8.5	1.7	159
Bodnapur	47.0	7.2	4.1	161
Jalgaon	38.8	5.0	4.6	99
Bijapur	37.6	4.2	4.8	143

Source: Ch. Krishnamoorthy & J. Venkateswarlu. 1974. In *Soil Fertility, Theory and Practice*, Ed. Kanwar, J.S. New Delhi: ICAR.

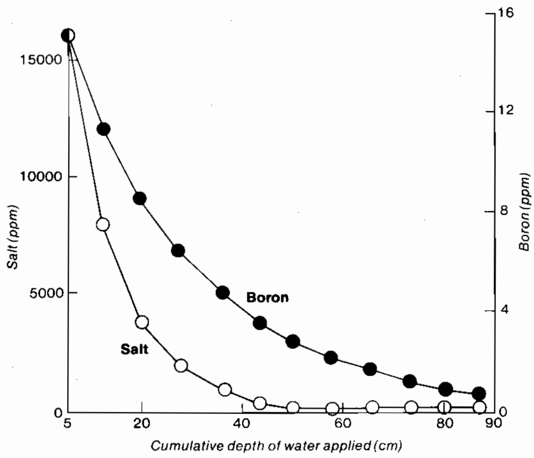

Figure 5. Relative rates of leaching of boron and salt in the soil profile.

But in certain situations, it may not be possible to resort to chemical amendments. An example is the inevitable need to use saline ground water as either supplemental or main sources of irrigation. While Yadav (1982) suggested 1 500 mmhos as the permissible lower limit of salts for irrigation water for semi-tolerant crops and 2 000 mmhos for tolerant crops, even higher saline water is being used in these regions.

Subsoil Salinity

Subsoil salinity is a problem in the low rainfall Deccan black soil region where it covers an area of 30–40%. It usually occurs at 70–90 cm depth in the ridge portion and at 45 cm in the lower elements of the catena. The low infiltration and impermeable underlying murrum are the primary causes. Water moves laterally picking up salts and emerges at the lower parts of the topography, depositing salts as it evaporates.

While efforts need be made to flush the salts out of the soil, it is also necessary that more and more crop varieties tolerant to salinity be identified. Krishnamoorthy *et al.* (1966) found safflower to have a high salt tolerance.

Future Research Needs

Vertisols have enormous yield potential, which is often not realized; they offer a great challenge to both scientists and farmers. They are widely distributed but many members of this order have somewhat similar chemical and physical properties, in spite of minor differences.

The most striking aspect of Vertisol morphology is its structure. It varies with depth, topography, climate, and soil material. The ESP and EMgP play a dominant part in soil dispersion. The most favourable structure for ideal plant growth is difficult to define as it involves soil, crop and climatic factors.

A well-aggregated soil could be maintained through *in situ* decomposition of organic residues. While this could be achieved through a minimum tillage, it also could be attempted through deliberate and annual incorporation of any organic residues. Set-line cultivation is a step in this direction.

Even if the water entry into the root profile is adequate, if subsoil fertility is sub-optimal, it might lead to poor crops as the root growth would be largely restricted to the top soil. The question of improving subsoil fertility management, more so in drylands, needs consideration.

The use of amendments to reduce ESP to 5.0 or less for growing successful crops is now proven. But what is more important is the need to consider the synergistic effect of exchangeable magnesium in conjunction with exchangeable sodium in faster breakdown of the soil structure. This appears to be a serious problem in basaltic Vertisols, which are inherently rich in magnesium and also weather faster leading to finer clay fractions.

Land configurations to provide more opportunity time for entry of rainwater into the profile are being identified. Unless the complex infiltration processes are completely understood, these configurations might create other problems. Surface crusting and subsoil compaction are a few of the examples that affect infiltration and permeability of rainwater.

A major physical problem of Vertisols is low non-capillary (10%) pore space, which limits drainage of excess water in the monsoon and develops oxygen stress in the root zone. In flat lands, raised beds provide better conditions for quick removal of free water. In rolling and undulating lands, planting on ridges increases the yield of crops. Similar land treatments need to be identified for other situations to overcome the problem of drainage. There is also a lack of information on leaching and drainage design criteria for salt-affected soil.

When the bulk density is high, there is impedance to root penetration and axiomatically the water use will be less leading to poorer crops. These interrelations need to be fully understood.

Entry of rainwater in the low rainfall Vertisols has to be improved to capitalize on the scope of charging the whole root profile with stored water for crop use. Vertical mulch is one such example. Plant available water capacity is an important soil property and needs field investigation. Empirical relations need to be worked out in this area of research.

Runoff and soil erosion are twin problems that need attention in the black soils. Providing more opportunity for rain water to enter the profile and also draining excess free water are essential. Provision of graded bunds and surface drainage are for surplussing arrangements. Broad-bed and furrow system and open graded furrows are the ways to provide more opportunity for entry of rainwater into the soil.

Acknowledgement

The help rendered by Dr M.S. Rama Mohan Rao, Senior Scientist and Mr N.S. Jayaraman, Scientist, Soil Conservation Research Centre, Bellary, while preparing the paper is acknowledged with thanks.

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L.D. Swindale* **Discussant — 2**

Soil Physical Factors in the Management of Vertisols in the Semi-Arid Tropics

In this paper I will focus on the physical problems of deep Vertisols and the approaches developed by ICRISAT to overcome them (ICRISAT 1981, Swindale and Miranda 1981).

Firstly, a key element in the ICRISAT technology is post-rainy season cultivation, i.e. cultivation immediately after the winter crop or post-rainy season crop has been harvested. The severe physical problems of Vertisols at this time in the cropping cycle are associated with the fact that the soil is dry and therefore hard. Moist Vertisols shear more easily and much less power is required for their cultivation to a given depth, or cultivation can be deeper for a given amount of power. Even so, whether moist or dry, Vertisols come up in big clods when cultivated even when animal-drawn equipment is used. The resulting soil surface is very rough, which is an advantage during the small showers that occur in the dry season because it helps to prevent loss of water and increases infiltration. Of course, the soil in this condition is not satisfactory as a seed bed.

The swelling and shrinkage of Vertisols is a real advantage in the development of a seedbed from a rough, ploughed soil surface. ICRISAT has calculated, and therefore built into its technology, that in the months of March, April, May and early June, there is near certainty of at least one shower of 10 mm, which is enough to cause substantial swelling followed by shrinkage and drying, causing the large clods to break up easily. Timely land preparation then allows the broad beds to be formed and an adequate seed bed to be prepared. This approach makes maximum use of the limited natural rainfall during the dry season.

The next important element is dry seeding before the rain starts. Wet Vertisols are very sticky and therefore hard to seed. If the initial rains are prolonged, seeding can be much delayed. Dry seeding provides an answer if the seed can be accurately placed, which is an important reason why improved animal-drawn cultivation equipment is essential to the technology that has been developed. Correct placement of seed and fertilizer are very important parts of the technology. When the seed is placed 10–12 cm below the surface and the surface is adequately compacted, the light showers that occur at the onset of the rains do not wet the soil sufficiently to cause the seed to germinate. When the soil is wet to the seed depth so that germination occurs, there is enough available water not only for the growing plant to emerge but to carry it over for about a week or more.

Climatic analysis has shown that once the rains have reached the intensity that will allow seedling emergence, they have also reached a frequency sufficient to sustain plant growth. When the plant is well developed, and root distribution with the crops ICRISAT is using and those traditionally used by the dryland farmers does not seem to be a problem, there is sufficient water storage in the soil for growth to continue. Admittedly growth sometimes occurs at reduced rates but the available water is sufficient to produce a crop. Of course in order to ensure that this is true it is important to have adequate infiltration and, in the wetter part of the season, adequate drainage.

As the authors of the keynote paper have pointed out, dry Vertisols have very large cracks. This is a considerable advantage with the early rains because water penetrates down the cracks to a considerable depth in the soil and aids greatly in charging the profile of these soils that are so impermeable when the soil is saturated. Early rains help to charge the profile for the first crop. Later rains, particularly when there tends to be a rapidly growing crop or a dry spell in the middle of the season, re-charge the profile for the second crop or provide water for a longer-duration intercrop where this has been included in the cropping system. In other words, there is sufficient rainfall distribution and sufficient

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movement through the cracks to allow adequate charging of the soil for two crops — one during the rainy season and one growing mostly on stored water in the second, i.e. post-rainy season.

In 1978 at ICRISAT, when rains were approximately 30% below normal, there was virtually no runoff at all from the watersheds under improved management because the well-spaced rains and the good crop stand caused the cracks to open several times during the season. Virtually all the water that fell infiltrated the soil. Crop yields in the improved maize-pigeonpea intercrop and maize-chickpea sequential crops were essentially the same as in other years when the rainfall was normal or greater.

The broad bed technology is not sufficient in itself to prevent erosion since Vertisols are very impermeable when wet and are extremely susceptible to erosion. The substitution of broad beds for narrow furrows and ridges reduces the tendency for breakthrough and severe erosion down the field. However, even though the broad beds have been graded to relatively low slopes, substantial erosion can occur in the absence of plant cover. Thus growing a crop during the rainy season, instead of allowing the soils to lie fallow is an extremely important aspect of the technology. As Smith *et al.* have pointed out, mulching helps reduce erosion. However, under Indian conditions the farmers harvest and remove all the grain and straw. Litter is mostly leaf fall from the leguminous crops. Crop production during the rains is an essential means to prevent erosion in such conditions.

Another important element of the technology is keeping the crops on the beds and the wheels of the equipment off them. Vertisols are very compressible and easily compacted when wet. Low tillage of the beds plus the incorporation of organic matter from leaf fall and root decomposition lead to improved soil structure and a reduction in power requirements for cultivation year by year. The practice of running the wheels in the same furrows causes the amount of cracking in the furrows to increase. This observation has led us recently to consider the extent to which this pattern of cracking could be manipulated to increase the infiltration rate of the soil and so increase the productivity. To some extent this is also a disadvantage since there is some evidence of root pruning in the later growing season of the crops. This may be reduced by applying gypsum in the cracks in the furrows and this technique is being tested currently.

In conclusion, I would like to make two points. Firstly, it must be remembered that the physical problems of Vertisols are amenable to chemical solutions such as the application of gypsum that I mentioned in the previous paragraph. Secondly, many of the treatments and practices to improve Vertisol management that are being studied and utilized in the industrial world are, for the moment, beyond the realm of possibility for farmers who use few inputs under rainfed conditions. There are many advantages to increasing the productivity and profitability of these soils. One of them is that it will provide farmers with sufficient resources to consider the possibilities of using more inputs and better management processes.

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Session 5
Physical Properties of Vertisols

Summary of Discussion

J.P. Quirk*

In the introduction to their paper the authors indicate that the total area of Vertisols in Queensland has been estimated to be 50 million ha, which is two-thirds of the Australian total or about one-fifth of the world area of Vertisols. At present, 1.2 million ha are cropped and it is estimated that a further 6 million ha have potential for cropping. Thus, because of the present and growing significance of Vertisols in Queensland's agriculture, the authors have made an extensive study of the physical features of the soil including water entry, water storage and especially aggregate stability in relation to run-off and erosion. In their studies of aggregate stability they have attempted to establish correlations between stability and such factors as clay content, cation exchange capacity, and exchangeable sodium percentage.

The authors make it clear that their soil physical studies are concerned with modelling of production and soil erosion.

Agricultural scientists have sought an accommodation in production systems between:

1. *Plant* and *climate*, for example, with early maturing or stress tolerant varieties.
2. *Plant* and *soil*, one example being the selection of aluminium-tolerant varieties of soya bean.
3. *Soil* and *climate* especially to take into account the erosivity of a rainfall event and the erodability of soil.

The authors note that:

1. Measures to reduce soil erosion include contour banks, stubble retention, and cropping practices. Monitoring of contour catchments shows stubble mulching reduces run-off and the additional stored water increases crop yield. No treatment eliminates erosion entirely and the most protective, i.e. stubble plus zero tillage, is the least profitable. Erosion process studies with simulated rain have shown the importance of rainfall energy in causing breakdown of aggregates to sizes < 0.125 mm. Rills carry much more sediment density rather than sediment size. Interflow can be an important feature of run-off from rough tilled soils protected by stubble.
2. Seedling emergence problems can be substantially alleviated by using presswheels to compress soil around the seed. Gypsum is used to modify structure in the surface of some soils to improve water entry and seedling emergence.

The measurements outlined in the tables and figures are concerned with the structural stability of a number of Queensland Vertisols ranging in clay content from 30–80%. In the surface horizons the structure ranges from massive to a very strong development of fine granular structure. The authors point out that the darker soils known as Black Earths coincide approximately with the Pellustert great group. Other Vertisols studied by the authors are known as grey, brown, or red clays corresponding to Chromusterts and Torrerts.

The authors state 'Soil structure is determined mainly by the way constituents generate and react to stresses during wetting and drying'.

Figure 2 is a central feature of the paper; it shows that a wetting rate of soil aggregates in excess of 0.1 cm^3/g in 2 minutes (equivalent to a rainfall of 5 cm/hr for a duration of 2 minutes) leads to incipient failure as discussed by Quirk and Panabokke (*Journal of Soil Science* **13:** 60–70, 1962). It may be noted from Figure 2 that for wetting rates < 0.1 cm^3/g in 2 minutes the geometric mean diameter is in excess of 1 mm and for wetting rates greater than this figure the geometric weight is < 1 mm.

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Having observed the characteristics of Figure 2 we now turn to Table 5 that demonstrates that a significant proportion of the aggregates are greater than 1 mm following immersion. This result would seem to be at variance with the rate of wetting effects in Figure 2 and may arise from permeability decreases for aggregates when immersed directly in water; this may be associated with entrapped air. It would be helpful if the authors were to provide the rainfall intensity for treatments 1 and 2 in Table 5. With respect to rainfall intensity, I would like to observe that in order to understand run-off events and associated erosion to a greater extent, it will be necessary to carry out research into the fine structure of a rainfall event.

The results presented in Table 4 suggest that the wetting rate is increased in the presence of 10 m equiv./litre of gypsum and that the increased rate leads to greater aggregate slaking. The difference reported for the wetting at 10 cm suction is not great and the effect of added electrolyte may find expression more specifically in the faster rate of drying of the surface soil thus giving rise to a more friable soil surface akin to those soils with an inherent tendency for self-mulching.

Table 7 presents clear evidence that compaction of the soil around sorghum seeds leads to greater establishment. The compaction is achieved by a rubber presswheel and the author's results suggest that such a procedure may be an important practice that could be applied more generally to Vertisols.

Erosion is the most important problem faced in using these soils for crop production and it is a sobering thought to realize that a 10 tonnes soil loss per ha is sometimes accepted as the upper level of permissible soil loss. However, this is the equivalent of a depth of 1 mm over a ha and it could be suggested that trading 10 tonnes of soil for about 2 tonnes of grain is a very poor long-term strategy.

It is worth recalling the work of Millington (*Australian Journal of Agricultural Research* **12:** 397–408, 1961), who working with Australian red brown earths, i.e. (Haploxeralfs) from the Waite Institute rotation plots, analysed yields for a 20 year period and has demonstrated that there was an 8–9 bushel per acre decrease in yield for each inch of rain in the month following seeding. He found that the bulk density increased 0.052 g/cm^3 for each inch of rain in the month following seeding and he suggested that half the grain loss per inch of rainfall could be attributed to effects of increase in bulk density. In experiments with applied nitrogen, Millington eliminated leaching as a factor causing decreased yields.

In another part of the paper, the authors state that 'there is a critical water content at which clay is readily dispersed by mechanical energy'. This water content, related to the liquid limit and close to saturation, was called the Disruptive Moisture Content (DMC).

I draw attention to this matter because there is an ever increasing proclivity to invoke the World Soil Map Unit or the U.S. Soil Taxonomy Great Group in order to arrive at detailed rather than general assessments of the soil's physical behaviour. In the absence of measurements relevant to a specific problem, then the Atterberg Limits ought not be ignored even though they are indeed empirical; they have been very successfully applied in the field of civil engineering.

One interesting remark made by the authors is 'Apparently the physico-chemical properties of the clay present in the soil override the effect of organic matter in determining aggregate size'. The physico-chemical and swelling properties of Smectites or montmorillonites have been studied extensively (see, for example, Quirk, in *Modifications of Soil Structure* John Wiley and Sons, 1978 and *Israel Journal of Chemistry* **6:** 213–234, 1968) but this is not an appropriate time to consider the connection between the paper under consideration and these studies.

One significant feature of the behaviour of clay soils remains to be explained, i.e. the basis for self-mulching; this represents a major challenge that could have extremely significant implications for all clay textured surface soils.

Session 6

Tropical High Mountain Soils

Chairman: M.E. Raymundo
Discussion Leader: G.J. Blair

Soil Resources, Demography and Land Use An Example of Steep-land Problems in Papua New Guinea

P. Bleeker*, G. Keig* and J.R. McAlpine*

In order to overcome constraints to food production in the tropics, it is essential that these constraints are reliably identified. Constraints imposed by soil, climate and other land characteristics are central to agricultural land evaluation and agrotechnology transfer, both of which require the matching of these characteristics with crop ecophysiological responses.

In this paper it is argued that the most widely used land evaluation methodologies are those derived within the context of western agricultural experience and that their application to other regions can lead to incorrect or inappropriate assessments of land-use potential, because determination of the nature of a constraint to agricultural production can only be made in the context of a relevant agricultural system. An absolute constraint under one system can be of positive benefit under another. The transfer of constraint criteria from one agricultural system to another must therefore be carried out with caution.

This issue will be discussed in relation to Papua New Guinea (PNG) where the occupancy and use of land is almost the antithesis of that which would be expected in terms of a western agricultural model of resource use. The contrast between actual and expected patterns of land use and the diversity of agricultural systems and natural resources found in PNG make it particularly necessary to develop and test land evaluation methods that are more appropriate to that country.

The first section of the paper presents a brief review of current concepts of land evaluation and considers in particular the FAO global framework. Subsequently, resource use and population distribution in Papua New Guinea are examined in relation to the environmental (agro-ecological) zones represented within the country. Contrary to what would be expected in terms of western-derived land suitability criteria, the largest proportion of the population is found to live in steep-land areas. The agricultural resources of the Chimbu Province, which contains large areas of high relief terrain, are then examined in detail. The results of the application to the Chimbu Province of a western-derived land evaluation methodology, which has been specifically modified to suit Papua New Guinea conditions, are presented. It is shown that the existing areas of occupation and intensity of land use are in direct contrast to the land-use potential as indicated by the land assessment. This disparity is partly due to the choice of farming systems used in the evaluation, as these were biased towards a western style of agricultural development when in fact development has been based on the resource-use pattern of the existing subsistence food production system.

It is concluded that new evaluation procedures will need to be developed that will concentrate on the matching of crop requirements with soil, land, and climatic characteristics. In particular, a new approach is required to the identification of constraints to crop production in which crop ecophysiological requirements are documented, evaluated, and ordered in such a way that dynamic modelling rather than static matching of crop requirements with land characteristics is possible. Most importantly, the constraint identification must relate to resources as they exist and should not be made in terms of their potential for modification. Some of the problems in developing such an approach are illustrated with reference to sweet potato (*Ipomoea batatas*) production in Papua New Guinea.

Current Concepts of Land Evaluation

Formalized land evaluation methodologies have

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had their origins in temperate western farming systems, the most notable of which is the extensive mechanized arable production of cereals within a market economy with measurement of productivity usually in terms of yield and/or profitability. Possibly the most widely known examples of western evaluation are those of the U.S. Bureau of Reclamation Classification (1953) and Klingebiel and Montgomery (1961). Clearly, the unmodified application of the production constraints relevant to western agricultural land evaluation procedures to other agricultural systems (e.g. humid tropical subsistence farming involving complex multiple cropping) could produce unreliable assessments of land-use potential. The danger in simply modifying western evaluation models for application to other areas is that, while they may produce correct results in terms of the explicit procedures employed, those results may be irrelevant or inappropriate to the form of agricultural development taking place within an area or country.

During the last decade, FAO has addressed the problem of developing a globally viable framework for land evaluation (FAO 1976). Significantly, this framework presents a generalized approach to the problem rather than a detailed methodology designed for universal application. Nevertheless, if the principles of the framework are adhered to, the applications that would be produced should be both reliable and appropriate. Simply stated, the framework requires the definition of both the land characteristics of an area and of the land utilization types that might be considered appropriate to that area. The requirements of each land utilization type are then matched against the existing land characteristics and an assessment made of the quality of the match.

Population and Resource Use in Papua New Guinea

The total area of PNG is 458 000 sq km, with a population of 3 011 000, of which 2 401 000 are rural village dwellers (National Statistical Office 1982).

The recent compilation of a national resource inventory for PNG has involved mapping and description of some 4 300 Resource Mapping Units (RMUs) using parameters relating to landform, lithology, soils, climate, and vegetation. In addition, the rural villages within each RMU have been identified from census maps and the total population of each RMU determined. The resource inventory has been stored in a microcomputer-based system from which information can be retrieved and processed for specific purposes.

To investigate the relationship between population distribution and agricultural resources for the country as a whole, the detailed landform and climatic parameters describing each RMU were simplified by reclassification into a smaller number of descriptive classes. Each unique combination of these classes for landform/climate constitutes an environmental (agro-ecological) zone, for which, by aggregation of the RMUs comprising that zone, a total rural population within that zone could be derived. Summation of these data for the whole of PNG has permitted for the first time analysis of rural population distribution by the entire range of physical environments within the country. An example of an analysis of the distribution of rural population in relation to landform type is presented diagrammatically in Figure 1.

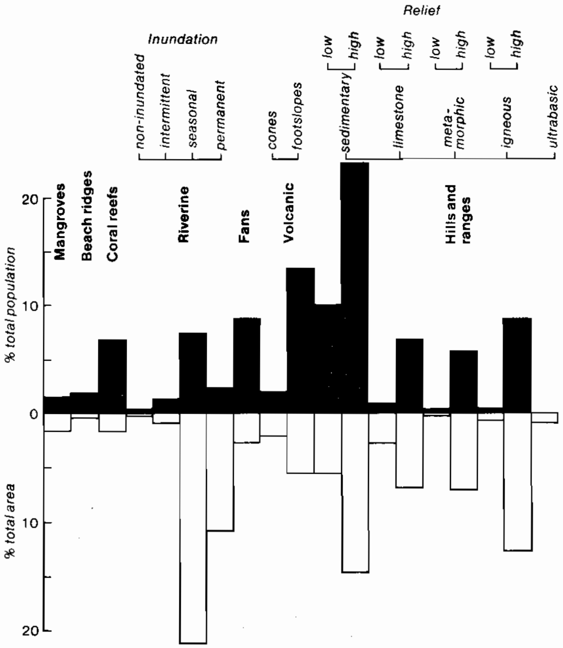


Figure 1. Percentage distribution of total area and population by landform type.

PNG contains 181 887 sq km (39.8% of total) of relatively flat terrain, comprising mangrove swamps, beach ridges, raised coral reefs, riverine environments, and alluvial fans. On these zones a total of 725 360 or 30.2% of the rural village population lives. However, distribution of the population between the various zones is not proportional to the zone areas. Thus, 6.7% of the rural population lives on raised coral reefs, which comprise only 1.7% of the total area of PNG, while 11.5% of the population inhabits riverine environments, which comprise 33.1% of the country's total area. This disproportionate distribution of population with respect to zone areas is clearly shown in Figure 1.

The remaining landform types comprise the steeper lands of PNG. These account for 275 971 sq km (60.2%) of the country and support a population of 1 675 736 or 69.8% of the rural village population. On these steeper lands, population distribution between environmental zones is again not uniform. The volcanic cones and footslopes comprise 7.9% of the total area, but support 15.2% of the rural population. Within environmental zones covering hills and ranges, there are 44 351 sq km of low relief terrain and 195 280 sq km of high relief terrain, accounting for 9.7% and 42.6% of the total area of PNG, respectively. Of the rural population that lives within these zones, 263 057 (11.0% of rural total) live in zones of low relief and 1 047 226 or 43.6% — nearly half the total rural population of PNG — live within zones classified as hills and ranges of high relief. Of particular interest is the large population living on hills and ranges of sedimentary lithology and high relief. This zone comprises 14.7% of the total area of the country but supports 23.2% of the total rural population.

The relative avoidance of lowland alluvial areas is in sharp contrast to the South-east Asian situation where areas of similar soil and climate are densely populated. This observation, and the apparent preference for steep lands, should clearly indicate caution in the transfer of land evaluation methods and soil constraint criteria even from areas with similar environments to those in PNG.

The same type of analysis has been carried out in relation to altitude, which is a direct surrogate of temperature (McAlpine *et al.* 1983), and rainfall. Lowland areas below 600 m comprise two-thirds of PNG but support only 45.2% of the rural village population. Intermediate altitudes between 600 and 1 200 m, which comprise 14.4% of the land area, hold only 8.1% of the population. This under-representation of population with respect to zone areas at lower altitudes is balanced by the greater proportions living in the highland areas between 1 200 and 2 800 m. These areas account for 16.7% of the total land area, but support 46.4% of the rural population.

An analysis of rainfall in relation to population distribution has been based on four mean annual rainfall classes. These are:

Less than 1 500 mm = dry subhumid
1 500–2 000 mm = subhumid
2 000–4 000 mm = humid
Greater than 4 000 mm = perhumid

The population is distributed approximately in proportion to the area of each zone, except for the perhumid zone, which occupies 22.3% of the total land area but supports only 9.7% of the rural population. Two-thirds of the total area of the country is classified as humid, and within this zone are found 76.7% of the rural population.

Thus, modal resource-use in PNG lies in highland and steep-land areas of sedimentary origin and with relatively (but not excessively) high rainfall. A Province typical of this pattern is now examined in some detail.

Agricultural Resources of the Chimbu Province

Chimbu is a very rugged mountainous Province located in the central highlands of PNG (Figure 2). It covers an area of approximately 6 000 sq km and has a total population of 178 500 of which 169 000 live in rural villages. Population densities on used land can rise to 170 per sq km (McAlpine 1970). The staple food is sweet potato (*Ipomoea batatas*).

In comparison with many other areas of PNG, the agricultural resources of the Chimbu Province are relatively well known. The main investigations of these resources have been carried out by Haantjens *et al.* (1970), Bleeker and Speight (1978), Humphreys (in press), and Scott *et al.* (in prep.).

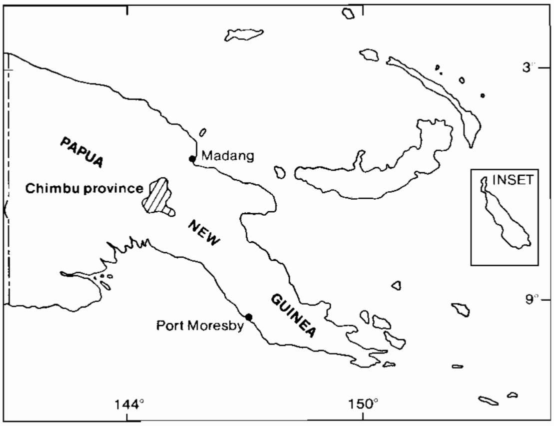


Figure 2. Location of Chimbu Province.

Physiography and Climate

The Province can be divided into three major regions, viz. northern, central, and southern.

The northern region is dominated by very rugged and steep mountainous terrain formed on Miocene igneous rock and lying mostly between 2 500–4 000 m. The highest peak rises to 4 508 m and was glaciated during the Pleistocene. Mean annual rainfall is approximately 2 500–3 000 mm. Mean annual maximum temperatures at 4 000 m are 8°C with minima of 0.6°C. At 2 500 m these increase to 15° and 5.5°C, respectively. The region is under forest or alpine grassland above 2 800 m but, below that altitude, is used for horticulture.

The central part of the Province consists of rugged hills and ridges of high relief and steep slope underlain by Mesozoic and Cainozoic calcareous and non-calcareous sedimentary material. Altitude reaches 3 000 m but for the most part lies between 1 500 and 2 000 m and decreases in a southerly direction. Mean annual rainfall is 2 500 mm and there is a slight dry season from May to August but monthly falls are still mostly in excess of 100 mm. At 1 600 m, mean annual maximum temperature is 24°C and the minimum is 13°C. Except in isolated higher areas, the whole of this region is used for agriculture. The centre of the region is partly separated by a short length of little used alluvial plain and isolated areas of heavily-gardened, dissected alluvial fans. These have relatively low slopes and are either under grassland or heavily gardened.

The southern part of the Province has large tracts of gently sloping volcanic plains at altitudes below 1 500 m. These are dominated by three extinct volcanoes of Pleistocene to Holocene age but also include significant areas of limestone and sedimentary rocks. Mean annual rainfall exceeds 3 500 mm, rising in the far south to 8 000 mm, and the pattern of seasonality is reversed in comparison with the northern and central parts of the Province. At 1 000 m, mean annual maximum temperature is 28°C and the minimum is 17°C. Because of the rainfall seasonality pattern, the southern region can be expected to receive significantly less radiation than other parts of the Province. The south is little used and is mostly covered by medium-crowned lowland hill forest.

While volcanic ash deposits are extensive in the southern region, ash from large volcanoes lying to the west is also thought to have blanketed the remainder of the Province. As these volcanoes ceased activity about 50 000 years ago, ash deposited from them on steeply sloping terrain has subsequently been removed or translocated by erosion. There is also evidence (Pain and Blong 1979) of several recent thin ash layers being laid down from other sources nearer the coast.

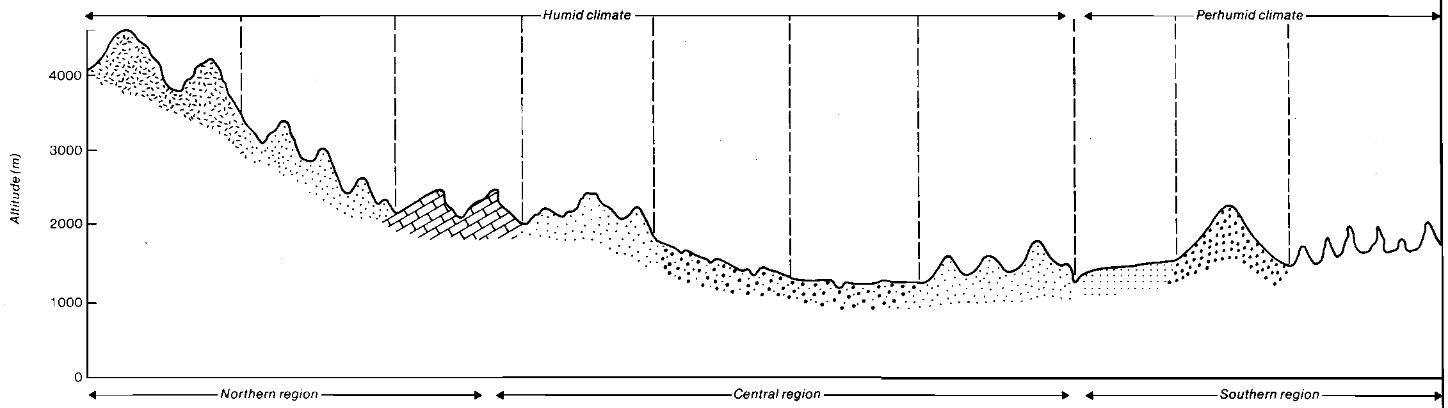
Regional variations between the main environmental zones comprising the northern, central, and southern parts of the Province are shown diagrammatically in Figure 3.

Soils

Much of the soil information collected during previous resource investigations in the Province has been classified to great group level according to the U.S. Soil Taxonomy (United States Department of Agriculture 1975). This is now the principal classification system used in PNG. It should be stressed that the classification of soils in Chimbu, which is presented here, is provisional only, as in most cases insufficient data are available to permit positive identification of soils. The problems involved in classifying soils in PNG have been discussed in more detail by Bleeker (1983). Six orders, eighteen suborders, and thirty-six great groups have been identified in the Chimbu Province and the most common of these are shown in relation to other environmental data in Figure 3.

High altitude peat soils (formerly called

LANDFORM	Rugged mountains glaciated above 3600m. Partly ash covered	Rugged mountains and hills. Partly ash covered	Very steep strike ridges and hogbacks	Rugged hills and mountains on rocks. Partly ash covered	Moderately dissected fans. Partly ash covered	Floodplain. Ash locally present	Hills and mountains. Partly ash covered	Little dissected fans and foot-slopes	Partly dissected extinct volcanic cones and domes	Karst lands: very rugged hills with broad valleys. Partly ash covered
ROCK TYPE	Igneous	Mixed sedimentary	Limestone	Mixed sedimentary	Alluvium	Alluvium	Mixed sedimentary	Volcanic ash (partly redistributed)	Volcanic	Limestone
SOILS	Cryorthents Cryandepts and Cryic great groups of Histosols Frequent rock outcrop above 4300 m	Troporthents Humitropepts and Tropic great groups of Histosols Hydrandepts on gentler slopes	Rendolls Hapludolls Tropudalfs Common rock outcrops	Humitropepts Troporthents Hydrandepts on gentler slopes	Tropaquepts Haplaquolls Plinthohumults Hydrandepts on gentler slopes	Fluvaquents Hydraquents Tropofluvents and various Histosols	Dystropepts Eutropepts Humitropepts on steep slopes Tropudalfs on footslopes Hydrandepts on gentle slopes	Hydrandepts	Troporthents Hydrandepts	Rendolls Hapludolls Hydrandepts in valleys and on gentler slopes. Rock outcrops very common



LAND SUITABILITY	Unsuitable	Annual crops — very low; tree crops — low; pastures — low to moderate	Annual crops — nil; tree crops very low – low; pastures very low — low	Annual crops – very low; tree crops — low; pastures low to moderate	Annual crops — low; tree crops — moderate; pastures moderate	Annual crops — low; tree crops — low; pastures — moderate	Annual crops — very low; tree crops — very low — low; pastures — low	Annual crops – high; tree crops — high; pastures – high	Unsuitable	Annual crops — low; tree crops — moderate; pastures — moderate
POPULATION DENSITY	Nil	Moderate	Low	High	Very high	Nil	Moderate	Low	Nil	Nil
INTENSITY OF CULTIVATION	Nil	Moderate to high below 2600 m	High	Very high	Very high	Low	Moderate	Low	Nil	Low

Figure 3. Environmental zones — Chimbu Province.

Alpine Peat and Humus soils) are found in mountainous areas above 3 400 m with mean annual temperatures of less than 8°C. Of these, the 'more or less' freely drained Cryofolists occurring in Alpine grasslands on gently to steeply sloping terrain are most common. Their poorly drained counterparts, i.e. Cryohemists and Cryofibrists, are found in flatter terrain and drainage depressions with typical peat bog vegetation. Very shallow Cryorthents and bare rock exposures are also common at these altitudes.

Below 3 400 m, with higher mean annual temperatures, the Cryic great groups grade into their Tropic equivalents. Of these, Troporthents are very common on steeply sloping terrain and are found on a wide variety of lithologies and vegetation types. Tropofibrists and Tropohemists are mostly confined to phragmites swamps in small floodplains where they occur together with Hydraquents and Fluvaquents. However, well drained parts of floodplains are covered by Tropofluvents.

Humitropepts are widespread under grassland and forest in the northern and central parts of the Province, mainly between 1 500 and 3 000 m, and are found on a wide range of parent materials with slopes generally greater than 20°. In similar areas with greater slopes, volcanic ash deposits derived from large extinct volcanoes to the west have been preserved, resulting in the presence of Hydrandepts. Both the Humitropepts and Hydrandepts (formerly called Humic Brown clay soils) have a very similar profile morphology. Locally on stable, gently sloping terrain, deep strong weathering of ash under the prevailing wet conditions has led to the formation of Palehumults. Other, but generally coarser-textured volcanic ash soils, provisionally also classified as Hydrandepts, are widespread in the southern part of the Province and are thought to be of local and more recent origin.

On steep to very steep slopes, generally below 1 500 m, Dystropepts and Eutropepts are very common on colluvial deposits, sediments, and low grade metamorphics. Under well drained conditions, footslopes in these areas are often dominated by Tropudalfs. Tropaquepts are the most common soils found on fine textured, old alluvial deposits, such as dissected fans. Here they are found locally, together with Plinthaquults, Albaquults and their somewhat better drained counterparts with high organic matter contents — Plinthohumults and Tropohumults. Tropaquepts also occur commonly on gently to moderately sloping terrain underlain by fine grained sedimentary rocks and on colluvial aprons.

On limestone and calcareous shales there is an intricate pattern of soils with Rendolls, Hapludolls and bare rock exposures and, to a lesser extent, Arguidolls and Tropudalfs.

Soil Fertility

Chemical fertility and bulk density data for the Province are provided in the resource survey studies listed above and in Bleeker and Healy (1980), Wood (1979), and Hide (in prep.). The major environmental differences in the Province are between the north/centre and the south and consequently, for the sake of brevity, the summarized data for topsoils (0–25 cm) are presented in terms of this division.

In the northern and central regions of the Province, data refer to soils that are mostly used for agriculture. Major soil fertility characteristics in these regions can be summarized as follows:

1. pH values vary little between the great groups. Almost all soils are within the 5.5–6.5 range; Mollisols on calcareous rocks are the only exception.
2. CEC and BS values are moderate to high for all soils.
3. Organic matter content is highest in the Hydrandepts (13%), which is attributable to the presence of gibbsite and allophane in the clay fraction with which it forms stable compounds (Sanchez 1976). Other great groups generally have low organic matter values (< 6%), the only exception being the Troporthents (7%).
4. Available nitrogen values show little variation and fall mostly within the moderate (90–135 kg/ha) range with only the Tropofluvents being slightly above and the Troporthents slightly below that range.
5. Available phosphorus contents are very low for all great groups, with values for the Tropofluvents (mean 9.8 μg/ml) being the highest. Moderate phosphate retention values characterize most soils but the Hydrandepts, as can be expected, have a

very high fixation capacity.

6. Exchangeable potassium values generally fall within the low (0.3–0.5 m equiv./100 g) range with very low values for the Hydrandepts and Tropaquepts. Mean values for the Hapludolls and Rendolls fall just within the moderate range (0.5–0.8 m equiv./100 g).

In the south of the Province, settlement is light. As the purpose here is to make a comparison between the north and the south, and as the data for the north refer mostly to cultivated areas, comparable data for similar areas in the south are emphasized, even though most of the area is under rainforest. Major soil fertility characteristics in the south can be summarized as follows:

1. pH values lie in the range 5.3–6.2 with lower values generally being associated with rainforest sites and higher values with cultivated areas.
2. CEC and BS values fall almost wholly within the high and moderate ranges respectively, the general trend being that BS figures increase with decreasing CEC values. There is some indication, although inconclusive, that CEC values decrease considerably after the clearing of rainforest.
3. Organic matter content under cultivation and fallow ranges from 12–19% and is about 10% higher under rainforest.
4. Available nitrogen values are all well above average (> 180 kg/ha) and show sharp decreases upon conversion from rainforest to cultivation.
5. Available phosphorus levels are all within the very low range (< 10 μg/ml) and phosphate retention values are high to very high.
6. Exchangeable potassium lies in the range 0.5–1.2 m equiv./100 g in cultivated areas, with the higher figures probably being due to the practice of burning cleared forest material to produce ash.

Although the differences in vegetative cover and cultivation between north and south Chimbu make a comparison of their soil properties difficult, it would appear that there is little difference between the two regions in terms of pH, BS, and available phosphorus, while organic matter, available nitrogen, exchangeable potassium, and CEC all appear to be higher in the south of the Province. It is interesting to note that the trend for organic matter and nitrogen in the Hydrandepts is quite the opposite to that which would be expected, as these values are significantly higher in the warmer southern part of the Province. This is likely to be attributed to the much less intensive cultivation pattern in the south.

Soil physical properties also vary between north and south Chimbu. For example, bulk densities of soils in the north are around 1.0–1.2 g/cm^3 (except for volcanic ash soils), while in the south the ash soils have significantly lower (< 0.70 g/cm^3) densities. In the light of these differences in both chemical and physical properties, the soils of the south could be rated in terms of western criteria as higher in agricultural potential than those of the north.

Land Evaluation for Chimbu Province

The earliest formal land evaluation for the Province was made in 1957 (Haantjens *et al.* 1970). The method used was that of Klingebiel and Montgomery (1961) extended to include a suitability assessment for tree crops and wetland rice. Subsequently this scheme was modified specifically for application to PNG conditions (Haantjens 1969). It provided suitability ratings for four distinct types of agricultural use, namely arable crops, tree crops, improved pastures, and wetland rice. Each of the environmental factors considered (e.g. slope, drainage, flooding, salinity) was given a rating (usually 0–5) and every individual factor rating was assessed according to its individual suitability for each of the four types of agricultural use. With some modification this scheme has been used by Bleeker (1975) to produce a large scale (1:1 000 000) land limitation and agricultural land-use potential map of PNG. Jackson (1982) has made extensive use of this map to delineate areas suitable for large-scale agricultural development, which the government considers to be both a necessary and desirable feature of future economic progress.

Using the methods of Haantjens and Bleeker, a suitability assessment for each of the main environmental zones within the northern, central and southern regions of Chimbu Province has been prepared and the results are presented in Figure 3. It shows that in both the northern and central regions of the Province agricultural land suitability is either nil, very low, or low, with the exception of some small areas of dissected fans that are moderately suitable for tree crops. This assessment can be explained by the dominance of very rugged, steeply sloping terrain, of high altitudes, and the frequent presence of shallow soils. It is only in the southern part of the Province that there are large areas with a moderate or high potential for agriculture. These areas comprise gently or moderately sloping terrain with deep volcanic ash soils possessing favourable physical properties, their only serious fertility limitation being their low available phosphorus content and very high phosphate retention.

It is interesting to note that if the criteria employed in three recent and major resource-assessment studies (FAO 1978, LRDC 1978, FAO 1980) were applied to the Province, very similar assessments of potential to that indicated above would be obtained. For instance, FAO (1980) in the 'Land Resources for Populations of the Future' project states that for production of sweet potato, which is the staple food crop of the Province, slopes of 0–8% (0–5°) are optimal and 8–20% (5–12°) marginal. Approximately equivalent slope constraint assessments are made in the agro-ecological zones project (FAO 1978).

The actual pattern of use of land is in direct contrast to that which could be expected from this assessed suitability of land. This is shown by a comparison between the assessed land suitability and actual intensity of cultivation presented in Figure 3. The northern and central region, which is classed as mostly unsuitable for agriculture, occupies 55% of the Province yet contains 95% of the rural population. Conversely, the southern region, which is judged to be moderately to highly suitable, occupies 45% of the area but holds only 5% of the population.

The reason for this apparent disparity between existing land use and assessed land-use suitability lies in the selection of possible agricultural uses for which the assessment was made. In this instance the four possible agricultural uses were linked to methods of production explicitly stated to be biased to commercial and plantation-type agriculture. As such, the applied constraint criteria would take into account the possible use of machinery, fertilizers, and associated managerial inputs. In this form of assessment, slope becomes a dominant constraint. While this type of land evaluation is valid for large scale agricultural development, the constraint criteria are not relevant to the largest sector of PNG agriculture, which is based on horticultural systems in which both food and cash tree crops are grown within the same subsistence resource-use framework.

There is a need for the development of new land evaluation techniques that are appropriate to the horticultural rather than arable production of root and tree crops within a subsistence resource-use framework. Any new techniques must be attuned to the dominant existing form of agriculture and must be free of western bias in constraint determination. The remainder of this paper attempts to indicate some ways in which this can be accomplished.

Sweet Potato — Ecophysiological Considerations

As sweet potato is the staple food crop for the majority of rural Papua New Guineans, it has been used for illustrative purposes in the following discussion of methods of identification of crop constraint criteria. Sweet potato has the highest solar energy fixing efficiency of any food crop (Hahn 1977). Its total food production per unit area exceeds that of rice and it provides higher food value (Villareal and Griggs 1982). The adaptation of this crop to a wide range of environmental conditions, as found in PNG, is attributable (a) partly to the genetic diversity of its cultivars, some 5 000 of which are believed to be grown in the country (Bourke 1982) and (b) to the diversity of farming systems within which the crop is grown.

For sweet potato, the most critical period of the growth cycle in terms of final tuber yield is that during which tuber initiation, or tuberization, takes place. For a 24 week growth cycle, tuber initiation is virtually complete by the eighth week after planting (Wilson 1982). During weeks 1–8, adverse environmental influences can lead to the development of non-tuberous rather than tuber-bearing root types, resulting in serious depression of yield. Factors that inhibit tuberization include waterlogged soils, dry and compact soils, high levels of nitrogen, and long daylength. By contrast, high potassium, well-aerated friable soils, low temperatures and short daylength encourage tuber initiation (Wilson 1982). Tuber bulking is also affected by environmental factors that act to suppress or promote tuber growth by influencing either the physical or chemical processes involved. The following discussion indicates how a study of known crop ecophysiological requirements might be used to derive a set of soil characteristics which, in the PNG context, could pose major limitations to the growth of sweet potato by their effect on either or both the tuber initiation and bulking phases.

Determination of Crop Constraint Criteria

There are two main methods of identifying the nature and degree of constraints to agricultural production. Firstly, they can be inferred from a consideration of the current distribution of a crop in relation to particular resource parameters. Second, crop constraint criteria can be determined directly from results of agronomic and crop physiological experimentation. This second method will subsequently be referred to as the 'experimental method'.

The inferential method of determining constraints relies mainly on resource information in the assessment of resource/crop relations and treats crops as static objects. Thus, a constraint is regarded as having a constant effect throughout the entire cycle of crop growth and development. By contrast, the experimental method emphasizes crop requirements and is frequently specific in regard to temporal variation in plant/environment relations. In deriving crop-specific constraint criteria, it is essential to consider the differential responses of the crop to changing environmental factors such as rainfall and temperature during the major phases of crop growth, rather than to assume a constant response over the entire growth cycle. Moreover, local management practices specifically designed to overcome environmental constraints must also be taken into account when the constraint criteria are matched with resource information.

A number of resource parameters will be discussed in relation to their effect on land suitability for sweet potato cultivation. The discussion of these parameters provides examples of the use of both the inferential and the experimental methods of determining constraint criteria.

Slope

An excellent basis for the determination of constraint criteria by inference can be provided by analysis of the detailed data on population distribution and land use in relation to resource factors contained in the national resource inventory of PNG. An example of this type of analysis for the whole of the country was presented in Figure 1. A similar analysis has been carried out for the Chimbu Province where, as an example, population distribution has been analysed in terms of slope classes.

Slope is generally regarded as a major constraint in land suitability assessment, yet in Chimbu Province 30% of the population live on slopes in excess of 30°, while a further 40% are found on slopes of 20–30°. More gently sloping terrain is only lightly occupied. Slope is usually considered a constraint because it hinders mechanization of production. While this particular problem is largely irrelevant to Chimbu horticulture, slope could still be regarded as a constraint in terms of human energy requirements.

Steep slope is also seen as a major constraint to agriculture through its effects on soil erosion. However, in Chimbu, soil erosion resulting from agricultural activity is not particularly noticeable in the field despite the general steepness of the Province. This may be a consequence of the horticultural rather than arable practices. Limited experimental evidence (Humphreys in press, also quoted by Bleeker 1983) indicates that, despite the relatively high annual rainfall, significant erosion only occurs on slopes in excess of 20° when plots are maintained in bare condition, an occurrence of very limited extent and duration under normal Chimbu agricultural practice. The evidence further indicates that erosion on garden plots and during fallow is remarkably low, even on slopes in excess of 20°.

This assessment of the role of slope in crop production as inferred from existing conditions and derived from experimental evidence leads to a possible conclusion that, given the high rainfall regime and the lack of tolerance of sweet potato to waterlogging, a reasonable degree of slope confers an environmental advantage in that it facilitates drainage. Thus, a determination of criteria relating to slope could well rate moderate to high slope as an asset, and low slope as a constraint.

Drainage

In a review of environmental effects on tuber yield of tropical root crops, Wilson (1977) concludes that 'On balance, therefore, it appears that the quantitative yield-limiting process in sweet potato is tuberization rather than photosynthesis, and hence the external factors which influence this process, e.g. water supply and oxygen, are likely to have considerable effect on yield'. This reduction of tuber yield on poorly drained soils is well recognized by the subsistence farmer in PNG and waterlogged soils at time of tuberization would be a major constraint to sweet potato cultivation in some areas if soil drainage were not facilitated by farming practices such as mounding, ditching, and planting on steep slopes. In the extreme case, even taking into account such management practices, there are some very high rainfall areas of the country where soils could not be adequately drained.

Bulk Density

Sweet potato tuber yield is reduced when soil compaction is either too high or too low (Sajjapongse and Roan 1982). Tuber size, rather than tuber number, is affected, indicating that the tuber growth phase is involved. Optimum bulk density was found to be from 1.3–1.5 g/cm^3. In the Chimbu Province, volcanic ash soils have bulk densities in the range 0.58–0.64 g/cm^3, which is well below the indicated optimum range. However, the high infiltration characteristics of such soils might outweigh any constraint imposed by low soil compaction for sweet potato cultivation.

Nitrogen, Potassium, and Phosphorus

Laboratory and field experiments with sweet potato cultivars outside PNG have indicated that high levels of nitrogen encourage top growth and inhibit tuber development (Tsuno and Fujise 1964). However, there is wide variation in nitrogen responsiveness between sweet potato cultivars (Haynes and Wholey 1968). Potassium increases tuberous root yield by encouraging tuberization, increasing sink capacity, accelerating the translocation of photosynthates, and hence promoting photosynthetic activity (Tsuno and Fujise 1964, 1965 a and b, 1968).

Fertilizer trials in Sierra Leone (Godfrey-Sam-Aggrey 1976) have indicated that the optimum ratio of potassium to nitrogen in applied fertilizer varies with the previous intensity of land use when the same cultivar is planted on different areas of the same soil (Oxisol). In an area that had been intensively cropped, nitrogen levels were moderate and potassium was very low giving an N:K ratio of 50:1. This area required a higher ratio of potassium to nitrogen in the applied fertilizer to give maximum tuber yield than did an area that had been under bush fallow for seven years. This newly cropped area had similar nitrogen but high potassium levels although potassium levels were still very low, and an N:K ratio of 34:1.

Inorganic fertilizer trials in PNG highlands have shown inconsistent results in relation to yield responses (Bourke 1982), which could be attributed to variability in soils, previous land-use intensity and the use of different cultivars.

On a young volcanic-ash soil in lowland New Britain (Bourke 1977), nitrogen was found to have the greatest effect on tuber yields, but soil potassium levels were very high, while total soil nitrogen was moderate to low, and N:K ratios were reduced to between 7.0 and 2.2. Nitrogen availability in this volcanic ash soil could be expected to be considerably lower (see Bleeker 1983). In a Soil Exhaustion Trial conducted in the same area, exchangeable K showed the greatest decrease over time, with consequent increases in N:K ratios, and in this experiment added potassium was found to increase tuber yield in the four plantings in which it was tested. Thus it would appear that there may be a ratio of nitrogen to potassium for each cultivar at which tuber yield is maximized, and the crop responds on either side of this ratio to that nutrient that diverges to the greater extent from the optimum requirement.

Phosphorus has no effect on photosynthetic rates in sweet potato leaves (Fujise and Tsuno 1962), and sweet potato cultivars can produce maximum yields at phosphorus concentrations of 0.05–0.15 ppm (Rendle and Kang 1977). No consistent positive response to added phosphorus was observed in lowland New Britain by Bourke (1977) on young volcanic ash soils.

pH and Exchangeable Aluminium

Field experiments on Ultisols and Oxisols in Puerto Rico (Talleyrand and Lugo-Lopez 1976; Escolar 1977) indicate that sweet potato is quite tolerant of high soil acidity (pH 4.7 in the top 25 cm) and exchangeable aluminium (greater than 50% in 25–50 cm layer). pH values in PNG soils are rarely less than 5, while exchangeable aluminium can reach 30% of total cations in some highland volcanic ash soils (D.P.I. 1983). Thus it appears unlikely that either of these soil characteristics would impose significant limitations on growth and development of sweet potato in PNG.

In a similar manner to that in which soil characteristics have been considered above, studies can also be made of those landform and climatic factors that could limit the suitability of land for sweet potato cultivation. In this way, detailed consideration of all available information on crop ecophysiology could produce a crop-specific set of environmental factors that would include only those factors likely to impose major limitations on crop growth in PNG.

Conclusion

In practice there have been two main approaches to agricultural land evaluation. The climatological approach has been concerned chiefly with the prediction of variability of crop development and yield over time. The techniques have been statistically oriented and mostly involve some form of dynamic modelling with the results tested against yield data. The resource inventory and evaluation approach has been mainly concerned with prediction of crop performance in terms of the spatial variability of soils and landform. Techniques of evaluation have mostly relied on the static matching of particular resource parameters with crop requirements to produce assessments of land suitability for specific types of agriculture. The most comprehensive evaluation studies include both climatological and resource approaches (e.g. LRDC 1978). A major FAO study in Africa (1980) has integrated the two approaches and extended the evaluation to include population and nutritional considerations.

A review of the literature, including annotated bibliographies of land evaluation (e.g. Laughlin *et al.* 1981), reveals that, although most land evaluation studies use the concept of crop constraint criteria in assessing land suitability, few give any indication as to the method of derivation of those criteria. Fewer still indicate that either an analysis of the relationship between existing crop distribution and environmental parameters has been undertaken or that an adequate review of the relevant experimental literature has been carried out.

This paper has attempted to demonstrate that unless information from both of these sources is related rigorously to resource inventory information, resulting land-use assessment can be misleading or inappropriate. The formal incorporation of procedures relating to survey of existing crop distribution and of relevant agronomic and experimental data is an essential step towards a more rigorous identification of soil and other resource-constraint criteria, and thus to more effective land evaluation procedures.

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C. Valverde*

Discussant — 1

Land Use: Technical Classification — An Example of its Use in the Andes and Peru

Firstly, as a discussant, I quite agree with the case study presented in relation to the mountainous Chimbu Province where the consideration of land evaluation is related to the ecophysiological aspects of the sweet potato as a way of determining the soil constraints and their importance in relation to a given agro-ecological condition. It is understandable that to deal with the heterogenous environment of the sweet potato grown in PNG, it is essential to have climatic data, basic meaningful soil information, and specially the knowledge of the farming system, where sweet potato plays the most important socio-economic role, before a good and real assessment of the land could be made. On the other hand, until the problem of correlation among the different soil classification systems in existence is solved, an individual soil can be classified into any of the existing systems, if their properties are known. In this respect, for example the FAO/UNESCO legend, to my understanding should not be designated as a taxonomic classification as such, and should not be judged on the criteria mentioned above.

Regarding my own paper, its purpose is to provide an example of the utilization of a simple technical classification by which we can establish technical groupings, each for a limited objective, which in this case was to group soils with similar fertility limitations. Given the availability of certain basic soil profile data that characterize experimental sites, it is possible and sometimes appears desirable to classify soils using only criteria concerned with soil fertility problems.

The example could also indicate one way of linking the gap between soil classification and soil fertility, which have a tendency to mutually exclude each other. The technical classification used is the one developed by Buol *et al.* (1975) under the title 'Soil Fertility Capability Classification FCC'. Its relevance in relation to fertilizer response assessment will be shown by using the data and results of 73 potato field experiments conducted through the Andes of Peru by Valverde *et al.* (1966) and McCollum and Valverde (1968).

In the densely populated highlands of Peru, agricultural practices are usually carried out in the inter-Andean Valley. The subsistence farmers operate in a wide range of climatic and environmental conditions that are influenced mainly by altitude, rainfall, soil types, and slopes; through the influence of these conditions and also population density many diverse farming systems have evolved where the main staple foods are potato, wheat, maize, and barley.

Whereas in Papua New Guinea, sweet potato (*Ipomoea batatas*) is the main staple food, the potato (*Solanum tuberosum*) is the dominant crop in the cropping system in the highlands of Peru.

Soil Fertility Constraints

To improve the farmer's cropping system, the most limiting factor to deal with is the conservation of soil fertility especially where erosion is severe due to slope. The normal practice to maintain fertility is a long fallow rotation and/or the frequent use of green manure to restore soil fertility.

As a result of the variation in temperature, rainfall, and topography there is considerable variability in the soils in the region. In many cases this limits the immediate possibility to have for all cases a detailed taxonomic classification, which usually takes time, laboratory facilities, and financial resources.

Soil fertility varies greatly. For example, pH values range from 4.5–8.0, while organic matter contents vary from 2–13%. However, these values usually are not indicative of nitrogen availability due to slow mineralization at low temperatures, especially above 9 000 feet above sea level; thus soil nitrogen content

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shows little value if any, as a diagnostic criterion unless it is correlated with crop response. Available phosphorus contents are low, with less than 7 ppm P (Olsen Modified). Exchangeable potassium values are usually in the range of 0.8–1.5 m equiv./100 g.

Crop Fertility Requirement (Experimental Phase)

The approach used to determine fertility constraints to crop requirements was to conduct experiments under changing environmental conditions of rainfall, temperature, location, and time.

The following criteria were used for the four crops studied:

1. To use existing large scale maps when available to select representative areas within a given agro-ecological zone.
2. To characterize the soil of the experimental site from the point of view of both taxa and soil fertility constraints.
3. To carry out a series of factorial field trials within the main crops of the farming systems used to study nutrient responses (mainly N, P, K, Mg).
4. To correlate soil analyses with crop production responses.
5. To use existing and obtained physical, chemical, and biological data for appropriate land fertility capability assessment.

In summary, the objective was to obtain enough basic data to determine crop requirements in the different environments of the Peruvian Andes where climate, especially rainfall, varies a great deal in its distribution causing either water stress or drought.

The results obtained during the first five years, in this case potatoes, were collated, analyzed, and correlated using the stepwise multiple regression analysis method. The factors studied were fertilizer response, location, years, varietal variability, and soil test data. Complete and detailed information of the results is given by Valverde *et al.* (1966) and by McCollum and Valverde (1968).

Land Evaluation — Soil Fertility Capability Classification

An outline of the technical classification FCC, developed by Buol *et al.* (1975) is given in Table 1. It essentially consists of three levels:

1. Type
   This is the highest category; it is determined by the average texture of the plow layer or upper 20 cm, whichever is shallower. USDA textures have been used, (Soil Survey Staff, 1975). A field estimate of texture by feel is probably adequate in the absence of laboratory data.
2. The Substrata Type
   This is the texture of the subsoil that occurs within 50 cm of the surface. It is used if the subsoil texture differs from that of the surface soil within the defined limits. If a textural change of this magnitude is present, no substrata type designation is employed. For example, a sandy soil where the clayey or argillic horizon is at 60 cm below the surface would be designated as S, whereas a similar soil with the argillic horizon beginning 40 cm below the surface would be designated as SC (sandy over clayey). On the other hand, if a sandy soil with a texture of sand in the surface has a sandy loam subsoil, it will be designated SL (sandy over loamy); if the subsoil is a loamy sand only S (sandy) is employed.
3. Condition Modifiers
   Unless otherwise defined the condition modifiers, in general, refer to chemical or physical properties of the plowed layer or top 20 cm, whichever is shallower. The modifiers indicate specific fertility limitations with possible different interpretations. Although the definition of these modifiers is written in rather specific terms in Table 1, it is not necessary to obtain the characterization with this degree of precision in order to make the system functional. Condition modifiers are used as a lower case letter for coding the soils.

A complete description of the condition modifiers is in Buol *et al.* (1975).

Relevance to Fertilizer Response

Using the standard format (Table 1) the soil profile information of 73 potato fertilization experiment sites were grouped only into five

Table 1. Fertility-capability classification (Buol *et al.* 1975).

TYPE:
Texture is average of plowed layer of 20 cm depth, (8″) whichever is shallower.
S = Sandy topsoils: loamy sands and sands (USDA).
L = Loamy topsoils: < 35% clay but not loamy sand or sand.
C = Clayey topsoils: > 35% clay.
O = Organic soils: > 30% O.M. to a depth of 50 cm or more.

SUBSTRATA TYPE:
Used if textural change or hard root restricting layer is encountered within 50 cm (20″).
S = Sandy subsoil: texture as in type.
L = Loamy subsoil: texture as in type.
C = Clayey subsoil: texture as in type.
R = Rock or other hard root restricting layer.

CONDITION MODIFIERS:
In plowed layer or 20 cm (8″), whichever is shallower unless otherwise specified (*).
*g = (Gley):
Mottles ≤ 2 chroma within 60 cm of surface and below all A horizons or saturated with H_2O for > 60 days in most years.
*d = (Dry):
Ustic or xeric environment; dry > 60 consecutive days per year within 20–60 cm depth.
e = (Low CEC):
< 4 meq/100 g soil by Σ bases + unbuffered KCl ext., Al, or
< 7 meq/100 g soil by Σ cations at pH 7, or
< 10 meq/100 g soil by Σ cations + Al + H at pH 8.2.
*a = (Al toxicity):
> 60% Al saturation of CEC by (Σ bases and unbuffered Al) within 50 cm, or
> 67% Al saturation of CEC by (Σ cations at pH 7) within 50 cm, or
> 86% Al saturation of CEC by (Σ cations at pH 8.2) within 50 cm, or
pH < 5.0 in 1:1 H_2O except in organic soils.
*h = (Acid):
10–60% Al saturation of CEC by (Σ bases plus Al) within 50 cm or pH in 1:1 H_2O between 5.0 and 6.0.
i = (Fe-P fixation):
% free Fe_2O_3/% clay > 0.2 or hues redder than 5 YR and granular structure.
x = (X-ray amorphous):
pH > 10 in 1 N NaF or positive to field NaF test or other indirect evidences of allophane dominance in clay fraction.
*v = (Vertisol):
Very sticky plastic clay > 35% clay and > 50% of 2:1 expanding clays; COLE > 0.09. Severe topsoil shrinking and swelling.
*k = (K deficient):
< 10% weatherable minerals in silt and sand fraction within 50 cm or exch. K < 0.20 meq/100 g or K < 2% of Σ bases, if Σ of bases < 10 meq/100 g.
*b = (Basic Reaction):
Free $CaCO_3$ within 50 cm (fizzing with HCl) or pH > 7.3.
*s = (Salinity):
4 mmhos/cm of saturated ext. at 25°C within 1 metre.
*n = (Natric):
> 15% Na saturation of CEC within 50 cm.
*c = (Cat clay):
pH in 1:1 H_2O is < 3.5 after drying, Jarosite mottles with hues 2.5 Y or yellower and chromas 6 or more within 60 cm.

fertility capability units (Table 2). The average yield response to phosphorus for each of the five groups is shown in Figure 1.

The response curves of the Lhd and Lad soils were completely different from the other three. However, the response pattern of the Lbd, Lbxd and Cbd soils were essentially linear and not significantly different. The 73 sites (73 experiments) could then be grouped into three categories, i.e. Lhd, Lad and Lbd soils.

Figure 1 also shows the difference in maximum and optimum yields for two of the grouped soils. For the others, maximum yields are probably beyond the range of rates studied.

After the soils were grouped by Fertility Capability Classes and by soil test results, the gross returns to fertilizer applications were compared. When fertilizer recommendations were based on soil test results (pH, phosphorus, and exchangeable soil potassium) the fertility classes average returns were greater by about 13% than when a single blanket recommendation was made.

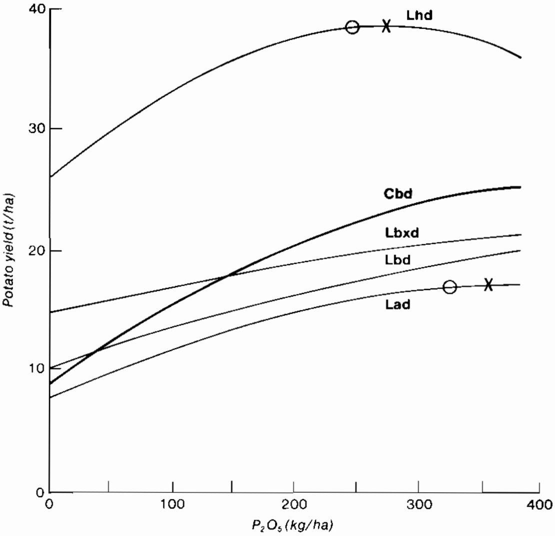

Figure 1. Differential phosphorus response of different fertility capability groupings in potato experiments in Peru.

It should be clearly stated that the grouping does not intend to replace soil survey but offers an interesting mechanism to use existing data from soil survey reports or site examination to group soils into reasonably homogeneous classes.

Conclusions

Land-use assessment can be more quantitative if the classification or grouping of the soils is done by using relevant information obtained through agronomic experimentation that takes into account the main factors affecting the cropping system within specific agro-ecological conditions. This is most imperative in the steeplands where a range of complex problems with economic, social, ecological, and political implication exists.

A technical classification system that must be practical and simple, but scientific in its construction, appears to be a good solution to fill the gap between soil survey maps and soil-capability assessment.

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Table 2. Classification of soils in potato trials — 73 locations in the Peruvian Andes.

Number of sites	Fertility–Capability Classification
23	Lad (Loamy, aluminium toxicity)
27	Lhd (Loamy, acid)
11	Lbd (Loamy, $CaCO_3$)
6	Lbxd (Loamy, $CaCO_3$, amorphous)
6	Cbd (Clayey, $CaCO_3$)

Source: Buol *et al.* 1975.

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A.J. Smyth* Discussant — 2

Some General Considerations relating to the Use of the FAO Framework for Land Evaluation

So complex is land evaluation that one has to be almost foolhardy to attempt it. Variations on the soil continuum that might affect crop growth are themselves extremely complex but these form only a part, sometimes a relatively minor part, of factors that must be considered to determine the suitability of land for a particular use. Obviously, in addition to the soil, we must consider the climate, the topography, the hydrology (surface and subsurface) and perhaps above all, the social and economic aspirations of the people whose land we would evaluate. What is more, we must interest ourselves not in these factors alone, but in their interaction and in the probability that one or more of the factors will change within the time span of prediction of the study.

Given this complexity, Dr Bleeker and his colleagues are surely right to store their data in the computer and to envisage the development of dynamic models that would contribute to evaluation. But, even with the assistance of computers there will be a continuing need for rather drastic selection of the data to be collected, distinguishing in particular between the data that are reasonably static and need be collected only once, and the data that must be collected in time sequence because its change with time is short term and critical to the choice of land use. Not all soil data belong to the first static category, because understanding the change in soils with time may be essential to determine the prospects of sustained land use of a particular kind. The FAO Framework for Land Evaluation (1976) stipulates that land be evaluated in terms of sustained use, that is to say in terms of sound conservation principles.

Obviously, all normally measured soil data are likely to be relevant to an assessment of productivity for a particular agricultural land use but productivity itself may be irrelevant if other compelling reasons render the use inappropriate on some sites. For example, the use in question may be socially taboo, or there may be no identifiable market, or the area may be plagued by pests such as the tsetse fly, or a necessary labour force may be lacking. These extreme examples serve to illustrate the range of considerations that may effect land suitability in the short term for a particular use. In practice, such considerations may cut down considerably on the range of data that is worthwhile collecting and examining in detail in land evaluation.

The FAO Framework for Evaluation was developed in the early 70s in response to a perceived need for an interpretive approach that was more specific than that provided by the Land Capability Classification of the US Soil Conservation Service (Klingebiel and Montgomery 1951). It was developed largely on the basis of ideas from field work carried out by Klaas Jan Beek and Jacob Beunema in Brazil, and Philippe Mahler in Iran. It also owes much to the Irrigability Classification of the US Bureau of Reclamation (1953) although the precise economic approach of that classification, in terms of payment capacity, has not been adopted, at least not as yet. The ideas from these sources were melded together by two committees, one within FAO and the other in the Netherlands and after several drafts, the proposals were eventually published in 1976.

As published, the FAO Framework can be considered to have three major parts. Firstly, and most importantly, a set of principles. Second, a system of presentation for land-evaluation findings. These suggest a flexible form of classification that emphasizes the distinction between land that is, or is not, suitable for a particular purpose and permits many kinds of use to be evaluated in parallel. Last, the Framework suggests an approach by which evaluation may be attempted. It does not provide any criteria by which any particular kind of land use may be judged. Subsequently FAO has organized working parties on the examination of criteria relevant to land evaluation for

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rainfed agriculture and, more recently for irrigated agriculture. I believe that similar studies in relation to forestry and to rangeland evaluation are being or have already been organized by Dutch institutes. The intention of these workshops is not to establish criteria, which can be universally applied, but to identify the factors that are likely to be especially significant in relation to these uses and to recognize their likely interactions.

The essential principle of the FAO Framework is that the suitability of land can only be assessed in terms of a carefully defined land use. Usually, the more detailed the study, the more precise must be the definition of the forms of land use. All the other aspects of the Framework stem from this principle.

Thus the process of Land Evaluation must start, in theory, by a definition of the various uses of land that are of interest to the people in the area concerned. It is important to emphasize that these definitions include not only the nature of crops in each evaluated farming system, but also the means (labour and other inputs) that are to be available to grow these crops. Having defined the uses to be evaluated, the range of factors that seem likely to bear on suitability need to be identified and, so far as possible, ranges of desirability, or acceptability, need to be defined for each factor. Data collection should then begin. In practice some of the data needed are likely to be available already — indeed in the case of climate and hydrology this is devoutly to be hoped.

The kind of analysis of crop requirement in terms of slope, drainage, bulk density, nutrients, and other chemical properties, which Dr Bleeker describes in his paper in relation to sweet potato farming in Papua, seems very well suited to the FAO Framework approach, provided that the requirements of any other crops that might be included in the farming systems are similarly considered and the whole examined in terms of any socio-economic constraints that may exist. It is certainly of interest that Dr Bleeker's findings appear to be at variance with criteria used by FAO to assess land suitability for sweet potato in their global syntheses (FAO 1980) and suggest that the latter should be re-examined. However, I am not sure that this casts doubt on the methodology of the FAO Framework itself, as Dr Bleeker's paper seems to imply. The Land Resources Development Centre work in Northern Nigeria (LRDC 1978), to which Dr Bleeker also refers, although not global did relate to an area of about 200 000 km^2 surveyed over a period of 10 years and the interpretive criteria, which were necessarily generalized, related to a savannah environment very different from that of Papua New Guinea.

Some soil scientists have criticized the FAO Framework because it seeks to emphasize an economic rather than a physical basis for comparison between lands of differing suitabilities. However, this feature of the system also stems from the principle of defined land use. How else but in economic terms can comparisons be made of the relative suitability of completely different kinds of land use? For example, land that is ideal for cassava may be better used for another crop for which it is relatively poorly suited merely because the poorly yielding second crop provides a better economic return.

In each case the evaluation must take account of the labour and other inputs required to produce the crop on the particular site on a sustained basis and to balance this against the value of the produce expected. The system allows a comparison of suitability to be made between an existing traditional system, such as that of sweet potato farmers of Papua, and an advanced system as elaborate as it seems wise to make it. The requirement that the farming system must be sustainable is designed to ensure, for example, that mechanized schemes are not recommended on steep slopes, such as those in Papua, without adequate engineering provision to prevent erosion — the cost of which would be obviously unacceptable. In other words the Framework recognizes that almost anything can be done almost anywhere, but the client may not wish to pay the required cost either in cash, or in effort, or in social inconvenience assessed in economic terms.

In undertaking land evaluation it is necessary to draw on all available experimental and background data. The evidence presented by Dr Bleeker and his colleagues in their interesting paper underlines the danger of accepting such evidence from too far afield and of the necessity not only of observing the technique of local farmers but of establishing perhaps by experiment, the reasons why these techniques are used. I believe, Mr Chairman, that if this is done there is no reason why the principles and broad methodology of the FAO Framework for Land Evaluation should not work satisfactorily in Papua New Guinea or anywhere else.

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Session 6
Tropical High Mountain Soils

Summary of Discussion

G.J. Blair*

Bleeker *et al.* questioned the appropriateness of existing land evaluation methodologies, developed primarily to serve the needs of western-style mechanized agriculture, for describing land-use patterns in 'less developed' shifting agricultural systems that are essentially horticultural. Bleeker *et al.* described the existing land-use pattern in Chimbu Province of Papua New Guinea (PNG) and related this land use to the growth requirements of sweet potato (*Ipomoea batatas*).

Discussant 1, Valverde, contrasted the land evaluation system used in Peru with that in PNG. The system used in Peru is the 'Soil Fertility Capability Classification' FCC developed at North Carolina State University, USA. Valverde describes the system as 'a simple technical classification by which we can group soils for a great variety of technical purposes and thus establish technical groupings, each for a limited objective which, in this case, was to group soils with similar fertility limitations'.

The FCC system extends basic soil taxonomy data by the inclusion of surface (0–20 cm) and subsurface (20–50 cm) textural information. Condition modifiers, which relate to chemical and physical properties of the 0–20 cm layers, are used to subdivide the major groups. Valverde presented information from 73 field experiments to show the use that is made of the FCC system in making fertilizer recommendations and suggests that the additional information on texture and chemical composition results in better land-use assessment.

Smythe outlined the FAO land classification system and indicated that this system emphasized economic rather than physical aspects. In his presentation of the main paper, McAlpine had stressed that in subsistence horticultural food-producing systems, such as that used in PNG, the value of the output is measured in kilojoules of energy rather than dollars and that the most appropriate land use was one that provided the inhabitants with a reliable supply of acceptable food that could be produced with the least possible modification to the natural ecosystem.

Despite the apparent conflict between the FAO and Bleeker *et al.* systems, Smyth was of the view that the FAO system could be used successfully in PNG.

In the general discussion session, it was suggested that the difference between the two systems was primarily in the degree of detail. The FAO system has been developed to map broad-land capability units whereas that used in PNG is a detailed analysis of land utilization of a small region.

The reliability and adequacy of data on basic information such as rainfall varies greatly from country to country and more needs to be done to upgrade this information base. Valverde stressed the importance of knowing not only the annual or monthly rainfall but also the variability of that rainfall.

The speakers agreed that, whilst data on climate were generally available, data on crop requirements and agronomy were generally obtained under 'artificial' experimental conditions, which made it difficult to extrapolate to the village farming system.

It was suggested that a great deal of information exists on a crop such as sweet potato, the staple food in Chimbu Province, PNG, which is not fully utilized. A wide range of genetic material is available from institutions such as IITA but, because of inadequate communication between researchers and practitioners, the information is not put into practice. This stresses the need for multidisciplinary teams to be

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involved in land-capability assessment studies.

The value of data collected for soil taxonomy to land-capability studies was questioned. Some participants were of the view that such information was of little value as collected, and that additional information such as that used in the FCC system was required. The value of soil taxonomy is further diminished in subsistence farming where ingenious conservation systems such as terracing, direct planting, mulching, etc., are practised.

The speakers held the general view that the major stumbling block in land-evaluation studies of subsistence agriculture is in understanding the complexity of the agricultural system and the problem of using the available information in such a complex farming system. McAlpine doubted the value of dynamic models in overcoming this problem at this stage.

Williams (CSIRO, Townsville) questioned the expectation of land-evaluation studies and suggested that the people already utilizing the land had, in fact, decided its use. McAlpine pointed out that in a high population growth society such as that in PNG, population was doubling every 25 years and the government was interested to have agricultural development in areas of apparent under-utilization. The value of land-evaluation studies is to advise the government on what degree of intensification is possible on various land units before environmental degradation occurs.

Greenland (IRRI) suggested that the Australian experience in PNG may be useful in other areas of the world to assess land capability in subsistence farming systems. He emphasized that the major problem worldwide was to make shifting cultivation more stable and to aim at sedentary agriculture in these areas. Greenland indicated that a network of people involved in land-capability studies would be advantageous. This would increase the flow of information and allow for a greater exchange of information and experience.

The major objective of land-evaluation studies should be the matching of crop requirements to long-term land quality. If this is to be successful, multidisciplinary teams need to be involved to integrate information of the existing land-use patterns and to project the long-term consequences of a change in the agricultural system.

Session 7

Mechanical and Engineering Problems of Soils

Chairman: M.E. Raymundo
Discussion Leader: A.K. Turner

Soil Mechanical Problems Associated with the Agricultural Use of Soils

E.L. Greacen* and B.G. Richards*

Soil mechanics is that branch of soil physics that deals with the mechanical strength of soil. It has developed as a discipline in civil engineering largely to provide answers to problems in the use of soil as a building material. Man has been using soils for roads and building foundations for thousands of years and it has been important, as witnessed by the tower of Pisa, that he is able to predict how the soil, almost always in a compacted state, will deform under an imposed load. This is the situation in civil engineering.

In agriculture, engineering problems with soil also arise in the building and maintenance of roads, dams and banks, but, as well as these, since the introduction of heavy mechanization to farming, serious problems in soil mechanics have arisen with respect to soil tillage. On the one hand, an open porous soil structure is required to provide at least a specified minimum root environment for the crop, while on the other hand the soil is expected to carry, without deformation, the machinery used to create this environment. Progress towards a satisfactory solution to this dilemma is slow because very little soil mechanics is taught in soil physics or in agricultural courses and, almost as a corollary, an experimental approach is not often encouraged in engineering design.

Basic Models in Soil Mechanics

In this regard it is interesting to look briefly at the history of the development of soil mechanics theory.

Soil mechanics relies almost solely on two old and basically unrelated models describing soil behaviour under mechanical stress and, more recently, a third more general concept dealing with pressure and volume.

The first of the two old models treats the soil as a brittle frictional material and is used to predict the maximum load that a soil can withstand without sudden shear failure. It is assumed that the maximum shear strength S is related to the normal load σ by the two soil strength parameters cohesion C and friction angle ϕ as

$$S = C + \sigma \tan \phi$$

This model is called the Coulomb equation and was developed by him in 1776, over 200 years ago (Coulomb 1776).

The second model of soil mechanics is that of linear elasticity. This model assumes that soil deformation is proportional to stress and can be described by the two deformation parameters Young's modulus of elasticity and Poisson's ratio. So long as the load is small compared with the maximum stress at failure, these parameters tell how much the soil deforms elastically on loading and how the pressure under a surface loading is distributed within the soil mass. The theoretical work on pressure distribution in the soil is based on the formula of Boussinesq (1885), not quite 100 years old, which applies to an ideal elastic mass. The Boussinesq formula has been modified empirically by Froehlich (1934) for non-elastic behaviour in soil.

Thirdly, an important aspect of soil mechanics deals with consolidation and compaction. Those processes have long been recognized and treated empirically in soil mechanics but the relationships were not properly realized until the Critical State model was outlined by Roscoe *et al.* (1958) at Cambridge. This model assumes that for a saturated soil straining at failure there is a unique relationship between the void ratio (or water content), the mean pressure, and the shear strength.

It is worth expanding on these three concepts. The Coulomb equation is best expressed graphically as the Mohr–Coulomb diagram (Figure 1). The failure line a–b is obtained in a shear test, for example in a direct shear box, by measuring the stress required to shear a rec-

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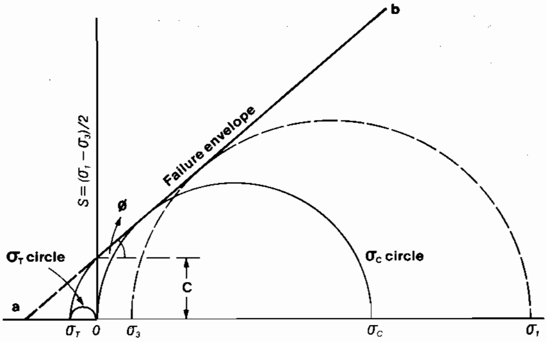

Figure 1 Mohr–Coulomb diagram with the failure envelope a–b given by Coulomb's equation in terms of C and ϕ. The principal stresses σ_1 and σ_3 are the axial and radial stresses for a triaxial test. Compressive strength σ_c and tensile strength σ_T are also shown.

tangular block of soil under different applied loads. For agricultural field work, a circular (Payne and Fountaine 1952) and an annular (Stafford and Tanner 1982) shear box have been developed. The Mohr circles show the relationships between the different aspects of soil strength. The principal stresses σ_1 and σ_3 are, in a triaxial test, the axial stress and the radial stress, respectively. The unconfined compressive strength σ_c is obtained as the axial compressive stress required to fail a cylinder of soil under zero radial stress. The tensile strength σ_T is obtained as the negative stress required to fail a cylinder of soil in axial tension. The tensile strength can also be measured indirectly by the Brazilian test (Kirkham *et al.* 1959) or by the clod rupture test (Rogowski 1964). In both cases the lateral load required to rupture the core or aggregate is measured; in both tests the soil actually fails in tension. As will be seen later, the Coulomb parameters may be used for predicting, for example, the bearing capacity of a soil under a wheel load, i.e. the resistance of the soil against general shear failure at the surface, or the ultimate bearing pressure — the pressure at which a soil will compress with local shear failure at depth.

Modifications to the Boussinesq formula made by Froelich (1934) for predicting pressure distribution in soil under a loaded plate take into account the concentration of the vertical stress caused by the non-elastic behaviour of the soil. For the soil in a hard near-elastic condition the equi-pressure bulbs under the load are spherical, but for softer, wetter soils the pressure bulbs become increasingly elliptical and penetrate deeper under the load (Figure 2).

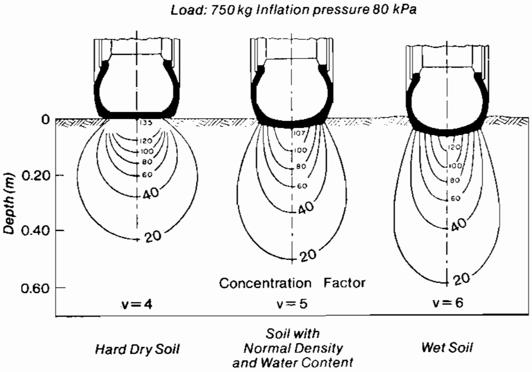

Figure 2 Pressure bulbs beneath a tyre calculated for three soil conditions with three values of the concentration factor in the modified Boussinesq formula (Soehne 1953).

Based on work by Soehne (1953), Jakobsen and Greacen (1983) give the pressure distribution with depth z under a tyre as $P_z = P_o (1 - \cos^v\theta)$ where $\theta = \tan^{-1}(b/z)$, b is the width of the tyre contact area, and v is the concentration factor, varying from 4 to 6.

The Critical State model is demonstrated in its most simple form as the relationship between the saturated porosity of a soil and the pressure. In Figure 3 the line a–b for the saturated condition is the consolidation curve giving the relationship between the equilibrium porosity and the applied pressure P. If at any particular pressure a shear stress is imposed so that failure conditions apply throughout the soil, the porosity will decrease to a new equilibrium value. The line c–d joining a series of these equilibrium values is the critical void ratio line and the soil is at the critical state. Croney and Coleman (1954) established this line for straining clay, and pointed out that the Atterberg constants lay on this line. Greacen (1960) suggested that the equilibrium pressure for the liquid limit was an effective stress of about 1 kPa due to soil water suction and for the plastic limit about 100 kPa. Reece (1977) inferred that the Critical State model applied to the unsaturated condition.

The two lines, the normal compression and compression with shear line for the unsaturated soil, are shown in Figure 3. Greacen (1960) doubted the scientific rigor of applying the Critical State model to unsaturated soil but applied it successfully later, in an empirical fashion, (Farrell and Greacen 1966; Jakobsen and Greacen 1983) to problems in agricultural soil mechanics.

Practical Applications of Soil Mechanics Models

The above models have been used either singly or in combination to solve problems in soil mechanics with acceptable reliability for many years. Failures in design can often be traced to unforeseen long-term changes in the boundary conditions or, at times, to over-simplifications of linearity or constancy in the parameters. In recent times the use of computers and sophisticated numerical procedures are allowing better applications of the old models, and new experimental techniques have been developed to give more realistic measurement of soil properties.

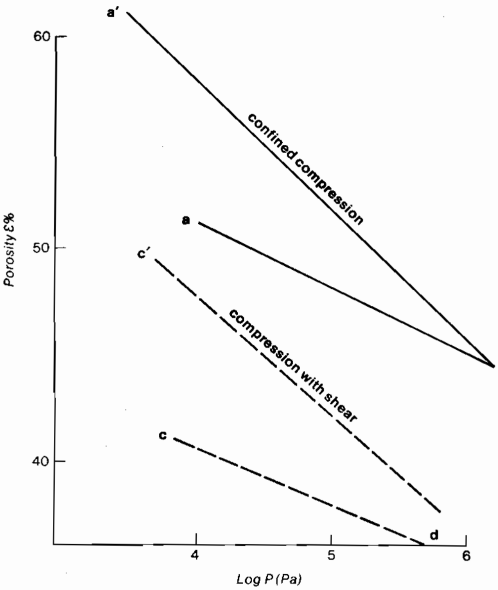

Figure 3 Compression curves for a sandy forest soil without (—) and with (- - -) shear for the saturated (a–b, c–d) and the unsaturated (a'–b, c'–d) condition.

Mechanical Impedance to Plant Roots

The mechanical resistance of a soil to penetration by a metal probe has been described by Farrell and Greacen (1966) and Greacen *et al.* (1968), using the three models, in terms of Coulomb strength, Boussinesq strain and Critical State compression. Based on their analysis, soil that had a resistance to a metal penetrometer of 2–3 MPa would resist radial expansion of a root cavity with a pressure of 0.3–0.4 MPa and for bean roots this was found to cause a 75% reduction in the rate of root elongation. Other workers (Goss 1977; Abdalla *et al.* 1969) found that a radial hydrostatic pressure of about 0.05 MPa applied to the outside of a bed of fine glass beads, in which the roots of barley were growing, was sufficient to cause the same 75% reduction in growth. They interpreted this as being the critical pressure on the root surface. The present authors do not agree with this interpretation but the problem has still not been resolved.

The criticism is often made that penetrometer resistance applies only to remoulded or compacted soil whereas roots in the field are able to take advantage of zones of weakness and old bio-pores in the soil (Russell 1977). This is certainly true in some situations but with root impedance problems we are often concerned with soil that has been remoulded and compacted by traffic. Under such conditions penetrometer resistance values of 2–3 MPa at field capacity predict seriously restricted root growth. A simple test for this critical value of soil resistance is whether an ordinary writing pencil can be pushed into the soil with the blunt end in the palm of the hand. It is interesting to note that Ehlers *et al.* (1983), working on reduced tillage systems, found that for conventional cultivation a penetrometer resistance of 3.5 MPa seriously restricted root growth while for untilled soil, with many biopores and cracks, the same effect did not occur until 5 MPa. This agrees with their observation that the plant roots were making some use of the biopores and cracks.

Greacen and Oh (1972) found that bean roots were able to overcome mechanical impedance up to a certain level, but with decreasing efficiency, by increasing the osmotic pressure in their cells in the zone of elongation. They found that roots were able to osmoregulate with 100% efficiency against soil water suction, but only with a lower efficiency against mechanical impedance. Russell (1977) does not accept Greacen and Oh's model, on the basis that not all of their data yield significant relationships in the predicted direction. The data he refers to have a relatively high error due to variability and narrow range, and while it is obvious that the model is not supported by all of the data, it is not invalidated by any of the data.

Compaction in Forest Soils

Light-textured forest soils in South Australia compact to depths of more than 0.8 m under traffic during a single cropping (40 y) of *Pinus radiata* and resistance to root penetration is generally increased. Root growth and productivity on replanting is reduced. Vehicular traffic, particularly during harvesting, is certainly responsible for part of this. In the virgin low-density state, (1 450 kg/m^3) the soil is virtually an open packed framework of sand grains (Julie Cooper, pers. comm. 1983), and in the unsaturated condition (when confined in a consolidometer) can support static loads of 1 MPa. Jakobsen and Greacen (1983) have shown though that under a shear stress, such as generated by tractor tyres, the soil collapses to a critical state density of 1 600 kg/m^3 under a load of only 0.33 MPa. They give total porosity ε in volume percent as a function of the normal pressure P(Pa) as

$$\varepsilon = \varepsilon_o - \alpha \log P - \beta w$$

where w is percent water content by weight and β is a constant.

The compressibility α of these light-textured soils was very low at 4.5, i.e. the porosity decreased by only 4.5 percentage points for a 10 fold increase in pressure, but under a shear stress at the same pressure the porosity could fall by as much as 11%.

In the field, measurements of compaction were made under repeated passes of a forwarder. This is a log-carrying vehicle with a fully laden weight of 26 tonnes running on 6 tyres, 500 and 550 mm wide with an inflation pressure of 320 kPa. After 27 passes, bulk density in virgin sites increased from 1 450 to 1 750 kg/m^3 at 0.5 m depth, the deepest point measured (Figure 4), while penetrometer resistance increased from 2.7 MPa to 4.2 MPa at 0.8 m depth. On an old snig track the density increased from 1 550 to 1 750 kg/m^3 after 27 passes, but penetrometer resistance at 0.4 m depth fell from an initial 5 MPa to 3.7 MPa after 9 passes. It then increased after a further 18 passes to near the original 5.0 MPa (Figure 5). This decrease in strength with compaction may have been due either to the soil having been compacted initially under different stress states at different water contents and then loosened and recompacted during the present tests, or, to a thixotropic effect. If this latter effect were important, we would expect the strength after 27 passes to increase well above 5 MPa after standing for some days, but unfortunately this was not measured.

The surface soil failed in general shear failure after repeated passes, and wheel ruts were formed up to 0.10 m deep after the 27 passes. The bearing capacity of the soil using Coulomb parameters C and ϕ (Terzaghi 1943) for a load of width b equal to 700 mm is 125 kPa. To reduce the contact pressure of the forwarder to this value, it would be necessary to replace the 500 mm wide tyres with 700 mm tyres. Pressure distribution with depth under the tyres, using Soehne's modification to the Boussinesq formula discussed above, show that the load imposed by the tyres would exceed the ultimate bearing pressure for these conditions down to a depth of 0.6 m and compression with failure would occur down to this depth (Figure 6).

There is evidence that similar compaction-at-depth problems occur in clay subsoils under irrigation for wheat and cotton in subtropical eastern Australia. Des McGarry (pers. comm. 1983) has shown that the shrinkage curves of clay cultivated when too wet show a marked loss of structural porosity. Also in these degraded clays the crop fails to extract water from the subsoil. Under dryland agriculture the soil is, on average, drier and harder during cultivation, particularly at depth, and structural damage is less likely to occur. Nevertheless yield responses to moderately deep tillage (0.2 m) have been reported from Meredin, Western Australia (Ann Hamblyn pers. comm. 1981) and from Rutherglen, Victoria, (John Angus, pers. comm. 1981). The problem in these soils seems to be limited water-storage capacity associated with poor

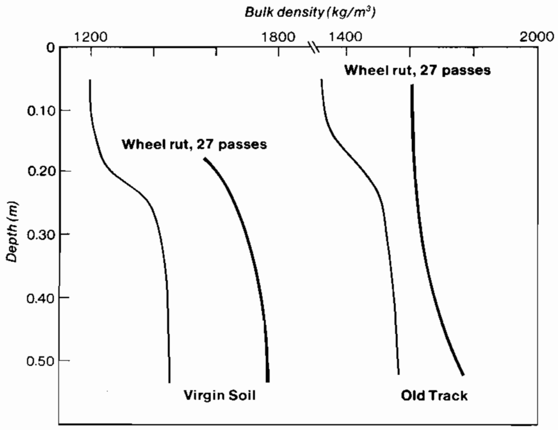

Figure 4 *Bulk density profiles of a sandy forest soil at 0 and 27 passes of a 26 tonne load on a virgin and an old track site.*

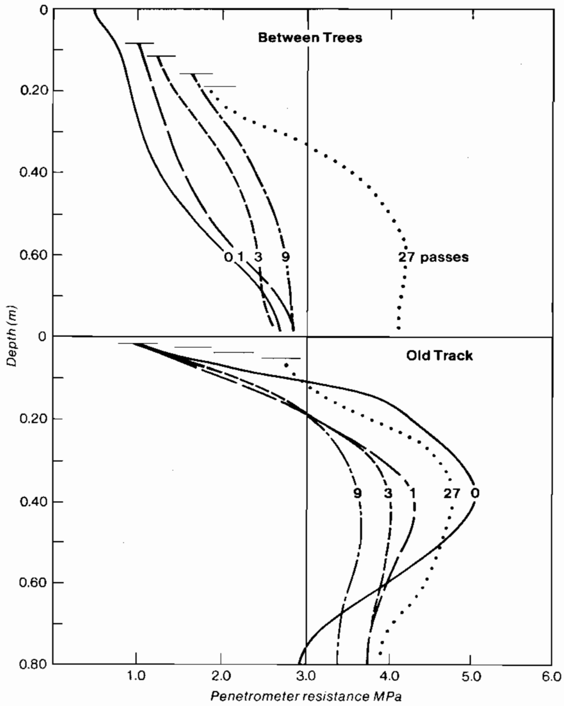

Figure 5 *Resistance to penetration of a 1 cm^2 field penetrometer after 0, 3, 9 and 27 passes of a 26 tonne load on a virgin and an old track site. The horizontal bars show depths of ruts.*

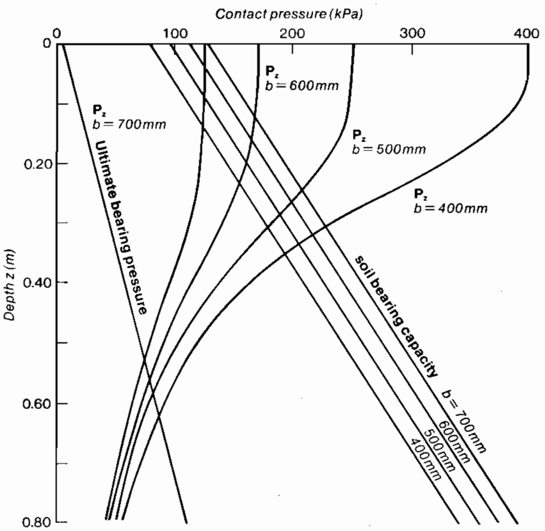

Figure 6 *Calculated pressure distribution under a 5 tonne load with diameter b of the contact area 40, 50, 60 and 70 cm and the bearing capacity as a function of depth and b, and the ultimate bearing pressure for a sandy forest soil of wet density 1 470 kg/m^3, $\phi = 30°$ and $c = 0.5$ kPa (Jakobsen and Greacen 1983).*

root activity at depth, poor infiltration, poor aeration, and low structural stability often due to sodicity. Solutions to the problem, which are under consideration, involve creating, by deep tillage, a soil structure that will satisfy the requirements of the particular crop, improving the stability of this structure by injecting gypsum and burying organic residues, and protecting this with a cultivation regime that reduces traffic to an absolute minimum or restricts it to permanent tracks. Using such an approach, as depicted in Figure 7, but with unlimited irrigation, Cockroft and Tisdall (1978) increased the yield of peaches on intractable clay subsoils from 18 to 72 t/ha over a period of several years.

Soil Mechanical Problems in Earthworks

Road Construction

Other soil mechanical problems relevant to

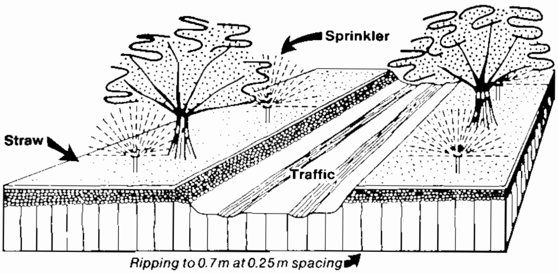

Figure 7 Diagrammatic representation of soil treatments applied to an orchard on a Red-brown Earth (Alfisol) (Cockroft and Tisdall 1978).

agricultural production and related to traffic are currently under investigation by the soil mechanics group in the CSIRO Division of Soils. New and low-cost methods of road building are needed for on-farm, rural, and outback roads. The low-cost requirement means in effect that on-site or near-site materials must be used where possible, and new methods of predicting the likely performance of these materials under changing conditions are required. A repeated-loading triaxial test has been developed to analyse road deformations and failure under repeated impact from traffic. Figure 8a shows the performance of a silty clay from inland Australia under the loading it would receive when used as a road surface. There are three states of compaction. For the normal compaction, the nonrecoverable displacement becomes excessively high after about 100 passes and the road fails. Figure 8b show the performance of the normal state under decreasing traffic stress. For the lowest stresses, recoverable displacement remained low even after 10^4 passes, suggesting that this silty clay could be suitable for use as a sub-base but not as a base course material for the road designed for 10^4 passes.

While roads may be designed on the basis of strength and deformation characteristics of the compacted soil material, it is important to take into account any possible change in these parameters. By far the most likely cause of failure is due to changes in the soil water suction.

An interesting example of the importance and application of soil water suction effects on soil strength concerned the use of a Black Earth in road building on the Darling Downs, Queensland. These clays are particularly susceptible to changes in suction and it is of the utmost importance to include suction as a design variable, and to consider infiltration and drainage and, in particular, the equilibrium state that will be achieved under the covered surface for both the climatic and man-made environment.

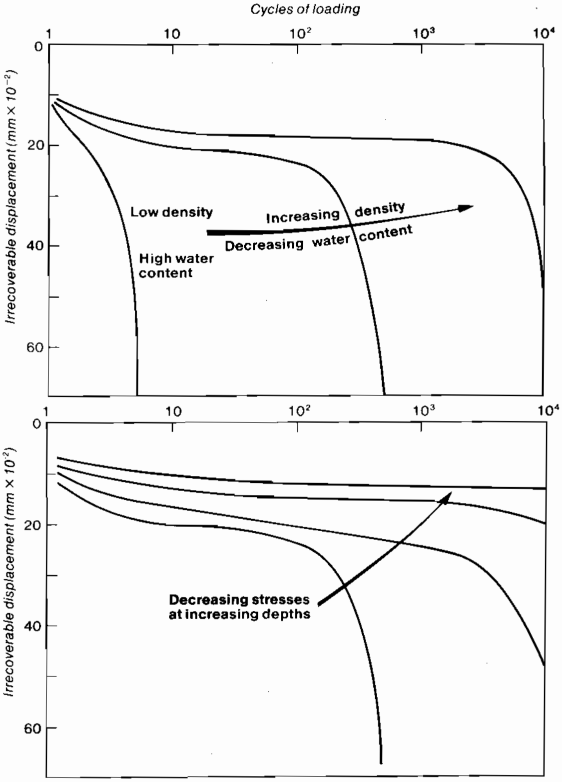

Figure 8(a) Deformation behaviour of a silty clay used as a road material at different states of compaction in a repetitive loading test.

(b) at normal compaction but with different impact stresses simulating subgrade pressures.

Soil suction versus depth profiles taken from under covers in the area are given in Figure 9. These suggest that under an impervious covering such as a sealed road the equilibrium suction would be given by the dotted line as 3.5 MPa (water content 31%). The specified Proctor compaction test on this soil, as shown in Figure 10, required an optimum moisture content (OMC) for packing of 42% with an equivalent suction of 0.45 MPa. Construction to standard specification for this road would have resulted in considerable drying back to the equilibrium condition.

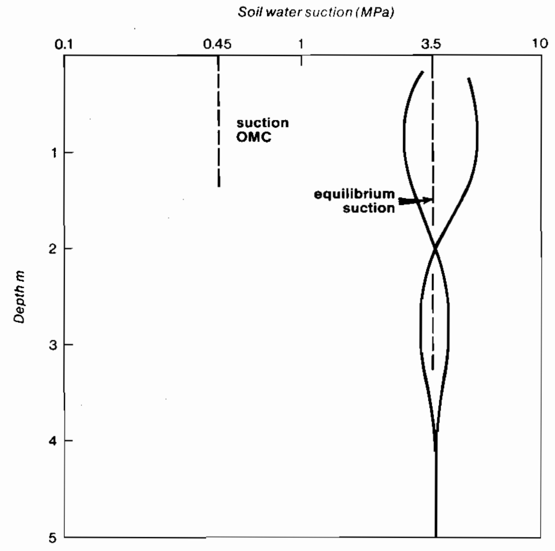

Figure 9 *Profiles of soil water suction versus depth for a sealed road in the Darling Downs, Queensland, constructed on Black Earth (Vertisol) clay.*

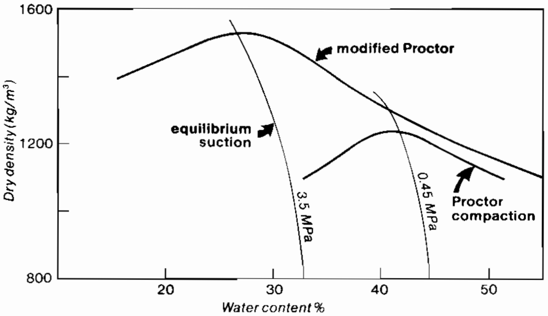

Figure 10 *Compaction curves for the Black Earth clay (Fig. 9) giving density versus water content for normal Proctor and heavy Proctor compaction.*

Using standard design methods for a rural road under Australian conditions, the clay compacted at OMC requires a good quality gravel base course layer of at least 450 mm thickness, whereas at the equilibrium suction only a nominal thickness, less than 100 mm, would be required. Furthermore, it was shown by testing that the resilient modulus of the clay at the equilibrium suction was higher than that compacted at OMC in spite of the lower density achieved by the normal Proctor compaction. Field trials showed that not only did the latter road perform better, but it cost considerably less to build and to maintain. Change in the effective stress as the soil water suction approaches an equilibrium condition following surface sealing is not a major factor in design.

Slope Stability Problems

Soil mechanics problems relevant to agriculture arise in regard to earthworks other than roads. Water-handling structures such as banks, channels, or dams are important for water and soil conservation. These structures are designed using traditional soil mechanics concepts and their failure is almost invariably a problem in slope stability. Indeed the tilled layer can be considered as a water handling structure, and its collapse and catastrophic loss during a rain storm should be dealt with as a slope stability problem.

Slope stability problems can involve completely different mechanisms of behaviour and each must be treated on its own merits (Richards 1980, 1982), but some general guidelines for their analysis can be set down.

1. With loose soil, shear strains tend to cause compression and for wet loose soil, as for example a tilled layer, pore water pressure and strain softening will tend to increase. If the pore pressures exceed the confining stresses, then liquification will occur leading to mud flows and general erosion. A possible solution would be to strengthen the tilled layer with crop residues.
2. With materials containing large amounts of clay minerals, the clay minerals will tend to re-align parallel to the direction of the shear strain. Consequently shear strain will invariably cause considerable strain softening in the clay.
3. With saturated expanding-lattice clay minerals, in particular, a reduction in the salinity of the soil water will tend to increase the strain softening behaviour of the soil (Emerson 1983).
4. A reduction in soil water suction will cause a dramatic decrease in stability. Most slope failures are the result of such a reduction, usually as the result of man's activity, e.g. removal of vegetation, changing hydrology, etc.
5. Tensile cracking due to settlement can sometimes allow water entry with an

accompanying change in salinity, dispersion, and collapse.

Strength Phenomena in Tillage and Compaction

Reference has been made above to subtle physical processes, e.g. thixotropy, that can have significant effects on soil strength, while propositions have been advanced as simple remedial treatments, e.g. to create a favourable structure at depth by tillage; in reality the specifications of a minimum favourable structure at depth are not known with any great confidence; they are complex and in practice are difficult to achieve.

Utomo and Dexter (1981) showed for some medium textured soils, that had been remoulded, an increase in strength (penetrometer resistance) and aggregate stability that was fairly rapid for the first few days but continued to increase for up to 2 weeks (Figure 11). They were able to demonstrate that this regain in strength was not destroyed by oxidation with hydrogen peroxide or sterilization with sodium oxide and mercury chloride. The maximum effect was obtained near the optimum water content for tillage, i.e. just below the plastic limit.

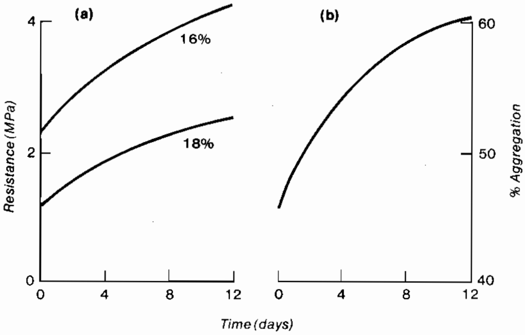

Figure 11 Thixotropic regain in strength for a sandy loam (plastic limit 18%) (Utomo and Dexter 1981).

Thixotropy has the following important practical implications:

1. It should not be overlooked in experimental work.
2. Successive tillage operations should be spaced by several days.
3. The soil should not be stressed mechanically immediately prior to heavy rain.
4. The practice of running the tractor wheel in the furrow would be expected to increase compaction considerably in thixotropic soils.

Regarding the structure requirements of plant roots, Pidgeon (1982) lists the requirements as first, a continuous pore system adequate for root development and drainage but not necessarily large in volume since, for example, a well developed cereal root system occupies only around 0.5% of the soil volume at say 0.5 m depth. Second, such a pore system should be combined with adequate bearing strength. It is inferred here that in general, deep loosening is usually aimed at creating too much macroporosity, but that the macroporosity should not be excessive and should be confined to continuous vertical cracks. His third requirement is for an adequate seed bed. This can be most efficiently arrived at by leaving the surface soil on the surface where natural forces of wetting and drying do the cultivation for us.

The rational increase in the practice of deep loosening that has occurred over the last decade has resulted from the contribution to our understanding of deep tillage made by Spoor and Godwin (1978). They showed that soils have a critical working depth below which it is not possible to loosen the soil efficiently with a single-footed tyne. They stress the importance of the correct moisture conditions for deep loosening, 0.1 to 1 MPa soil water suction, and the need to dig an inspection pit to check the results of the work. Pidgeon (1982) makes the point that the Paraplow appears to fulfil most of these requirements for soils in the U.K. This is a new implement with a slanted foot which lifts the soil and creates cracks under tension without inversion. The surface soil is left smooth and, depending on the initial condition, in good shape for seed bed preparation.

Tillage Systems

The requirements of a tillage system are to create optimum soil conditions for crop growth, to maintain or enhance an adequate soil structure, and to protect the soil against erosion. A different system has to be developed for every circumstance. In southern Australia these requirements on the Red Brown Earths and brown calcareous soils are largely met by including several years of clover pasture in the cropping rotation. This was influential in causing the decrease in soil erosion in the 1940s, particularly in South Australia.

With intensification of cropping, usually as a result of economic factors, the practice shifts towards continuous wheat or wheat-fallow with all the features that lead towards difficult tillage and increased vulnerability to erosion. The modern approach to this tillage system problem has been towards reduced tillage, as in direct drilling, with a shortening or complete avoidance of periods when the soil is under bare fallow. Besides saving on fuel these systems have the indirect advantage that there are longer periods under vegetation; this maintains a more continuous and a better supply of energy to the soil biota with an accompanying improvement in soil structure. This is expressed in improved water infiltration and drainage, a higher water holding capacity, and better aeration. The better supply of energy derives from the fact that a greater part of the rainfall is used in plant growth since much of the water falling on bare fallow is lost by evaporation. It is the improvement in the physical properties of the soil and the better hydrological performance of the system that makes reduced tillage the basis of conservation-tillage systems.

Solutions to other problems in the soil mechanics of tillage are often sought in reduced tillage systems, i.e. doing away with the tillage operation. Krantz *et al.* (1978) cite the case of 20 million hectares of Vertisols in India that because of tillage problems, are left fallow during the rainy season and cropped only in the post-rainy season when the soil is in a satisfactory state for tilling. These soils have a high content of montmorillonite clay with only a narrow range of water content when they can be tilled efficiently. Poor surface drainage is also a contributing factor.

From an analysis of daily rainfall data over a long period it was found that, even though the soil surface was dry, primary tillage could be done by bullocks immediately following harvest of the post-rainy crop at physiological maturity. This was possible only if the land was cultivated in a bed and furrow system and not in a flat condition. This left the soil in a rough, largely weed-free condition and allowed easy final bed formation and seed bed preparation after an early premonsoon rain. Where the land was left flat the dried surface structure was massive and too hard for bullocks to till. An effective seed bed is required for this dry seeding practice in order to allow rapid growth of the root system and reduce evaporative loss from the soil during this period of likely water stress. This system allows cropping during the rainy season as well as the usual cropping during the post-rainy season.

A further advantage of the new tillage system is the saving of work by taking advantage of the tilth-mellowing effect which follows primary ploughing. Larson and Allmaras (1971) and Utomo and Dexter (1981) have shown the reduction in clod strength and the production of fine aggregates that follow wetting and drying.

A similar problem occurs in the drier wheat growing districts of southern Australia, where direct-drill systems are being developed largely for conservation of soil and fuel. Again in this case, as in the Indian Vertisols, the probability of successful crop establishment depends on the frequency and size of the opening rains and the rate of drying of the layer of soil under the seed. Seedling establishment is best described by a model of root elongation against soil strength as determined by the water balance of the surface layers. The amount and disposition of the available water depends on the amount of rainfall and the storage capacity of the soil. Cumulative evaporation from the soil surface E_s as a function time is given as $E_s = Ct^{1/2}$ where C is proportional to the square root of soil water diffusivity. Since diffusivity for untilled soil may be up to 4 times greater than for a tilled soil we would expect the untilled soil to dry two times as quickly. The lack of an effectively mulched seed bed might forbid the use of direct drilling in these drier areas.

Rainfall frequency and amount, and soil parameters, determine the soil-water regime and crop establishment conditions in semi-arid environments. It should be possible to design appropriate tillage systems for an area on the basis of the crop requirements for a seed bed, the climatic environment, and the hydraulic and mechanical properties of the soil.

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R. Lal* Discussant — 1

Compaction, Erosion, and Soil Mechanical Problems on Tropical Arable Lands

Although theoretical soil mechanics has advanced greatly over the past two centuries, its application to practical problems of soil management has not been given the attention it deserves. This ever widening gap between theory and its application is evident in the vast tracts of unproductive and degraded lands in the tropics that were once biologically productive (Kovda 1977).

The use of heavy machinery compacts the soil, reduces infiltration and water transmission, and accelerates soil erosion. These problems are associated with such practices as deforestation and new land development, tillage systems, mechanical harvesting, and other farm traffic. These problems are discussed by Greacen and Richards (1984) and are reviewed in this report in relation to their relevance to tropical agriculture.

Deforestation

Bringing new land under cultivation is still considered an easy method of increasing food production. The annual rate of deforestation in the tropics is estimated to be about 11 million ha. These largely misguided efforts, however, are seldom successful (Wood 1950; de Wild 1967; Bauer 1978). Mechanized land clearing results in severe soil compaction, low infiltration (Table 1), and accelerated runoff and soil erosion (Table 2). Furthermore, the effects of compaction persist for many years, and the root growth of crops is adversely affected. Similar effects caused by logging operations have been reported by Greacen and Richards (1984). Little attention has been given to designing machinery that is suitable for land development in the humid and subhumid tropics. Use of traditional construction equipment for arable land development in this region is the primary cause of severe soil mechanical problems. The machinery requirements obviously vary for different ecologies, land uses, types of soil surface management, and farm sizes. The problem of removing tropical forests 'without upsetting the delicate balance between climate-soil-vegetation' has yet to be solved.

Tillage and Soil Compaction

The rate of root elongation is related to soil mechanical resistance and root pressure. Greacen and Richards (1984) indicate that under laboratory conditions even a low radial hydrostatic pressure of 0.05 MPa can reduce the rate of root elongation by as much as 75%. Under field conditions, however, it is difficult to establish the critical resistance values that limit root growth. In spite of high soil resistance, the cracks and bio-channels created by decaying roots and earthworms are preferential paths of root development. The importance of bio-channels in preferential root growth in confined soils, though amply demonstrated in temperate and tropical soils, is difficult to express in soil mechanics models. The osmoregulatory effects of roots growing through confined media are rather small and vary among soils and crop species.

Soil compaction caused by vehicular traffic is a severe problem in tropical arable lands. Mechanical tillage has a variable effect on root growth, depending on initial soil conditions, the crop grown, and the micro-climate. Root growth is affected by methods of seedbed preparation, primary and secondary tillage operations, and surface soil conditions (Table 3, Figure 1).

Not much progress has been made in applying principles of soil mechanics to assessing tillage needs and defining 'adequate' seedbed preparation for a range of soils in the tropics. No doubt, mechanization of the traditional planting stick has helped to bring large areas under cultivation, but this has been brought about with a complete disregard for soil characteristics and their constraints. The challenge is to develop innovative techniques for bringing seed into

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Table 1. Effects of methods of deforestation on soil bulk density and penetrometer resistance of 0–5 cm layer (unpublished data of R. Lal).

Treatment	Bulk density (g/cm^3)				Penetrometer resistance (kg/cm^2)			
		Pre-clearing				Pre-clearing		
	1978	1979	1980	1981	1978	1979	1980	1981
Traditional farming	0.64	1.06	1.07	1.27	0.21	0.96	0.52	1.32
Manual clearing	0.68	1.17	1.17	1.39	0.20	1.4	0.75	1.19
Shear blade	0.70	1.19	1.37	1.38	0.26	1.0	1.84	2.19
Tree pusher/root rake	0.60	1.24	1.32	1.42	0.20	1.3	0.73	1.23

Each figure is a mean of 25 separate analyses.

Table 2. Effects of methods of deforestation on runoff and erosion (modified from Lal 1981).

Treatment	Runoff (mm/yr)	Soil Erosion (t/ha/yr)
Traditional farming	3	0.01
Manual clearing	35	2.5
Shear blade	86	3.8
Tree pusher/root rake	202	17.5

Table 3. Comparison of maize root densities for 0–10 cm depth at 12 weeks (mg/cm^3) when grown in monoculture or with leguminous crops in the second season (Maurya and Lal 1980).

Crop combination	No-tillage	Conventional tillage
Maize	1.04	0.39
Maize-cowpea	0.43	0.42
Maize-soybean	0.78	0.25
Maize-pigeon pea	1.13	0.33
Cowpea	0.33	0.24
Soybean	0.65	0.13
Pigeonpea	0.92	0.13

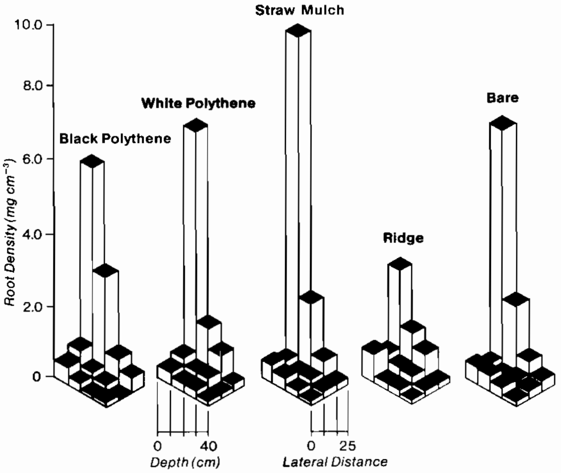

Figure 1. Effects of different mulch materials and methods of seedbed preparation on root growth of maize 10 weeks after seeding (Maurya and Lal 1981).

contact with soil without destroying the soil by excessive, expensive, and often self-negating mechanical soil manipulation. We have yet to define tillage needs in relation to soil characteristics. Agronomists have no choice but to use the tillage implements supplied to them. Soil scientists and agricultural engineers must define the optimum bio-physical environments of the seedbed for tropical soils and crops, and assist engineers in designing adequate machinery and tyre pressures, or in track design. Tillage is expensive and potentially destructive, and yet we have little advice to offer farmers on how to approach it.

There are no practical criteria for assessing tillage requirements. Just as fertilizer requirements can be determined from soil and plant chemical analysis, so should there be routine methods for evaluating tillage requirements for a range of soils and crops. The available research information is distinguished by its lack of progress in developing practical criteria for assessing soil compaction in relation to plant response. The conventional soil mechanical characteristics of bulk density, porosity, infiltration, penetrometer resistance, etc. have severe limitations. Crop response cannot be related directly to soil bulk density or total porosity. Many deep-rooted crops (such as cassava) respond differently to bulk density than shallow-rooted cereals. Rice grown in a flooded sandy soil grows better on compacted than puddled soil (Table 4). Cassava roots can tolerate high levels of soil compaction (Table 5). The critical limits of compaction also depend on tillage methods. Crops can tolerate higher levels of compaction in an untilled mulch than in plowed bare soil. The effects of soil compaction are further confounded by the soil temperature and moisture regimes.

The available procedures do not lend themselves to simple and routine field analysis of soils with high spatial variability. Even if soil properties related to compaction can be routinely monitored, the values so obtained do not reflect the dynamic nature of those properties. They do not take into account, for example, the drastic changes that can take place in bulk density, porosity, penetrometer resistance and crust strength of the seed zone following a heavy rainstorm. Rather than respond to the initial level of these characteristics, plants usually respond more to the magnitude of these changes. Much research needs to be done in developing methodologies and criteria for assessing soil compaction and practical field methods for alleviating it.

It is useful to evaluate the relative importance of preventive and curative measures for alleviating soil compaction. Biological methods of alleviating soil compaction (such as including clover pasture in crop rotation and using reduced tillage) are also relevant for tropical soils (Table 6). Reduced tillage has the additional advantage of increasing the possibility of multiple cropping on difficult-to-manage Vertisols in the tropics and subtropics. No-till and mulch farming techniques for tropical soils have been widely

Table 4. Effects of tillage methods on rice grain yield (Unpublished data of Ogunremi, Lal, and Babalola).

Tillage methods	Rice grain yield (t/ha)
Compacted	6.0a
Puddled	5.1 ab
No-tillage	4.9a

Means followed by the same letter are not significantly different at the 5% level of probability.

Table 5. Effect of bulk density on root length density and root weight density at two dates during the season (Maduakor and Lal 1983).

Depth	BD 1.4		BD 1.6		BD 1.8			
(cm)	*RLD*	*RWD* × 10^{-4}	*RLD*	*RWD* × 10^{-4}	*RLD*	*RWD* × 10^{-4}	RLD LSD (0.05)	RWD LSD (0.05)
			106 days after planting					
0–30	0.251	0.457	0.664	1.753	0.579	1.762	ns*	ns
30–60	0.396	0.624	0.593	1.032	0.096	0.536	ns	ns
60–90	0.353	0.504	0.477	1.881	0.488	0.745	ns	ns
			185 days after planting					
0–30	0.398	1.108	0.482	1.769	0.605	1.787	ns	ns
30–60	0.412	1.960	0.597	1.638	0.585	1.668	ns	ns
60–90	0.352	1.252	0.503	1.985	0.285	1.125	ns	ns

RLD = Root length density (cm/cm^3).
RWD = Root weight density (g/cm^3).
*ns = Not significant at 5% probability.

Table 6. Effects of grass and legume cover crops on water infiltration properties of an Alfisol (Lal et aL 1979).

Cover crop	Cumulative infiltration cm/3 h	Infiltration rate cm/ha
Brachiaria	64 ± 43	19 ± 16
Paspalum	65 ± 6	14 ± 1
Cynodon	66 ± 53	18 ± 14
Pueraria	76 ± 28	16 ± 14
Stylosanthes	74 ± 15	16 ± 2
Stizolobium	77 ± 14	21 ± 4
Psophocarpus	124 ± 49	42 ± 8
Centrosema	72 ± 40	18 ± 8
Control	71 ± 65	13 ± 8
Pre-seeding	44 ± 17	9 ± 4
LSD (.05)	66	17

proven to alleviate soil erosion, water loss, crusting, high soil temperature, and low levels of soil organic matter content. Tillage effects are, however, generally evaluated in isolation while other components of the cropping system are kept constant. Methods of seedbed preparation, particularly those based on reduced and no-till systems, have specific agronomic requirements. The potential of no-till for various ecologies could be more fully realized by developing these packages of agronomic practices.

Soil Erosion

The impact of high intensity rains on surface soil accelerates sheet and rill erosion. Changes in the use of tropical and subtropical steeplands often lead to slope instability, resulting in mass movement, debris flow, and landslides. The mechanism of slope failure should be investigated.

Mechanical tillage often makes the soil susceptible to erosion. The structural properties of tropical Alfisols with low activity clays are adversely affected by primary and secondary tillage. The data in Table 7 show that there is more cumulative infiltration in plots without than with tillage operations. Even where mechanical tillage is eliminated, the infiltration rate and structural properties are directly related to the quantity of crop residue mulch (Table 8). Consequently, there is more runoff and soil erosion from mechanically tilled than from untilled land with an adequate quantity of crop residue mulch (Table 9).

Biological methods of erosion control may be more effective than mechanical curative techniques. The factors that are responsible for structural deterioration of tropical soils, including slaking and dispersion caused by rain drop impact, need to be investigated.

Table 7. Effects of a range of tillage methods on cumulative infiltration (Unpublished data of R. Lal).

Tillage treatment	Cumulative infiltration (cm/3 h)
No-tillage with residue mulch	168
No-tillage, chiselling at the end of rainy season	80
No-tillage without residue mulch	138
Mouldboard ploughing and 2 harrowings	68
Disc ploughing and rotovation	71
Ploughing at the end of rainy season, harrowing when seeding	74
Ploughing, harrowing, with mulch	79
Ploughing, harrowing, with ridging	59
LSD (.05)	50

Table 8. Effects of mulch rate on soil physical properties (Adapted from Lal et al. 1980).

Parameter	Equation	Correlation coefficient
Percent water stable aggregates (> 0.5 mm)	$Y = 42 + 7.36X - 0.41X^2$	0.98**
Dispersion ratio	$Y = 26.9 \exp(-0.09X)$	0.97**
Erosion ratio	$Y = 71.9 \exp(-0.09X)$	0.96**
Earthworm activity (casts/m^2/month)	$Y = 1.41X + 2.66$	0.98**

X = mulch rate (t/ha).

Table 9. Effect of slope and soil surface management on soil erosion (t/ha) (Lal 1976).

Treatment	Slope (%)				Mean
	1	5	10	15	
Bare fallow	7.5	80.4	152.9	155.3	99.0
Maize (mulch)	0.0	0.0	0.1	0.0	0.0
Maize (plowed)	1.2	8.2	4.4	23.6	9.4
Maize (no-till)	0.0	0.2	0.1	0.1	0.1
Cowpea (plowed)	0.6	5.6	3.3	7.6	4.3
Mean	1.9	18.9	32.2	37.3	

Conclusions

Introduction of mechanized agriculture in the tropics and subtropics leads to a rapid decline in soil productivity. The deterioration in soil quality is caused by compaction, accelerated runoff and soil erosion, and soil-tillage interactions. The problem is aggravated by the lack of appropriate equipment and machinery designed specifically for arable land development and seedbed preparation. The application of theoretical concepts of soil mechanics to these practical problems deserves attention.

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T. Woodhead* Discussant — 2

Soil Mechanical Problems in a Tropical Rainfed Rice-Maize Cropping System

Soil mechanical problems will be considered here to be of two sorts: those that bear upon the practising Asian rice farmer, and those that affect the research pertinent to those farm problems. The on-farm problems have many parallels with those discussed by Drs Greacen and Richards. But in researching these problems for tropical rice soils, we have so far drawn only on Mohr-Coulomb theory; we have yet had no need of Boussinesq theory nor of the Critical State Model. It is likely, however, that we (or our engineering cooperators) will have need to draw on a fourth branch of theory, i.e. soil-implement interaction. Like our Australian colleagues, we also have computer power on which to draw when our research is sufficiently advanced so that we can make effective use of finite difference and iterative techniques.

The CSIRO work in South Australia reports compactions of forest soil to depths of 1 m that result, inadvertently, from vehicular traffic, and in eastern Australia inadvertent sodicity prevents irrigated wheat and cotton from extracting subsoil water. My parallel is the Philippines paddy field where the compaction of the soil is a deliberate act of water conservation. For the Australian forest soil, compaction increased bulk density from 1.4–1.6 t/m^3; for the paddy soil, even when compacted, density rarely exceeds 1.2 t/m^3. Nonetheless, compaction of paddy soils does have adverse consequences for rice/non-rice cropping systems.

Preparatory to discussing these consequences, let me explain that in much of South Asia and Southeast Asia, rice yields per unit land area are now sufficiently high, and the new varieties' growth seasons sufficiently short, that government policies and farmer practices are each favouring the expansion of rice/non-rice cropping sequences such as a rice-maize, rice-wheat, and rice-legume.

But as Drs Greacen and Richards showed, cropping sequences present specific problems of soil structure and soil mechanics. A soil that is puddled for a rice crop has a more-or-less amorphous structure with a compact layer at 20–30 cm depth. As the soil dries, the shear strength of this compact layer (as manifest in a cone penetrometer index for a Maahas clay Typic Tropaquept) can reach and exceed the 2 MPa that can significantly affect the extension of roots of maize. But after the harvest of bunded rice on this puddled soil there may well be plentiful water in the soil below the compact layer, and such water would be available to the roots of a follow-on maize (or legume) crop provided that the roots could penetrate the layer, and provided oxygen also could penetrate the layer.

For the eastern Australia sodicity problem, one of the remedies considered by Drs Greacen and Richards was the use of deep tillage. That is the technique that we too have investigated for our rice/maize cropping system. Using a single subsoiler tine, we disrupt the compacted layer and disturb the soil to 35–40 cm depth; maize seeds are then planted along the tilled strip. Amongst practical considerations, turnaround time is a factor of high importance in achieving a successful cropping system. It is a factor that interacts with soil-water content, and also with considerations of the energy and labour that can be put into the turnaround operations. It will depend also on the availability and usability of drawbar draft and whether the usable draft at a particular state of soil wetness is sufficient to disrupt the soil to the required depth. It is pertinent to consider also the land preparation for the rice that follows the maize: if by strip tillage one cultivates only 10% rather than 100% of the paddy, and after harvesting the maize repuddle only 10%, are there savings on inputs of time and energy? and is any of your valuable land-preparation water lost by percolation? (The latter question was raised also by Drs Greacen and Richards during their discussion of cropping systems and the attendant tillage.)

They discussed also the questions of tilth

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and of germination and establishment of plants. Our strip tillage produced a tilth that was very cloddy and that caused germination and establishment of maize plants to be less on our strip-tilled plots than on zero-tilled or on mouldboard ploughed/harrowed plots. However, in a subsequent experiment we showed that good establishment could be achieved if the cloddy tilled strip was mildly compacted.

Our measurements of soil frictional properties and our use of Mohr-Coulomb theory are rather more rudimentary than those of Drs Greacen and Richards. Using a shear vane apparatus we found that cohesion and internal friction angle were affected more by soil-water content than by tillage. Like earlier workers, we also found friction angles greater than 45°, and it may be that even in these soils that have been puddled during many years, the soil geometry is too complex for a valid Mohr-Coulomb analysis.

But although it did not influence the frictional properties, the extra porosity created by our strip tillage did have the expected effect on crop rooting. Roots on the zero-tillage and conventional-tillage plots were by and large confined to the surface soil, whereas roots in the strip-tilled plots were able to proliferate much more at depth. Regarding the orientation of roots in the strip-tilled plots: in a direction perpendicular to the line of tillage the roots have a rather small lateral spread, but along the line of tillage the roots extend much more widely. So we have here the basis of a technology for promoting the proliferation of roots at depth. However, mention was made earlier of problems with traction at high soil-moisture contents; fortunately, these probably can be overcome by pulling the tine with a winch driven by a 6 h.p. (4 kW) tiller.

Drs Greacen and Richards emphasized that tillage systems must be crop (and seed) specific. The strip tillage system here described is suitable primarily for crops that have seeds large enough to ensure good seed-soil contact in a fairly coarse-structured soil zone. Additionally, the crop must comprise plants that individually are large enough to allow planting in rows separated by 0.5 m or more. Maize, and various legumes, are the specific crops to which this technology is directed. Postplanting cultivations, and the soil cohesion and friction that they produce, may also need to be crop specific. In the strip tillage experiment, for reasons of precision of measurement, soil was not 'hilled up' around the stems of the maize plants; in consequence, several plants were blown over, particularly on the zero-tillage and strip-tillage plots. In reality, a farmer would of course choose to hill up; we may perhaps conclude that for some rice soils a follow-on crop cannot be entirely cultivations-free. For the Maahas clay here studied, rudimentary measurements showed that the effort required for hilling-up was not significantly affected by the antecedent tillage.

The final measurement of the experiment concerned the state of the soil for the succeeding wet-season rice crop, and sought to determine whether the strip-tilled soil would allow water to percolate at a wasteful rate. Measurements showed that the percolation rate was the same for all treatments, and for all treatments it was so high as to require a considerable repuddling to prevent excessive water loss. This finding is very much in agreement with that reported by Drs Greacen and Richards.

But repuddling and land preparation for a rice crop pose questions very different from those trafficability problems addressed by the CSIRO group. Work by agricultural engineers at IRRI (specifically for long-term rice-rice systems) has shown that the load-bearing capacity of a puddled soil is strongly influenced by the pressures imposed during cultivation. Findings at IRRI and elsewhere are that four-wheel tractors are likely to experience mobility problems after two or three years of preparing land twice per year for wetland rice, and that restoring the bearing capacity of a wetland soil after using a four-wheel tractor is likely to be a difficult operation. If questions of loadbearing in rice fields do assume importance, it may be that the puddled soil is one of the few soils sufficiently homogeneous and isotropic for a valid application of analytic Boussinesq theory.

A brief reference must be made to the constraints of researching soil mechanical problems as distinct from the problems *per se*. A major constraint, as in many field programs in soil physics, is the problem of site (and plant) variability at the large scale, and of the effects of soil type (and climate) at the smaller scale that are the concern of this workshop. In research-farm operations, inadequate control of groundwater may cause problems in experiments both for wetland rice and for dryland non-rice crops.

Site inhomogeneity and shallow and variable groundwater levels were to some extent responsible for the result from our strip tillage experiment that the growth of the maize plants was not increased by the deeper rooting that was encouraged by the strip tillage. Despite attempts to lower the water table, the maize on this particular site had little need of the deeper roots.

Looking to future research — there may be need for application and/or development of theory of soil/implement interaction to aid design of implements for cultivation, both of flooded and unflooded rice soil. Natural, as well as managed, restructuring of puddled riceland soils needs to be studied; like Drs Greacen and Richards, we also shall need to research the effects of organic matter amendments — both on the soil structure itself and also on the mechanical aspects of root proliferation and of water and gas flows. The mechanical effects of soil clods and surface crusts, particularly on seedling emergence but also on root proliferation, may also prove to be topics to which increased effort needs to be directed. To research further the technique of strip tillage, a line source sprinkler, by which a controlled gradient of soil-water content can be established across an otherwise homogeneous field plot, might allow examination of the critical-depth concept as applied to previously-puddled soils. Correspondingly, measurements would be made of the reactive draft exerted by the single tine; and from them and from supporting observations of the zone of disturbance, estimates could be made of the effectiveness and efficiency of soil shatter.

Session 7
Mechanical and Engineering Problems of Soils

Summary of Discussion

A.K. Turner*

Our understanding of soil as a medium for plant growth is organized under the title of Soil Science, of which the suborder unit of Soil Physics is intended to include topics related to the physical aspects of soil. One of the main streams of physics is mechanics, which in turn branches to statics and dynamics. The study of soil and its response to forces has been traditionally made by engineers involved in foundations and earthworks. Hence an almost separate science/technology has developed that is partly outside the accepted scope of Soil Physics, but which nevertheless is closely linked with soil.

Within Soil Mechanics, a substantial body of knowledge has been built up over many years, based on theory, experiment, and experience. This knowledge has been used extensively for prediction behaviour in various stress situations; this approach is called modelling nowadays, but has been the essence of Soil Mechanics. This is not to imply that all such models developed over the years are perfect for all possible situations, and consequently there is scope for improvement and extension to a wider range of problems.

In the paper by Greacen and Richards, the authors make the point that these contributions have been largely ignored by the agriculturally-orientated soil physicists. Hence their paper is an important contribution aimed at reducing this gap, and it can be read equally well in either direction, i.e. by agriculturalists and engineers. Unfortunately, such an understanding of these two streams of soil physics is not evident in most textbooks, and the paper is most useful for this reason in particular.

The topics outlined include explanations of: the physical development of roots; compaction effects due to superimposed loads, tillage, and sodicity; low-cost roads using local materials (including reference to the development of a triaxial shear test for repeated loadings); thixotropic soils; tillage systems; and the stability of embankments and steep slopes (landslides).

In his contribution, the discussant Woodhead emphasized the need for more information to do with foundations for low-cost rural buildings, which are often built on swelling Vertisols, for example. He also discussed at length the physical problems associated with the cultivation needs of rice as a crop, as against a following crop of a different type, in relation to minimizing water conservation and energy consumption. Finally, if tillage programs are to become more site-specific, how can the results from one test site be transferred to another?

In his contribution, the discussant Lal raised the issue of the unwillingness of soil engineers to extend their concepts into soils where biological activity is important to the physical properties. Better machinery needs to be developed to take into account the optimal needs of plants, without the associated problems of compaction. An aspect that was ignored in the main paper was that of high surface temperature, its conduction through soils, and the subsequent effects on plant growth.

In the overall discussion, reference was made to the related aspects of water movement through soils, compaction, and energy consumption. An important issue will be the extent to which tillage can be made more site specific, and whether machinery manufacturers will respond to such a challenge, with better and more appropriate designs, particularly in relation to compaction.

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Finally, the author raised a different topic in relation to soil and fluid mechanics, i.e. the erodibility of soil by sheet flow and the subsequent transport of the eroded material by laminar and turbulent conditions. This engineering-type problem has been virtually ignored in the design of plot experiments intended to compare land use and soil loss, and until more effort is directed towards such an understanding, there will be real problems in interpreting the results from most of these types of experiments.

Session 8

Final Discussion

Chairman: J.R. McWilliam
Discussion Leader: C.R. Panabokke
Rapporteurs: G.J. Persley and
E.T. Craswell

Research Opportunities for ACIAR

The Chairman, Professor McWilliam, began the session by pointing out that ACIAR's purpose in convening the workshop was to identify problem areas that would be appropriate subjects for ACIAR projects. He urged that the discussion focus on the following issues:

1. The identification of the most urgent soil constraints to food production in developing countries.
2. The capacity and comparative advantage of Australian expertise in soil science to tackle these problems.
3. The need to integrate ACIAR's programs with current national and international research efforts as well as the program that would be developed by the new International Board for Soil Research and Management (IBSRAM).

Dr Panabokke, discussion leader, then introduced and led the discussion on the following major topics:

Soil Classification and Land Use

The discussion leader pointed out that Soil Taxonomy had become widely accepted as an international language of soil science. Nevertheless, tropical soils were not adequately covered by Soil Taxonomy mainly because they are not well represented in the USA where this classification scheme was developed. Australia, having large areas of soils in the tropics, could provide a base for research to improve Soil Taxonomy for tropical soil classification. Furthermore, there is a need to make Soil Taxonomy more relevant to agronomists by focussing more on the surface soil properties that affect crop growth. Australian involvement in such research would have the added benefit of increasing communication between Australian soil science groups and the international soil science community.

The need for a universal soil classification scheme was discussed and ACIAR support for the proposed International Reference Base of Soil Classification was suggested.

ACIAR could contribute to the resolution of some of these problems by supporting research aimed at developing new and simple methods of soil analysis specifically for tropical soils. The research of Dr Gillman on the charge characteristics of tropical soils was a good example of the type of work needed. The results could be used to define further diagnostic features that could be used in the classification of tropical soils. A special research effort was needed because population growth in many tropical countries was expanding the use of marginal soils such as acid sulphate soils, skeletal soils, and sandy, saline, alkaline, strongly acid, and steepland soils, for which technology was not available to sustain stable crop production. ACIAR should co-operate to develop a network on soils and crop performance that would provide better information for the discriminatory use of soils. The International Benchmark Sites Network for Agrotechnology Transfer (IBSNAT) funded by USAID was attempting to provide more specific information on crop productivity than traditional land evaluation methodology by developing dynamic simulation models of crop growth. ACIAR could become involved in this effort through IBSRAM.

In considering Land Evaluation, the discussion leader pointed out that the relevance of the work in the highlands of Papua New Guinea to the hilly lands of Nepal, India, Indonesia, and Thailand should be explored to determine which components could be directly applied and which principles were transferable. Assessments of the agricultural resource potential of hilly lands should not ignore the evaluation of the genetic potential of crops adapted to highland environments.

Another major point from the discussion was the need to evaluate land with an eye to changes in socio-economic conditions and land use. The multiple land-use surveys conducted in Kenya, might, for example, be especially relevant to the farming systems project that ACIAR planned to develop in Eastern Africa.

Soil Structure Deterioration

Research in this field in the tropics has been relatively neglected. Work in Australian laboratories on the basic principles of aggregation and crusting in Alfisols and Vertisols should be used to help identify the physical problems of tropical soils in an organized manner. In particular, structural breakdown due to the interaction of soils and implements needs study. Minimum tillage systems should be developed for areas with a long dry season. Australian scientists should form a strong symbiotic association with scientists in developing countries to tackle these problems.

Alfisols are especially prone to surface crusting and erosion so the best soil management is to maintain a legume cover crop such as *Stylosanthes*. However in countries such as India, farmers preferred to grow a cash or food crop. ACIAR could greatly assist through research to develop technology that would enable farmers to grow good crops on marginal lands.

Another approach would be for ACIAR to fund a workshop and network on Alfisols, which would ensure that Australian experience in this field was utilized to solve this problem.

In the case of soils such as Vertisols, the structural deterioration of the surface soil critically influences the hydraulic properties of the soil. Research on the management of crop residues, amendments such as gypsum, and tillage were needed to develop ways of increasing water storage in Vertisols. The use of deep-rooted plants to encourage the formation of vertical cracks and pores might be more appropriate to developing countries where the equipment for deep ripping and profile inversion was not available.

Erosion

In developing countries, the major cause of increased soil erosion is population pressure, which is forcing farmers onto fragile soils unsuited to cropping; the problem therefore has social as well as technological dimensions. Technically, the problem should be tackled on a landscape or watershed basis. Greater involvement of agronomists and soil scientists is needed to determine an understanding of erosion processes that have been neglected by engineers who have dominated past work on erosion control. The research in Queensland on the principles determining erosion in Vertisols may be transferable, with adaptation and testing, to similar soils in India and other countries. In the steeplands of Asia, Oxisols and Ultisols are more unstable and erosion prone than similar soils in South America because they are derived from different parent materials and are generally on steeper slopes. Research is needed to quantify the loss of productivity caused by erosion. Most importantly, however, better soil conservation programs are urgently needed.

Australian research has recently shown that some soils that are structurally stable are nevertheless erosion prone. The mechanics of soil failure in landscapes is influenced by the ponding of water at the base of soil conservation structures such as terraces. Once a critical void ratio is reached, the soil liquefies and flows. Research is needed on these basic processes of erosion but this work should be linked to agronomic research on erosion control measures. Foremost among these in countries such as the Philippines is the use of shrub legumes like *Leucaena* planted every 3–4 m to stabilize slopes.

In drier areas, soil erosion caused by water could be controlled by tree planting in watersheds as in the case of the Watershed Management Program in India, which also utilized diversion bunds to separate arable and non-arable land. Nevertheless, research was needed to develop better alternative approaches to the problem.

In the Sahel, there is a need to understand better the mechanisms of erosion. Rainfall simulators and ring infiltrometers could be used to study the erosion of soil by water but methods to examine the detachment of soil particles due to wind erosion are not available.

Inefficient Use of Water in Dryland Systems

Research should be undertaken to develop ways of maximizing the storage of water in the soil profile. This could be achieved by modifying the soil surface, as in the case of the broad-bed technology developed for Vertisols by ICRISAT or by trapping runoff water as had been tried in the Sahel. Another approach is to fit the cropping patterns to the seasonal rainfall. With this approach, Australian expertise in using soil-water balance data to model crop growth would be especially valuable because it would shorten the research process required by conventional site-specific methods. Modelling would be a particularly useful approach in the semi-arid tropics where rainfall is extremely variable. The models should be based on sound physical principles, should be robust and, for humid tropical areas, should be able to take into account waterlogging and flooding that are not normally included in water-balance models developed in Australia.

Research is needed to develop better methods for measuring the plant available water content (PAWC) of soil profiles, which is a critical parameter in research on soil water.

Soil Acidity

Much of the research needed in this field centres around better defining the factors in acid soils that limit the growth of crops. Better physico-chemical characterization of soils, such as cation exchange capacity and proportions occupied by calcium and aluminium, and also the levels of calcium and aluminium in the soil solution as influenced by the soil solution ionic strength, are needed for an understanding of the factors affecting plant growth on these soils. This research should be linked to crop breeding improvement programs designed to select plant varieties that are tolerant of acid soil conditions. This approach could be particularly profitable since soil constraints do not change with time, and therefore require much less breeding work than needed for resistance to plant pathogens, which tend to change regularly.

The first step in any research program on acid soils should be to review the current state of knowledge in the field. While the major research need is to develop techniques for characterizing the soils in the laboratory, a strong link between laboratory and agronomic field research should be established at the beginning of the program. Australia has expertise in centres such as Townsville, Brisbane, and Perth that should be utilized. Kalimantan (in Indonesia), Thailand, Malaysia, India, and West Africa have problems with acid soils and might be interested in a co-operative research program supported by ACIAR.

Nutrient Deficiencies

The low inherent fertility of Australian tropical soils provides a wide range of nutrient deficiencies in crops and gives a comparative advantage to Australian scientists in research to diagnose and correct such deficiencies. Research supported by ACIAR should concentrate on the diagnosis of deficiencies of secondary and micro-nutrients that have been neglected in the humid tropics. Any research on nitrogen should recognize that because of the dynamic nature of this nutrient, a modelling approach is more likely to be successful in describing changes in nitrogen availability to crops than a simple availability index established by a soil test correlation.

The availability of many nutrients to tropical crops is critically influenced by transformations in the soil organic pool. The role of soil organic matter in nutrient cycling needs further research, particularly in low activity clay soils in which the soil organic matter may greatly contribute to the cation exchange capacity.

Research to correct nutrient deficiencies should be aimed at low-input technologies where possible. Biological nitrogen fixation by legumes is the main source of nitrogen for Australian agriculture so ACIAR should develop a major research program in this field, particularly on *Rhizobium* strain selection. Another important related area is that of Vesicular Arbuscular Mycorrhiza, for improving the plant's ability to recover nutrients, especially phosphorus, which could be useful in developing low-input technologies for the tropics. The ability of plants to grow in low-fertility soils varies and this should be exploited in research to fit crops into low-input systems. As part of this effort, sources of phosphorus indigenous to developing countries should be sought, evaluated agronomically and made available to farmers where feasible.

Salinity

Salinity is becoming a critical limitation to crop growth in many parts of the semi-arid tropics. For example subsoil salinity affects 30–40% of the Vertisols in the Indian Deccan. Plot-to-plot irrigation is exacerbating the salinity problem in 1.4 M ha of irrigated Vertisols. Drainage is the answer but it is expensive. The extent to which salinity is an engineering or a soil-plant problem was discussed. ACIAR could help by funding research to define parameters for diagnosing salinity effects on different plants. The methods would also be useful in areas such as the South Pacific where coastal rather than dryland salinity is a problem.

Conclusion

The session ended with a discussion of ACIAR co-operation with IBSRAM. It was proposed that ACIAR support bilateral research partnerships between developing countries and Australian scientists that could be developed as research cells within the Soil Management Networks organized by IBSRAM. These arrangements would centre around a series of topics, e.g. acidity, erosion, Vertisols etc. Since few developing countries can respond immediately to develop research in a particular area, the networks would provide the linkages as well as the impetus for the work. The networks, with research cells composed of Australian and developing country scientists, would bridge the chasm between the basic research in a particular field and the more applied or adaptive research being conducted in the developing countries.

Appendix I

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Participants, International Workshop on Soils, 12–16 September 1983, Townsville, Queensland, Australia.

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Appendix II

International Board for Soil Research and Management (IBSRAM)

International Board for Soil Research and Management (IBSRAM)

The creation of IBSRAM at the Townsville Workshop was one of the high points of the meeting. This was achieved during the first two days (12–13th September) when the IBSRAM concept and proposal were presented to the participants in open session. IBSRAM was proposed as an organization to ensure that existing soil information and newly developed technology can be adapted by national country programs, and ensure that gains in the genetic potential of food crops can be more fully realized on the wide diversity of soils found around the world.

Specifically, IBSRAM will:

- disseminate present knowledge on soil use;
- see that research is undertaken to create new knowledge and apply it to increase food production on a stable, continuing basis; and
- help ensure the availability of trained soils personnel in all countries.

IBSRAM is visualized as a small core of headquarters staff with information and training divisions to support action programs in soil management research institutions around the world. The proposed organization will meet the need for soil research to be done where the problems exist, for local institution-building and on-site training, and for economy in administration. It will bring together national soil research leaders and scientists from international organizations and developed country institutions in networks that will enable well-planned, multidisciplinary work to be conducted and the results shared through co-operation within and between countries and between national and international groups. IBSRAM will not itself undertake training and research, but will promote and coordinate soils activities in a similar manner to the way in which the International Board for Plant Genetic Resources (IBPGR) helps conserve the world's germplasm of important food crops.

The need for IBSRAM was the subject of three papers (by Drs Jones, Panabokke, and Lopes) that are reproduced in full at the beginning of this publication. A series of presentations on possible soil management networks for IBSRAM was then given. These covered the problems of Oxisols and Ultisols, land clearing and development, Vertisols, arid lands of the Sahel, wetlands, Alfisols, skeletal soils, water management, and acid savannahs. The training component of IBSRAM and the association of IBSRAM with other international activities were also discussed.

The main driving force behind the formation of IBSRAM was a 15-member Interim Committee appointed at a conference on 'Soil-related Constraints to Food Production in the Tropics' held at the International Rice Research Institute in June 1979. The Interim Committee held its final meeting at Townsville and, prior to the meeting, had canvassed nominations for the IBSRAM Board, which would take over from them. The IBSRAM board members were elected by a committee chaired by Professor J.R. McWilliam and composed of those members of the Interim Committee, who had not been nominated, and representatives of donor agencies.

The Board members elected are:

Professor C.F. Bentley, Edmonton, Canada — Chairman
Dr R. Fauck, ORSTOM, Paris
Dr W. Goedert, EMBRAPA, Brasilia
Dr D.J. Greenland, IRRI, Manila
Dr R.J. McCracken, USDA, Washington
Dr R.J. Millington, CSIRO, Canberra
Dr C.R. Panabokke, Colombo, Sri Lanka

The election of the Board and the creation of IBSRAM was unanimously endorsed by the meeting at large.

Appendix III

Acronyms and Abbreviations

Acronyms and Abbreviations

ACIAR	Australian Centre for International Agricultural Research
AE/E	Actual evapotranspiration/potential evapotranspiration
AWC	Available water capacity
CEC	Cation exchange capacity (m equiv./100g)
CIAT	Centro International de Agricultura Tropical
COLE	Coefficient of Linear Extensibility
CSIRO	Commonwealth Scientific and Industrial Research Organization
DMC	Disruptive moisture content
ECA	Economic Commission of Africa
EMBRAPA	Empresa Brasileira de Pesquisa Agropecuaria
ESP	Exchangeable sodium as % of CEC
FAO	Food and Agriculture Organization of the United Nations
FC	Field capacity
FSR	Farming systems research
GI	Growth index
IBSNAT	International Benchmark Sites Network for Agrotechnology Transfer
IBSRAM	International Board for Soil Research and Management
ICAR	Indian Council of Agricultural Research
ICOMLAC	International Committee on Low Activity Clay Soils
ICOMOX	International Committee on Oxisols
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IITA	International Institute of Tropical Agriculture
IRAT	Institut de Recherches Agronomiques Tropicales et des Cultures Vivrieres
IRRI	International Rice Research Institute
ISNAR	International Service for National Agricultural Research
LRDC	Land Resources Development Centre
OAU/STRC	Organization of African Unity/Scientific Technical and Research Commission
OMC	Optimum moisture content
ORSTOM	Office de la Recherche Scientifique et Technique Outre-Mer
P	Precipitation
PAWC	Plant available water capacity
PNG	Papua New Guinea
PWC	Permanent wilting coefficient
RLWC	Relative leaf water content
RMU	Resource mapping unit
SAT	Semi-arid tropics
SAWMIRCS	Soil and water management in rice cropping systems
SCS	Soil Conservation Service (USDA)
SMSS	Soil Management Support Services
SMU	Soil management units
TARO	Tanzania Agricultural Research Organization
UNEP	United Nations Environment Program
USAID	United States Agency for International Development
WARDA	West African Rice Development Association