MANAGEMENT OF VERTISOLS IN SUB-SAHARAN AFRICA

PROCEEDINGS OF A CONFERENCE
HELD AT ILCA, ADDIS ABABA, ETHIOPIA
31 AUGUST–4 SEPTEMBER 1987

SEPTEMBER 1988

International Livestock Centre for Africa
P.O.Box 5689, Addis Ababa, Ethiopia

PHOTOS

Front cover

Vicia faba *growing on broadbeds (right) and on traditional ridges (left) on a pellic Vertisol in Wello, Ethiopia.*

Back cover

Bread wheat growing uniformly on broadbeds on a pellic Vertisol in northern Shewa, Ethiopia.

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ABSTRACT

This volume contains 19 papers and 26 abstracts from an international conference on the management of Vertisols in sub-Saharan Africa and other parts of the world. Three papers and one abstract overview the importance, distribution, agroclimatology and properties of Vertisols and the Indian Vertisol technology experience. Eight papers and 10 abstracts deal with resource assessment, while six papers and 15 abstracts review the resource management of Vertisols. Two papers highlight inter-institutional modes of operation and networking concepts in Vertisol research and development. Opening and closing addresses to the conference, and recommendations, are also presented.

KEYWORDS

Vertisols/Vertic soils/Clay soils/Waterlogging/ Cracking/Resource assessment/Agroclimatology/ Physical properties/Chemical properties/Soil water/Nutrients/Irrigation/Soil fertility/ Resource management/Soil surface drainage/Tillage/ Animal power/Land use systems/Cropping systems/ Forages/Economic evaluation/Vertisol technology/ Traditional farming systems/Institutional support/ Networking/Sub-Saharan Africa

RESUME

Ce volume regroupe dix-neuf documents et vingt-six résumés de communications présentés lors de la Conférence internationale sur la gestion des vertisols au sud du Sahara et dans d'autres parties du monde. Trois de ces documents et l'un des résumés portent sur l'importance, la distribution, l'agroclimatologie et les propriétés des vertisols ainsi que sur l'expérience indienne en matière de technologies relatives aux vertisols. Huit documents et dix résumés traitent de l'évaluation des ressources, et six documents et quinze résumés font référence à leur gestion. Deux documents sont consacrés aux modes interinstitutionnels de fonctionnement et au concept de réseau en matière de recherche et de développement des vertisols. Les allocutions d'ouverture et de clôture ainsi que des recommandations sont également présentées.

MOTS CLES

Vertisols/Sols vertiques/Sols argileux/ Engorgement/Formation de fentes/Evaluation des ressources/Agroclimatologie/Propriétés physiques/Propriétés chimiques/Eau du sol/Eléments nutritifs/Irrigation/Fertilité du sol/Gestion des ressources/Drainage superficiel/Travail du sol/Force animale/ Système d'occupation des sols/Système cultural/Fourrages/Evaluation économique/ Technologies des vertisols/Systèmes agraires traditionnels/Appui institutionnel/Réseau/ Afrique subsaharienne.

PREFACE

The African food crisis poses a serious challenge to all those involved in agricultural research on this continent. Soils, plants, animals and water are natural resources amenable to management interventions designed by research for increased and sustained food production. The conference on which this book reports reviewed experience and progress in the improved use of African Vertisols and developed important recommendations for future research and development of this resource.

Vertisols, sometimes called cracking clay soils, cover approximately 80 million hectares of Africa, and have been generally regarded as rather marginal for arable cropping. The majority of African Vertisols are therefore not cultivated and carry large numbers of animals, both domesticated and wild. However, much evidence has been produced that Vertisols can be transformed into productive crop land if their management addresses their inherent physical problems. It is also the general experience that improvements in tillage quality will lead to higher increases in crop yields on clay soils compared to light soils. Since heavy clay soils are very difficult to till by hand, their tillage for cropping tends to be either mechanised or animal-powered. Strong crop/livestock interactions are evident in the latter case, where animal power contributes to the necessary soil cultivation and where more livestock can be fed on the basis of the enhanced production of crop residues and by-products. Experience also suggests that animal power tends to have comparative advantages over tractor power in tilling cracking clays, especially in the wet phase. Research on draught animal technologies

for the management of Vertisols is therefore likely to have a considerable impact on the productive performance of entire farming systems on these soils. This research approach has been taken by the joint ILCA/ICRISAT/IBSRAM/Government of Ethiopia Vertisol Project. These bodies were responsible for organising the conference, the proceedings of which are presented here.

Research on the soil-water-plant-animal complex is inherently interdisciplinary. Therefore, programmes must transcend institutional borders so as to mobilise complementary and synergistic forces for faster achievement of their goals. A careful integration of extension services into these programmes is necessary for early transfer of validated technologies to the farming community.

More than 500 participants from 21 countries attended this conference. It is hoped that this event contributed to enhanced knowledge of the valuable African resource of Vertisols and to increased motivation among researchers and development workers to bring this resource into a stage of higher and sustained productivity.

Dr John Walsh
Director General
ILCA

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OPENING ADDRESS

Opening speech by Comrade Dr Geremew Debele, Member of the Central Committee of the Worker's Party of Ethiopia, Minister of Agriculture

Honourable delegates, invited guests, ladies and gentlemen, comrades.

On behalf of the People and Government of Socialist Ethiopia, I take great pleasure in welcoming you all to Ethiopia for the Conference on Management of Vertisols in Sub-Saharan Africa.

Many African countries are experiencing declining human food production, on a per caput basis: over the past three decades, per caput grain production in sub-Saharan Africa, as a whole, has declined from 170 kg to 118 kg, which is far below subsistence levels. Food imports in the mid-1980s claimed some 20% of total export earnings, and nearly 30% of the population was fed with imported grain. At the same time, sub-Saharan Africa's population has been growing rapidly, and is projected to triple by the year 2025.

Total per caput food production in sub-Saharan Africa in the period 1982-84 was 8% lower than a decade earlier, with 31 out of 39 countries showing a negative trend. Similarly the overall economic background in Africa has not been favourable in recent years. Per caput GDP, which grew at 1.3% per year in the 1960s, virtually stagnated in the 1970s, with an average growth rate of only 0.7% per year, and actually fell in the first half of the 1980s. Inflation averaged 15% per year from 1974 to 1984, and the gross domestic saving rate declined by a third. The

ratio of foreign debt service payments to export earnings deteriorated during the 1980s. The ability of governments to raise revenue, expressed in terms of current revenue as a percentage of GNP, declined slightly--from 15 to 14%--in sub-Saharan Africa as a whole, and markedly--from 17 to 12%--in the low-income countries. This is reflected in the increasing difficulties experienced by the governments of our subregion in maintaining the quantity and quality of their services in the face of growing budgetary deficits.

The human population of sub-Saharan Africa is essentially a rural one. Of the 440 million people only 25% live in urban areas, a much lower proportion than in other parts of the developing world. This population is growing at a high rate of more than 3% per year, and is projected to triple by the year 2025.

The fact that domestic food supplies less and less adequately meet the most basic dietary demands of an ever-increasing population not only poses serious threats to the future of this part of the world, but also presents heavy challenges to all those involved in agricultural research and development.

In rural societies agricultural land and the people using that land are the most important resources on which the necessary economic expansion and diversification can be based. Sub-Saharan Africa is a region of enormous environmental diversity. The main sources of this diversity are variations in rainfall, temperature and soils. Technologies for increasing labour, capital and land productivities must be adjusted to such environmental variability if they are to

have any significant impact. The generation of such technologies needs efforts well beyond those currently expended on this work. Total expenditure on agricultural research in sub-Saharan Africa between 1981 and 1983 was only US$125 million per year, a figure which contrasts sharply with the enormous expenditure on the importation of 14 million tonnes of basic food commodities into the continent. The growth rate now needed in domestic African crop and livestock production is close to 4% per year. Actual rates of growth over the past 15 years have been only about one third of this.

To improve food production, increases in land and labour productivity are essential, and for this purpose technological innovations that reduce costs are required. The lack of adequate cash, credit and input supplies in Africa's rural areas dictates a low-input development strategy.

There is an urgent need to reverse this alarming situation of the subregion. Although this responsibility largely rests in the hands of the governments and peoples of the region, the role that international agricultural research organisations could play in generating food production technologies, given the existing limited technical and financial resources of national institutions, cannot be over-emphasised.

Any national agricultural production strategy must ensure that desired changes are brought about as quickly as possible making optimum use of available resources. Sub-Saharan Africa is faced with dramatic domestic food shortages. The major goal of agricultural development strategy must therefore be to increase agricultural output substantially in the shortest possible time. The

resources available for the implementation of agricultural production strategies in sub-Saharan Africa are equally dramatically limited with respect to both research and development.

What is required, therefore, is a most rigorous scrutiny of development programmes with regard to their technical validity and potential impact on increasing food production. This is a process of clearly defining priorities of work and of allocating budgets--public or other--to activities that will most effectively bring about the envisaged increase in food output.

To exemplify the nature of such a development strategy, based on optimum use of resources for maximum possible production impact, the case of your host country, Ethiopia, may be cited. We have just started the implementation of a new national strategy to achieve food self-sufficiency during the period 1987-89 and to fortify this self-sufficiency within the perspectives of the Ten-Year Plan.

This strategy is not only a new concept of assigning priorities to development efforts, but is also quite radical in reforming practices of resource allocation. Technical manpower, agricultural inputs and other supplies and technical support facilities are being reallocated and concentrated in areas of high productive potential, while resource allocation to areas with low productive potential is being scaled down. The purpose, of course, is not to downgrade still further those areas of low productive potential, but to consolidate scarce resources in such a way as to have a very substantial impact on national food production: this can obviously best be achieved where the natural potential is highest.

New technologies are therefore being generated for these areas, and the maximum possible effort is being made to transfer these technologies to the farm level in order to achieve the necessary break-through in production in the shortest possible time.

To give you an idea of the scale of the effects I may mention that out of the total number of 568 Weredas (administrative sub-units) in the country, 148 have, after a careful selection procedure, been designated as agriculturally high potential areas which will receive preferential input treatment in our development strategy.

Vertisols, the subject of your conference, are--at least for Ethiopian conditions--soils with considerable productive potential, but they are generally underutilised using traditional production technologies. Ethiopia has 13 million hectares of Vertisols, half of this area being in the highlands, above 1500 m altitude. The fact that about 25% of all Ethiopia's presently cropped land--about two million hectares--are Vertisols may explain our keen interest in the best possible outcome of this conference. Future expansion of Ethiopia's food production will be largely based on the reclamation and improvement of waterlogged lands in the highlands, and the development of major river basins which are predominantly Vertisols. We believe we can learn a great deal from the experiences of other countries in the management of these soils.

Another strategy of central importance in the drive towards self-sufficiency in food in Ethiopia is the resettlement scheme. Resettlement of the population from the densely populated, severely degraded highland regions of the country to the

fertile plains is an essential condition for increased food production in the country.

In accordance with Party guidelines and the Ten Year Plan, my Government has successfully resettled over half a million people since the drought in 1984/85. The fact that the soils in resettlement areas are predominantly Vertisols may further explain our interest in this conference.

Reclamation and improvement of waterlogged Vertisols on the Ethiopian plateau will substantially increase food production. As capital and technology are limited in our country, reclamation work will largely be implemented through mobilisation of available labour within the community.

Our villagisation endeavour, which we consider a precondition for planned use of our land resources, will offer some useful experiences in this connection.

A number of my colleagues in the Ministry of Agriculture, the Institute of Agricultural Research and the Agricultural University will be presenting detailed reports on the nature, ecology and agricultural utilisation of Ethiopian Vertisols. I hope this exposure of the Ethiopian scene to such a distinguished gathering of international experts will contribute to clearer ideas and concepts, and ultimately to the better utilisation of this vast cropland resource in our country.

I sincerely hope that you will come up with detailed suggestions for research and development on the improved agricultural utilisation of Vertisols for human food production. These

suggestions should take into account not only the ecology and pedology of the Vertisols, but also the socio-economic environments and resource constraints prevailing in our production systems. It is only then that we will be able to make reasonable use of these soils.

Finally, I would like to take this opportunity to thank the International Livestock Centre for Africa (ILCA) for organizing, and ICRISAT and IBSRAM for sponsoring, this important conference at a time when Africa is searching for technological solutions to its food crisis.

I wish you maximum possible success in your deliberations and an enjoyable stay in Ethiopia. I now declare this conference open.

OVERVIEWS

DEVELOPING, TESTING AND TRANSFERRING IMPROVED VERTISOL TECHNOLOGY: THE INDIAN EXPERIENCE

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ABSTRACT

Vertisols are widespread in India and are generally used to grow annual crops. In many areas Vertisols are fallowed during the rainy season, which subjects them to soil erosion. Improved cropping systems have been developed for Vertisols in less-assured rainfall zones (less than 750 mm per year), based on post-rainy season production of sorghum or safflower. These systems do not remove the problem of rainy-season fallows. Rotation of crops with grassland or farm forestry is now being studied. Improved cropping systems in assured rainfall zones (more than 750 mm per year) promote cropping in both rainy and post-rainy seasons. The systems are proving successful and are being adopted quite rapidly by farmers, particularly where crops in current demand, such as soybeans, wheat and certain pulses, are included in the systems. The components of the package of practices which are perceived as most beneficial by farmers are double cropping, the use of improved cultivars and the use of fertilizers and pesticides. Land and water management practices are perceived as less attractive because the benefits tend to be long-term and they must be shared with society in the form of erosion control and reduced downstream flooding.

Adequate weed and disease control and the unsuitability of some crops to the practice of dry seeding are technical problems that limit adoption. Lack of inputs, labour, credit and extension services and inadequate marketing and distribution systems are institutional problems. The new watershed-based systems also require more cooperation among farmers than traditional crop production systems.

INTRODUCTION

The farming systems of the semi-arid tropics (SAT) are characterised by low agricultural productivity. The soils in these regions often have low fertility and are difficult to cultivate. The rainfall is low, erratic, and highly seasonal, and the socio-economic resources are limited. The current level of crop production in these harsh environments is inadequate to meet the needs of rapidly increasing populations.

Of the major soils of the SAT, Vertisols are some of the most productive for rainfed agriculture. Their high water-holding capacity allows them to compensate better than most other soils for the low and erratic rainfall, which is a major constraint to crop production in the SAT. Because of their high potential to increase productivity and their wide occurrence in the SAT, the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) has given a high priority to the development of improved farming systems for the Vertisols. Recent research has shown that, with proper management, the productivity of many of these soils can be increased several fold, growing two high-yielding improved crops each year instead of the

traditional single crop of low yield potential. At the same time, runoff and erosion are reduced. The technology includes a number of interrelated components that enable farmers to improve the workability of the soil and better control the moisture level.

This paper, which draws heavily upon an earlier paper by Virmani and Swindale (1984), discusses traditional and improved farming systems for the Vertisols in the Indian SAT environment. Because maintenance of long-term productivity under intensive farming systems in the tropics is a serious cause for concern, the discussion includes the implications for reducing the current degradation of the soil.

VERTISOLS AND THEIR ENVIRONMENT

Vertisols and associated soils cover approximately 257 million ha of the earth's surface (Dudal and Bramao, 1965). They occur extensively in India (72 million ha), northern Australia (71 million ha), Sudan (63 million ha), and Chad and Ethiopia. Vertisols also occur in Central America and Venezuela.

Vertisols and associated soils occupy 22% of the geographical area of India (Murthy, 1981). In the central region of the country, known as the Deccan Plateau, the soils are derived from weathered basalts mixed to some extent with detritus from other rocks. In other areas, particularly in the south, the soils are also derived from basic metamorphic rocks and calcareous clays. In the west, in Gujarat, they are derived from marine alluvium.

Vertisols develop mainly on the gentle slopes--usually less than 3%--of terraces, plains and valley floors in association with vertic Inceptisols, Fluvents, hydromorphic, and salt-affected soils. Occasionally they form on low smooth ridges, but seldom occur on slopes greater than 8%. They are more common at elevations below 300 m, but extensive areas in India are above this altitude (FitzPatrick, 1980). Vertisols usually have impeded drainage; their parent materials are mostly basic and fine textured, such as basic igneous rocks, limestone, and river or lacustrine alluvium (Young, 1976). Surface gilgai are not common.

The Deccan Plateau, the main area with black soils in India, is a region of low relief with broad ridge remnants of the basaltic plateau, separated by wide, shallow valleys. Vertic Inceptisols of moderate depth and shallower Entisols occur on the plateau remnants. Entisols also occur on the steeper upper slopes of the pediment surface below the ridges, grading through Inceptisols to Chromusterts on the more gentle slopes to the middle and lower pediment. Chromusterts occur on the depositional surfaces below the pediment, sometimes with Pellusterts on the lowest, flattest land surfaces. Hydromorphic and salt-affected soils occur in depressions on the slopes and in the numerous drainageways.

On the eastern fringes of the Deccan Plateau, black soils occur in transported detritus derived mostly from basalts overlying granites and gneisses of the basement complex. Where the basement rocks are soil-forming, they give rise to red brown Alfisols.

The climatic environment, extending from arid through semi-arid to subhumid tropics, is characterised by dry and hot pre-monsoon months (April to June) and dry, mild winters. The mean annual rainfall, equal to about 30-75% of the potential evapotranspiration, ranges from 500 to 1200 mm (Table 1), of which 80 to 90% is received during the monsoon season from June to September.

SOIL DEGRADATION

In India, Vertisols are particularly subject to soil loss by water erosion under the traditional systems of bare-fallowing during the rainy season. Losses are promoted by the combination of intense storms and lack of plant cover. In research watersheds, introduction of a crop during the rainy season reduced erosion losses from 30 to 60 t ha^{-1} $year^{-1}$ (Binswanger et al, 1980).

Erosion losses during the rainy season are also promoted by the low infiltration rates of Vertisols once the soil profile is filled to field capacity (Table 2). A high percentage of rain falling onto the soil will then be lost as runoff, with substantial risk of erosion.

Assessment of the extent of soil loss is hindered by the variable high intensity storms that cause the major water erosion losses. Losses under traditional monsoon fallowing are substantial; measurements at Sholapur, on land with a 1-2% slope, indicate that 50 cm of soil has been lost by erosion over the past 100 years (All India Coordinated Research Project for Dryland Agriculture, personal communication). The consequences are frightening: in the SAT environment, Vertisols have great potential for

Table 1. Climatic characteristics in areas of Vertisols and associated soils.

Climatic particulars	Arid[a]		Dry semi-arid[a]			Wet semi-arid[a]	
	Rajkot (22°18' N)	Bellary (15°09' N)	Ahmednagar (19°05' N)	Hyderabad (17°27' N)	Tiruchi-rappalli (10°46' N)	Bhopal (23°17' N)	Indore (22°43' N)
Annual mean rainfall (mm)	673.8	510.1	677.3	764.4	867.6	1208.9	1053.4
Annual mean temperature (°C)	26.8	27.6	25.3	25.8	28.9	25	24.4
Maximum summer temperature (°C)	39.4	38.1	39.4	38.7	37	38.4	39.9
Minimum winter temperature (°C)	19.2	17.4	13.1	13.4	21	10.1	9.6
Average minimum temperature (°C)	33.9	22.2	32	20	33	31.5	17.5
Percent of evapotranspiration covered by rainfall	30	29.8	42	43	41	77	58
Number of dry months[b]	10	10	6	8	9	4	6
Number of wet months[c]	1	0	2	3	2	3	4

a. Climatic classification by Troll (1966).

b. When available water (rainfall + water stored in soil by previous rain) covers less than half of potential evapotranspiration (PE).

c. When rainfall exceeds PE.

Source: Murthy et al (1982).

Table 2. Initial and equilibrium infiltration rates of a Vertisol at ICRISAT Center, near Hyderabad, India.

Time from start (hr)	Infiltration rate (mm hr^{-1})
0-0.5	76
0.5-1.0	34
1.0-2.0	4
After 144	0.21 ± 0.1

Source: Virmani and Swindale (1984).

productive cropping because their stored water can carry crops through drought periods and support a crop in the post-rainy season. Erosion reduces the long-term productive capacity of the soil.

TRADITIONAL DRYLAND FARMING SYSTEMS

The use and management of Vertisols in India vary widely and depend upon the development of local technology. Flocks of sheep and goats graze on common lands during the cropping seasons, and on stubble and trash during the fallow. Manure is exchanged for feed. In the Indian SAT, the traditional cropping patterns on Vertisols and associated soils can be related to the constraints imposed by the combination of agroclimatic and soil characteristics. On the shallower vertic soils, cropping is confined to the rainy season because the limited water storage capacity is insufficient to support crop growth for very long after the rains have ceased. On Vertisols cropping patterns and land use vary. A few Vertisols are cropped during the rainy season,

with the growth period extending beyond the end of the rainy season because long-duration cultivars are commonly used. However, many--perhaps 50% or more (Krantz and Singh, 1975)--are fallowed during the rainy season and produce a single crop grown on stored moisture in the post-rainy season.

Michaels (1981) has confirmed that rainy season fallows can be separated into:

- "Dry" fallows, in which the rainfall during the rainy season is unreliable and bare-fallowing is essential to attempt to accumulate sufficient water in the profile to grow a crop on stored water in the post-rainy season (exemplified by Sholapur, Table 3).

- "Wet" fallows, in which the rainfall during the rainy season is adequate to excessive and cropping during this season risks losses from waterlogging and flooding. Because maximum water storage in the profile is assured at the end of the rainy season, crops grown in the post-rainy season on stored moisture are relatively assured, although the productivity is low (exemplified by Hyderabad, Table 3).

Where rainy-season fallow is practised the common crops grown in the post-rainy season are sorghum, safflower, wheat and chickpea. Examples of multiple cropping systems are intercrops (sorghum/oilseed) or a 2-year rotation of wheat-chickpea or wheat-linseed (Krantz and Singh, 1975). Sorghum may be grown throughout the Indian SAT, but production of wheat and chickpea is largely confined to the northern areas. Less common, but still important, are some specialist crops such as chillies.

Table 3. Reliability of a 90-day rainy season crop on three Vertisol areas[a] (Probability expressed in percentage of years).

	Sholapur deep	Hyderabad deep	Akola medium deep
Annual rainfall (mm)	742	761	840
Probability of emergence before 15 July	65	85	92
Probability of seedling survival	49	76	80
Probability of good growing conditions throughout	33	62	66
Probability of adequate soil moisture for post-rainy season sorghum:			
after rainy season crop	60	50	NA[b]
after rainy season fallow	80	83	NA

a. Available water-holding capacity of deep Vertisols is assumed at 230 mm and of shallow Vertisols at 120 mm.

b. NA = not applicable. The water-holding capacity is far too low to meet post-rainy season sorghum water needs.

Source: Binswanger et al (1980).

Where crops are grown during the rainy season, multiple cropping and sole cropping are practised with many different crops (Spratt and Choudhury, 1978; Willey, 1981). Sorghum or cotton are commonly grown with pigeonpea as an intercrop, or sorghum in the rainy season may be followed by chickpea in post-rainy season. However, two crops spanning both seasons are grown on less than 10% of the Vertisol area (Krantz and Singh, 1975).

Fields are prepared with a single pointed-stick plough and a blade harrow 'bakhar'. Seed is either broadcast or placed through a seed tube attached to the plough. The only nutrient input is an occasional small application of manure. Cultivars are usually long season, tall, local landraces with characteristically low harvest indexes.

Although productivity is low, it is reasonably stable; use of inputs and loss risks are low. The system was satisfactory while population pressures were also low and population increases could be accommodated by expansion onto unused land. Increasing populations now require increasing productivity per capita and per unit of land.

PREVAILING PRODUCTION CONSTRAINTS

The Indian farmer's traditional system has several major problems and limitations. The poor internal drainage of the heavy soils can severely restrict operations during the rainy season, especially if rainfall is excessive and/or slope of the land is minimal. The cultivation equipment is not versatile for operations under difficult soil conditions. The crop cultivars, although resistant to some pests and diseases, have limited

yield potential and little ability to respond to inputs such as fertilizers. The farmers' crop options are often limited by the use of long duration cultivars. Animal production is a minor activity.

IMPROVED CROPPING SYSTEMS

Virmani et al (1982) have classified the Vertisols of central India into two broad production zones on the basis of annual rainfall (Figure 1):

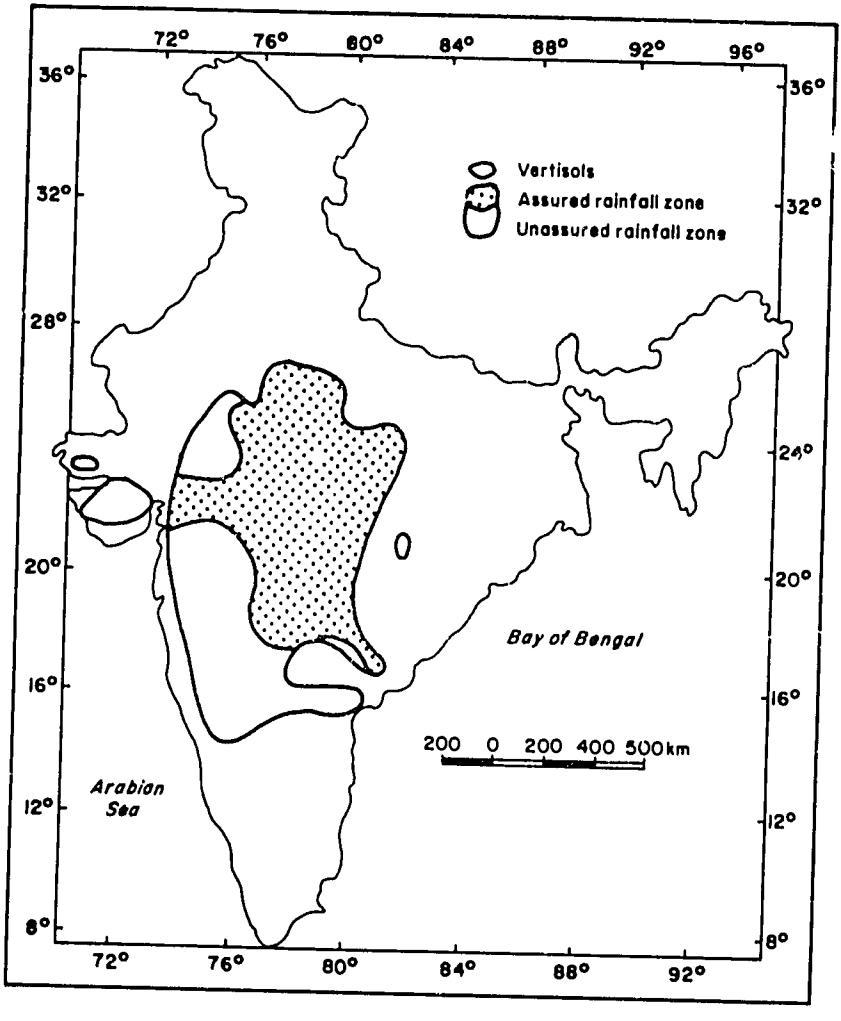
- Unassured rainfall zone, including the drought-prone areas of Maharashtra and north Karnataka, which receives erratic rainfall ranging from 500 to 750 mm, equal to 40-48% of annual potential evapotranspiration.

- Assured rainfall zone, extending from Hyderabad to Gwalior in central peninsular India, which receives mostly assured rainfall ranging from 750 to 1250 mm, equal to 43-77% of annual potential evapotranspiration.

Different strategies are needed in each zone. In the unassured rainfall zone sorghum or safflower grown in the post-rainy season as sole crops have been most successful. Improved cultivars used with moderate doses of fertilizers and good weed control increase yields significantly (Rao and Rao, 1980).

Sowing 3 to 4 weeks before traditional dates (into late September) was found to increase average yields from 770 to 1870 kg ha^{-1} in a long-term experiment by Randhawa and Venkateswarlu (1980). Improved use of available water was considered to be the reason for the increase.

Figure 1. The Vertisols areas of India where rainfall is assured and unassured.



Cropping in the post-rainy season still leaves the land susceptible to erosion during the early rains. Various land treatments such as land smoothing, guide bunds or broadbeds-and-furrows, and short duration cover crops such as mung beans, have been recommended by various authors, but with limited success. Current research has concentrated on rotating crops with grassland or pasture, with buffel grass and stylo as the main grass and legume components, but this practice has not yet attracted much farmer interest. The same is true of rotation with farm forestry. Farmers prefer to seek access to irrigation water.

For the assured rainfall zone ICRISAT has developed an improved farming system, the key elements of which are:

- Growing the same crop in both rainy and post-rainy seasons. Each of the two crops is more productive than the previous single crop.

- Use of improved cultivars and improved cropping systems which increase the number of options for the farmer, including sole crops, sequential crops, and intercrops.

- Use of fertilizers, usually N and P, and less commonly Zn.

- Introduction of improved management techniques.

The key to the success of the system is improved management: the basic elements are:

- Shaping land to promote disposal of excess water by introduction of broadbeds-and-furrows and grassed waterways.

- Rough ploughing land immediately after the previous crop is harvested when there is still a little moisture remaining in the soil.

- Completion of seedbed preparation after the first pre-monsoon rain, which always occurs between harvest in January or February and onset of the southwest monsoon in June.

- More precise placement of fertilizer and seed.

These developments have required a great deal of research and planning. Prediction of areas where the rainy-season rainfall is assured and where dry seeding can be used, selection of improved crop species and cultivars, selection of the best combinations for improved cropping systems, and development of simple bullock-drawn equipment have all been significant tasks.

An important aspect of the improved system is that it contains a package of options for the farmer. While the physical productivity gains are greatest when all options are introduced (Table 4), the farmer has the option of selecting only those components which are desired or possible.

The basis of the technology developed at ICRISAT is a system of semi-permanent graded broadbeds-and-furrows laid out on a gradual slope (usually 0.4-0.8%). Each bed is slightly raised, acting as a 'minibund' for good moisture conservation and erosion control. The broadbeds are adaptable to a range of sowing arrangements to accommodate different crops; the number of rows per bed can vary from one to four, giving effective row arrangements from 150 to 30 cm. The

Table 4. Synergistic effect of variety selection, soil management, and fertilizer application in a maize/pigeonpea intercropping system on a Vertisol at ICRISAT (1976-77).

Treatment	Yield (kg ha^{-1})		
	Local maize variety	Improved or hybrid maize variety	Pigeonpea[a]
Traditional inputs and management	450		320
Improved soil-, and crop-management alone	600		64
Fertilizer application alone	1900		452
Improved soil-crop management and fertilizer	2610		837
Traditional inputs and management		630	500
Improved soil-, and crop-management alone		960	640
Fertilizer application alone		2220	540
Improved soil-crop management and fertilizer		3470	604

a. Pigeonpea variety was the same in all experiments.

furrow is shallow but provides good surface drainage to prevent waterlogging of the crops growing on the bed. Excess water is drained through a system of field drains and grassed waterways.

The two major cropping systems that have been developed at ICRISAT to utilise both the rainy and post-rainy seasons are:

- a "sequential" system of rainy-season maize or sorghum (two rows per broadbed) followed by a post-rainy season chickpea (four rows per broadbed); and

- an intercrop system of maize or sorghum and pigeonpea (one row of pigeonpea at the middle of the bed and one row of cereal on either side).

Maize has been the better cereal to use in these systems because it avoids the late-season disease problems of sorghum.

The yields of these two systems at ICRISAT over 4 years from operational scale watersheds of several hectares are given in Table 5. Improved seeds and adequate fertilizers were used as part of the technology. Both systems substantially outyielded the traditional rainy-season fallow system growing only a post-rainy season crop of chickpea or sorghum without the benefit of raised beds or improved seeds and fertilizers.

The good performance of the intercrop is worth noting. When the two improved systems were compared, the intercrops gave only a little less maize and rather more pulse than the sequential system, and gross returns were similar. The intercrop may be attractive in practical terms in that both crops are planted in one operation at the beginning of the rainy season. This avoids a possible problem with the sequential system in which the post-rainy season crop has to be established at the end of the rains when the upper soil layers may have dried out, and when the farmer has a peak labour demand to harvest his rainy-season crop. This is one of the reasons why the intercropping systems have given more stable net returns than the sequential system in these operational watersheds (Ryan et al, 1980).

Economic analyses of the results from 1976 to 1981 at ICRISAT have shown that the improved

Table 5. Grain yields (kg ha^{-1}) from an intercrop system and a sequential system compared with traditional rainy-season fallowing from Vertisol operational scale watersheds at ICRISAT.

	1976-77	1977-78	1978-79	1980-81	Mean
Maize/pigeonpea intercrop system					
Maize	3291	2813	2140	2918	2791
Pigeonpea	783	1318	1171	968	1060
Maize-chickpea sequential system					
Maize	3116	3338	2150	4185	3197
Chickpea	650	1128	1340	786	976
Traditional fallow and single post-rainy season crop					
Chickpea	543	865	532	596	634
Sorghum	436	377	555	563	483

technology based on maize intercropped with pigeonpea can increase profits by about 600% compared with the traditional system based on rainy-season fallow followed by post-rainy season sorghum and chickpea. The improved system has generated profits averaging Rs. 3650 ha^{-1} $year^{-1}$ over 5 years, compared with only Rs. 500 ha^{-1} $year^{-1}$ from the traditional system. These profits represent a return to land, capital and management; the cost of implements has been deducted (Ryan and Sarin, 1981).

ON-FARM STUDIES OF THE IMPROVED SYSTEMS

On-farm studies of the improved systems developed at ICRISAT began in 1981. The objectives were to:

- verify whether the ICRISAT experience could be replicated in farmers' fields;
- evaluate the performance of the various technology options;
- test the ability of delivery systems to support demands of the improved systems and to utilise the increased production; and
- study the technical and economic performance of the options under farmer conditions.

The initial on-farm trials were conducted in one village with a soil type similar to that at ICRISAT. It was conducted by farmers under ICRISAT supervision and monitored by the state Department of Agriculture. Later, the trials were expanded to 28 locations involving 1406 farmers in four states: some trials were supervised by ICRISAT, others were supervised by the state Departments of Agriculture or other agencies and monitored by ICRISAT, and others were handled without any direct ICRISAT involvement.

Von Oppen et al (in press) analysed the ICRISAT-managed trials in the states of Andhra Pradesh, Karnataka and Madhya Pradesh (Table 6). They found the results to be consistent over time. The improved cropping systems yielded 3000-4400 kg ha^{-1} against 500-700 kg ha^{-1} with traditional systems. Average gross returns were four to five times those of traditional systems. Except for the first year in Madhya Pradesh where some farmer-

Table 6. Economic performance of Vertisol technology at ICRISAT collaborative on-farm test sites: 1981/82 to 1983/84.

Test site and year	Improved technology		Traditional technology		Marginal rate of return (%)
	Operational cost (Rs ha^{-1})	Gross profits (Rs ha^{-1})[a]	Operational cost (Rs ha^{-1})	Gross profits (Rs ha^{-1})[a]	
Taddanpally, Andhra Pradesh					
1981/82	1181	3055	595	1625	244
1982/83	1035	3957	448	1722	381
CV of gross profits (%)		42		50	
Sultanpur, Andhra Pradesh					
1982/83	1062	3576	448	1722	302
CV of gross profits (%)		37		50	
Farhatabad, Karnataka					
1982/83	1194	3323	1142	2186	--[b]
1983/84	1226	4494	1188	2207	--[b]
CV of gross profits (%)		23		31	
Begumgunj, Madhya Pradesh					
1982/83	2348	1172	866	786	26
1983/84	2321	2743	1250	1611	106
CV of gross profits (%)		76		89	

a. Profitability is measured in gross profits.
Indian Rs. 13 = US $1.00.

b. The differences in operational cost are too small to get a meaningful value for marginal rate of return.

Source: Von Oppen et al (in press).

recommended cropping systems failed, marginal rates of return were 106 to 381%. Generally a cereal/pigeonpea intercrop performed better than a cereal-chickpea sequential crop. At all locations the improved systems showed a coefficient of variation of gross profits lower than those for the traditional systems. This indicates reduced risk with the improved technology.

Overall the on-farm trials gave substantial increases in productivity and rates of return and testified to the overall viability of the improved systems. However, the wide range in rate of return from 25 to over 2000% indicated a need for closer monitoring of the components of the technology and particularly of the crop combinations suggested by the farmers. Other components which need attention are:

- contribution of broadbeds-and-furrows to long-term increases in productivity and erosion control;
- efficiency and utility of the wheeled tool carrier and other implements;
- methods of controlling the pigeonpea pod-borer (*Heliothis armigera*);
- dry seeding; and
- cropping system rotations.

EARLY ADOPTION BY FARMERS OF THE NEW TECHNOLOGIES

Farmers do not all adopt new technologies, even when they appear well-suited to their conditions, and those who do so, adopt the technologies

piecemeal and at different rates. Two years after ICRISAT managed on-farm trials at Begumgunj village in Madhya Pradesh, Foster et al (1987) surveyed the response by farmers (Table 7). Double cropping, the most important innovation, has been well adopted. So have its economically most productive components: rainy-season soybeans, improved cultivars and increased use of chemical fertilizers and pesticides. Components contributing to improved workability or water management were not adopted.

Similar results were obtained in separate studies conducted as part of a large watershed development project carried out near Indore in Madhya Pradesh by a British technical team in association with the All India Coordinated Research Project on Dryland Agriculture (AICRPDA) and the College of Agriculture at Indore (Raje, 1983). The area under double cropping increased over the 5-year period of the project (1975/76 to 1979/80) from 190 to 1224 ha and the cropping intensity from 103 to 139% without the addition of any irrigation.

The problems and constraints to adoption of parts of the package as perceived by farmers were both technical and institutional. Prominent among the former were:

- Weed control imposes problems in several of the double cropping systems tried.

- Pest and disease controls were not fully integrated into the initial packages of practices and hasty ad hoc solutions created bad impressions among the farmers.

Table 7. Use of components of the double cropping technology package in Begumgunj, Madhya Pradesh, by 18 watershed and 7 non-watershed farmers in 1986/87.

Practice	18 watershed farmers			7 non-watershed farmers
	Number using before 1982a	Adopting during field trials	Number using in 1986-87	Number using in 1986-87
Rainy season soybeans dryland	4b	14[b]	13[c]	4[c]
Dryland double cropping	Probably none	17	9+4[d]	1+3[d]
Summer ploughing	18	-	18	6
Improved drainage furrows	0	18	2	0
Broadbeds	0	18	0	0
Dry rainy season sowing	0	8	1	0
Improved seed	3	13	16	4
Use of chemical fertilizer	4	11	15	5
Using recommended dose of fertilizer	-	-	4	1
Mixing seed and fertilizer	All who use fertilizer at seeding time			
Row seeding rainy season crop	1	14	14	5
Chemical plant protection	1	6	7	6
Use of wheeled tool carrier	0	18	0	0

a ICRISAT field trials began in 1982.

b. In [illegible] es wet and dryland.

c. Including those growing soybeans on land that can be irrigated, 23 of 25 farmers grew soybeans in 1986-87.

d. The second number indicates the number who planned to double crop but had to fallow in the post-rainy season because of a moisture shortage.

Source: Foster et al (1987).

- Failure of late season rains or labour bottlenecks created problems with sequential post-rainy season crops. Farmers were not always willing to accept intercropping as a substitute because post-rainy season cereals (wheat in the north and sorghum in the south) are important for subsistence food and forage.

- Farmers perceive dry seeding as a risky practice because early season rains are erratic in some regions, the practice is not suited to all the crops that farmers wish to grow, and interactions with pests, weeds and diseases are sometimes adverse.

- Lack of bullock power. Many small farmers do not have bullocks and rental of bullocks is not common.

- The wheeled tool carrier (WTC) that was part of the ICRISAT package was too expensive. The WTC is a form of intermediate technology between traditional animal-drawn implements and tractor-drawn modern equipment. Lack of credit, lack of bullock power, small size of holdings and the intermediacy of the WTC all mitigate against its use.

Prominent among the institutional constraints were:

- Supply systems for fertilizers and agricultural chemicals are weak in the dryland areas.

- Credit needs to be expanded. Short-term credit should embrace both rainy and post-rainy seasons. Medium-term credit is needed

to enable bullocks and WTCs to be purchased and long-term credit is needed for land development. Weakness of cooperatives, a subsidy orientation among farmers and a poor record of credit repayment--aided and abetted by politicians--contribute to the lack of both inputs and credit.

- Extension services are sometimes, but not always, inadequate. Suitably trained extension personnel may not be available or their abilities to train farmers may be inadequate. Not all farmers are responsive or willing to cooperate.

- Local marketing and distribution systems may be unable to cope with the increased production of less-favoured crops such as sorghum or maize. Some on-farm trials failed because local authorities did not anticipate the increased supplies of coarse grains, and catastrophic price reductions occurred.

The demand for farm labour increased with the improved technology by 300 to 400 hours ha^{-1}. Even in rural India, where unemployment rates are high, the technology faced labour bottlenecks for weeding during harvest and during the mid-season harvesting and planting of sequential crops.

The components that farmers have been less willing to adopt all relate in one way or another to land and water management: improving soil tilth or reducing puddling when the soil is wet, improving water infiltration into the soil, reducing runoff, and improving drainage. To make these improvements, the farmer must change his style of farming: he must grade and shape the land, install grass-protected drainageways, use

more efficient but more expensive equipment, and ensure that field drainage is connected to community drainage channels and the regional drainage system. Short-term economic benefits of these improvements, although significant, are less than the benefits of using improved seeds and fertilizers. Furthermore, the benefits from reduced erosion and water control accrue to society as much as to the farmer, perhaps even more so.

It is not difficult to understand that the farmer is reluctant to adopt these practices. If society is to share the benefits it should also share the cost. Greater efforts by local or state government are required. Tax revenues may appropriately be used to ensure the adoption of these valuable practices. Government must also undertake public works needed to improve community and regional drainage canals.

Generally, the components adopted from the packages of practices were those that were already known or in use to some extent. The on-farm trials raised farmer awareness of these practices. Hence those practices such as improved drainage furrows and dry seeding prior to the rainy season at Begumgunj (Table 7), which have been adopted to a limited extent, may spread over time or if a special extension effort is made, particularly if the perceived technical problems can be overcome and the most important institutional constraints are removed. It is also important to remember that when farmers are attracted to a new innovation, for whatever reason, they will themselves find ways to make it succeed.

CONCLUSIONS

Vertisols are widespread in India. They occur in arid, semi-arid and subhumid climates and generally have potentials far above their present use in traditional agriculture. These soils are generally used to grow annual crops. In many areas the soils are fallowed during the rainy season and are then subject to serious erosion from high intensity storms and the lack of plant cover. Grazing and farm forestry are minor activities at present.

Two broad production zones have been delineated on the basis of annual rainfall; the boundary lies approximately at 750 mm. Improved cropping systems have been devised for both zones. For the drier zone, use of improved cultivars of sorghum and safflower grown in the post-rainy season with the addition of chemical fertilizers improves yields and profits, and resists drought better than traditional cropping systems. Unfortunately the soils remain susceptible to erosion during the early rains. There seems to be a place for grassland or farm forestry in rotation with annual crops, but this has not yet received adequate research attention.

In the more assured rainfall zone, systems for cropping the soils in both the rainy and post-rainy seasons have been successfully developed. Farmers are adopting double cropping and the related use of improved cultivars and fertilizers, particularly in areas where the crops produced--soybeans, wheat and certain pulses--are in demand or receive effective government price support.

Other constraints to increased use of double cropping are both technical and institutional.

Weed, disease and pest control are the major technical problems, while input supplies, labour, credit and extension services are the major institution ones.

Farmers have been reluctant to accept improved tillage practices and land treatments that improve surface drainage. Farmers seldom perceive drainage as a problem. Furthermore the economic benefits are long term and thus unattractive compared to the use of improved cultivars, fertilizers and even pesticides. Reduced soil erosion and improved flood control are benefits that accrue more to society as a whole than to the individual farmer.

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AGROCLIMATOLOGY OF THE VERTISOLS AND VERTIC SOIL AREAS OF AFRICA

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ABSTRACT

Vertisols and vertic soil cover 43 million ha in 28 countries in Africa. These soils are found in diverse agroecological environments. Niger, Chad, Somalia and southern Zimbabwe have large areas of arid tropical Vertisols. This region is characterised by low rainfall and a very short growing season. Such areas are used for extensive agriculture; where irrigation water is available Vertisols are highly productive. Large investments are required to develop and sustain irrigated agriculture in these Vertisol regions.

About 20 million ha of African Vertisols and vertic soils are found in dry semi-arid tropical climates. The growing season in these areas varies from 60 to 200 days, and under dryland conditions, one or two crops can be successfully grown. Some drainage is needed during the rainy months of the year. The cost to develop sustained agriculture in dry semi-arid tropical areas is relatively low.

Twenty-five percent of the Vertisol and vertic soils area of tropical Africa occur in dry/wet semi-arid climates, where the growing season varies from 180 to 300 days. These soils occur in high rainfall areas (>1000 mm year^{-1}), and lack of drainage is a major constraint to

increased agricultural production. These Vertisol regions are more suited to rangeland agriculture and agroforestry, because the cost to develop these areas for sustained arable crop production is relatively high.

Vertisols and vertic soils are potentially a highly productive group of African soils. If properly managed, they could be highly productive, but are highly prone to erosion. For sustainable agriculture on Vertisols, farming systems which include effective conservation techniques need to be developed and introduced.

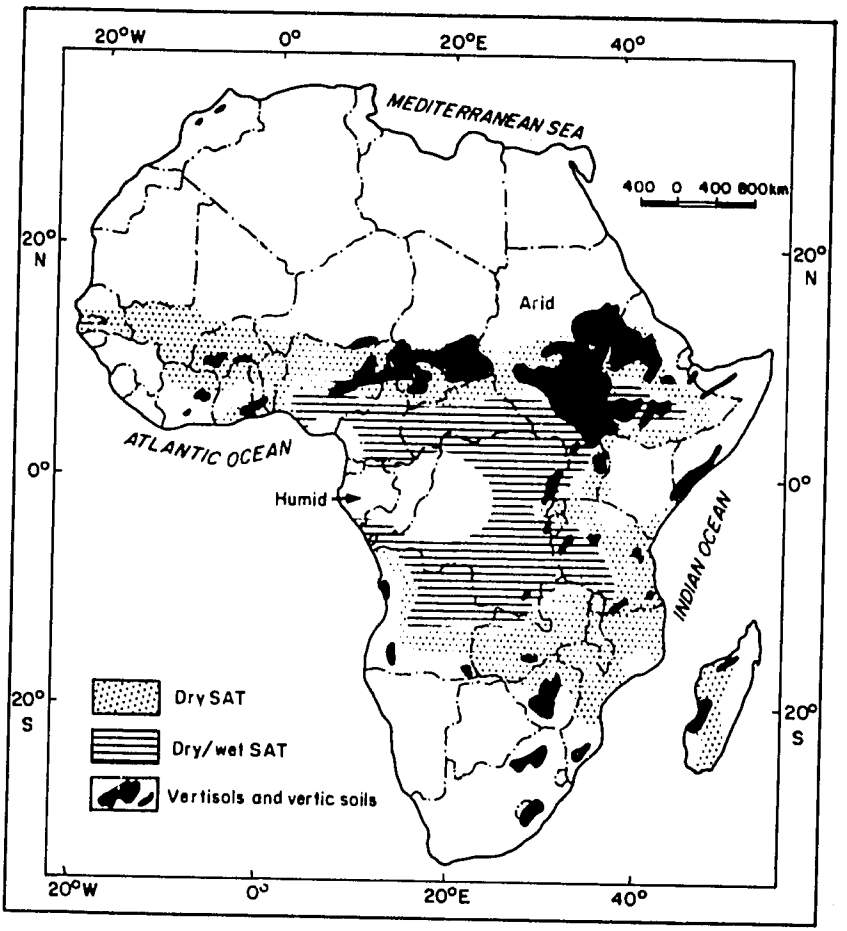
INTRODUCTION

This paper examines agroclimatic features in those areas of tropical Africa with Vertisols and vertic soils. Climatic features, particularly moisture, have been defined as the physical environment in which programmes to implement Vertisols technology will occur. No attempt has been made to catalogue the climate of the continent of Africa; but examples of climatic analysis have been cited to develop general principles in agronomically relevant terms. The paper focuses on the major climatic constraints and opportunities for dryland agriculture in African Vertisols and vertic soils areas.

DISTRIBUTION OF VERTISOLS AND VERTIC SOILS IN AFRICA

Vertisols and vertic soils occur extensively in Africa (Figure 1). From an estimated global 300 million ha, 43 million ha are located in tropical Africa (Dudal, 1980). This estimate falls far

Figure 1. Distribution of African Vertisols and vertic soils, and climatic zones of Africa according to Troll.



Source: Troll (1965).

short of the 80 million ha in the vertic soil group suggested at the conference on 'Management of Vertisols Under Semi-Arid Conditions' organized by IBSRAM (Latham, 1987). From generalised soil maps in Africa (Hubble, 1984), we estimate that the total area of soils having 'vertic' properties in management-related terms, may be of the order of 100 million ha.

African Vertisols and vertic soils are found mainly in the tropics, between 18° N and 23° S latitudes. Only a small area of Vertisols in Lesotho and South Africa occurs outside tropical Africa (Figure 1). There are 28 African countries which have Vertisols and vertic soils (Table 1).

Table 1. African countries with Vertisols and vertic soils.

West Africa	Senegal, Burkina Faso, Cote d'Ivoire, Ghana, Togo, Dahomey, Nigeria, Niger, Cameroon, Morocco.
East Africa	Somalia, Ethiopia, Kenya, Tanzania, Sudan.
Central Africa	Chad, Central African Republic, Zaire, Burundi, Uganda.
Southern Africa	Angola, Zambia, Zimbabwe, Botswana, South Africa, Lesotho, Mozambique, Madagascar.

THE CLIMATE OF TROPICAL AFRICA

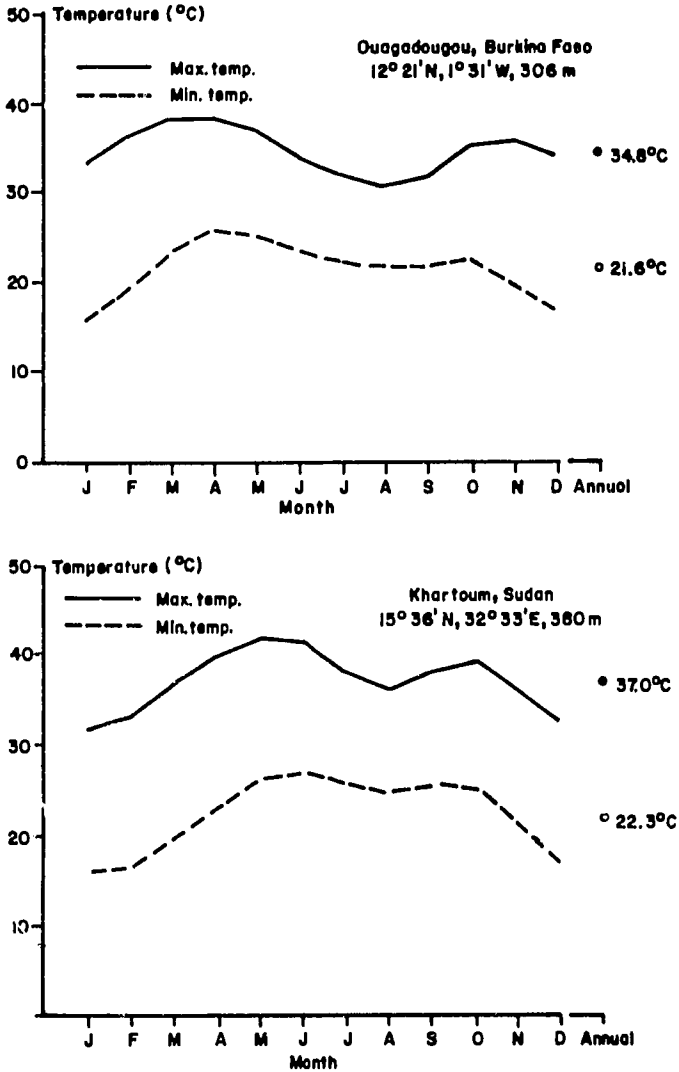
Climate is a primary determinant of arable agricultural development, and therefore an assessment of climate in agronomically relevant terms is essential. The data bases used in this paper are FAO, 1984; IAR/ILCA/ICRISAT, 1987; and WMO, 1971.

THERMAL ENVIRONMENT OF VERTISOLS AND VERTIC SOILS IN AFRICA

The thermal environment in the Vertisol areas of tropical Africa is greatly modified by altitude. In West and East Africa, in areas ranging from 200 to 500 m, mean annual temperatures exceed 28°C, and day temperatures rarely fall below 30°C. Average daily minimum temperatures range from 18 to 28°C in Ouagadougou, Burkina Faso, and Khartoum, Sudan. The hottest months are April to June, when maximum temperatures are around 40°C. Following the onset of the rainy season in July, maximum temperature declines. On an annual basis, the diurnal difference between the maximum and minimum temperatures is about 12-15°C (Figure 2).

In the highlands of East Africa, Vertisols and associated soils occur at altitudes of 1000-3000 m. In these areas mean monthly maximum temperatures rarely exceed 30°C and the minimum temperature is usually below 15°C. In the single peaked rainfall areas the temperatures are relatively high during March and May (Figure 3). In the rainy months of June to September, the mean maximum temperature is around 20°C. In the winter months from October to February the minimum temperatures are quite low. Frosts are common above 2000 m. In the highlands of East Africa

Figure 2. Monthly and annual maximum and minimum temperatures at selected lowland locations in West and East Africa.



receiving bimodal rainfall (e.g. Nairobi, Kenya), temperatures are more or less uniform throughout the year (Figure 3).

In southern Africa the mean monthly maximum temperatures rarely exceed 35°C and minimum temperatures do not generally fall below 15°C. The diurnal difference between maximum and minimum temperatures, on an annual basis, is around 12°C (Figure 4).

HYGRIC ENVIRONMENT

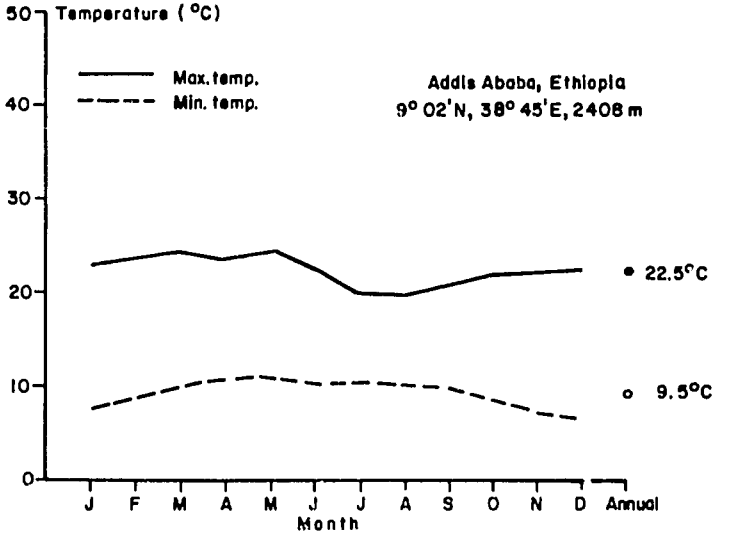
Research on the moisture environment of African Vertisols and vertic soils has assessed moisture adequacy for arable agricultural production. The length and characteristics of the growing season based on water budgets have been studied in some detail.

In order to discuss systematically the hygric environment, the climate of tropical Africa where Vertisols and vertic soils occur has been classified according to the Troll (1965) system. Such a zonation of climate is essential for adaptation and transfer of agrotechnology. This is analogous to concepts used extensively in soil resource assessment (Moore, 1978; Swindale, 1982). The relevant classes devised by Troll are:

3. Dry/wet semi-arid climates with 4.5-7.0 humid months.
4a. Dry semi-arid climates with 2.0-4.5 humid months.
5. Arid climates with less than 2.0 humid months.

These zones in Africa are shown on Figure 1.

Figure 3. Monthly and annual maximum and minimum temperatures for two selected highland locations in East Africa.



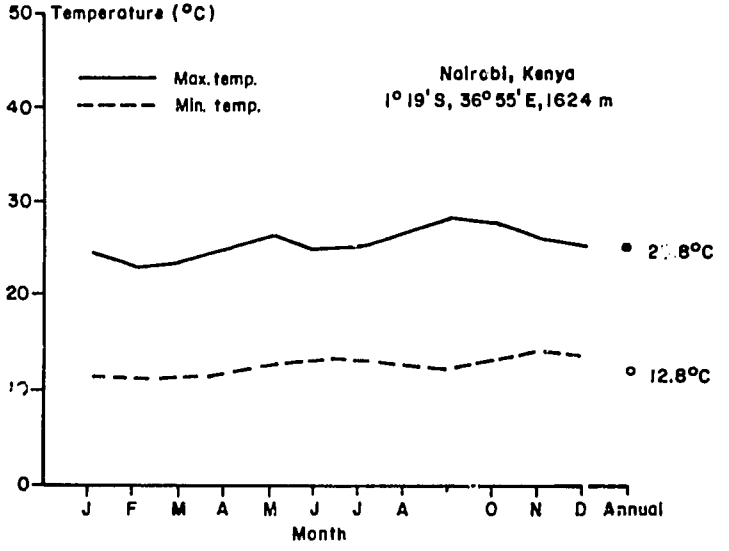
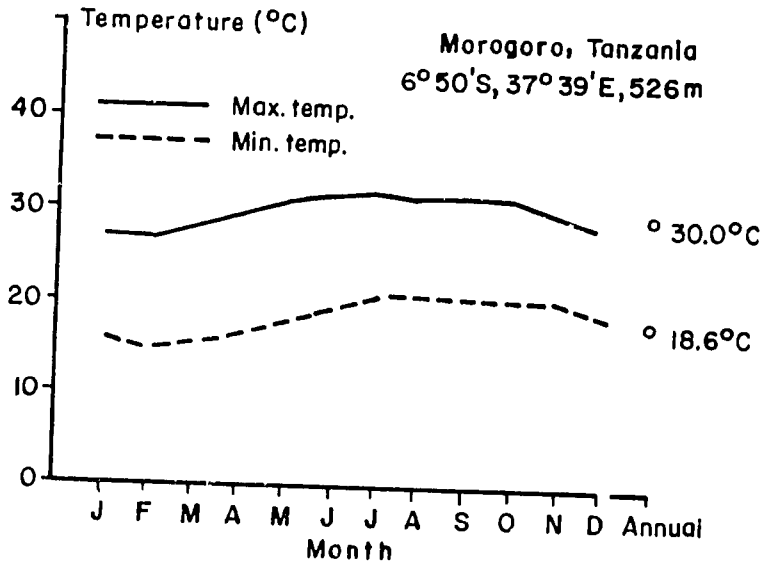


Figure 4. Monthly and annual maximum and minimum temperatures at a typical southern African location.



Troll defined a humid month simply as one in which mean rainfall exceeds potential evapotranspiration. The vegetation associated with Troll's three climate classes for Africa listed above are dry savannah woodland, thorn savannah, and semi-desert, respectively. The term "semi-arid" was not invented by Troll. It was introduced by Thornthwaite (1948), and later used by Meigs (1953) in the preparation of world arid zone maps. ICRISAT has accepted the climatic classification of Troll as the working definition for its mandate region. This classification is ecologically oriented, emphasises the length of the dry season, and the length and quality of the wet season, all of which are relevant for improved agricultural production and soil water management.

A number of classifications have evolved to describe African tropical climates. Climate classification is essentially a geographic technique that allows simplification and generalisation based on climatic statistics (Hare, 1951). ICRISAT scientists believe it is best to adapt a climate classification scheme already in use and doubt if any further refining or integration of different climatic systems will be useful. Troll's agroclimatic classification adequately describes the hygric environment for crop production in tropical Africa. It takes into account rainfall adequacy to meet the evapotranspiration needs and is therefore oriented to agronomic management.

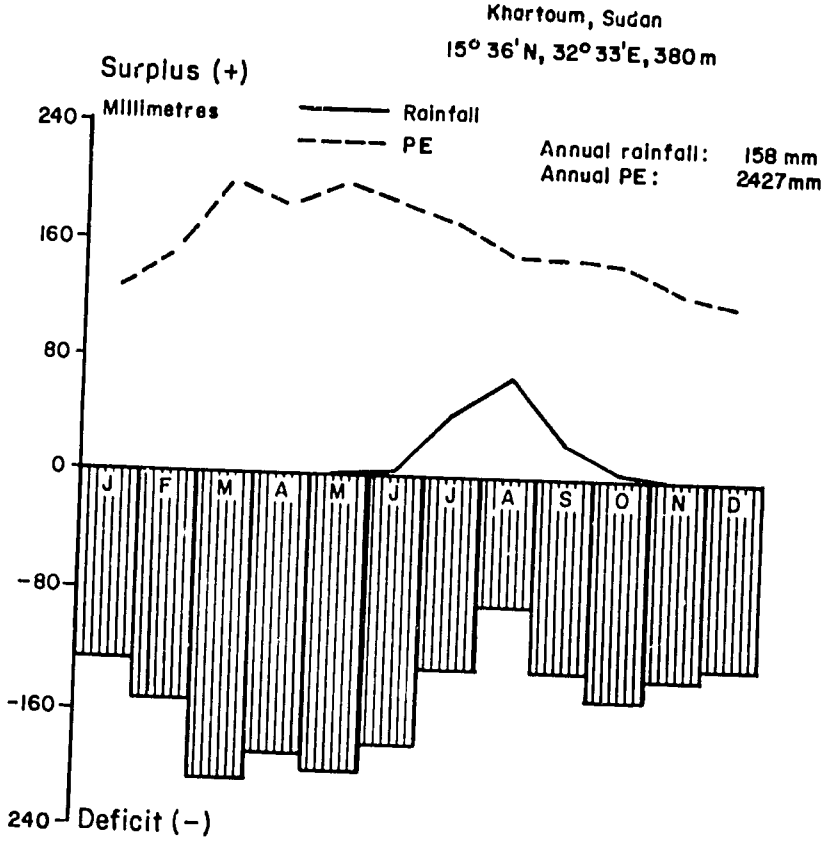
Only a small area of Vertisols and associated soils occur outside the semi-arid tropical zone (Figure 1).

Vertisols and vertic soils of the arid tropics in Africa

Niger, Chad, Sudan, Somalia, Zimbabwe and Botswana are some of the countries with large Vertisols areas in the arid tropical zone. An example of rainfall, potential evapotranspiration (PE), and water budget for this climatic zone is shown in Figure 5 for Khartoum, Sudan. Monthly PE exceeds the monthly rainfall in all months of the year. The annual rainfall of 158 mm meets only a small fraction (about 6%) of the annual PE needs.

Some 9 million ha, or about 20% of the Vertisol area, are in the arid tropics. In this climatic region the rainfall is scanty, and varies from 100 to 500 mm year^{-1}. The annual rainfall varies widely from year to year (coefficient of

Figure 5. Rainfall, potential evapotranspiration (PE) and water balance in an arid Vertisol location in tropical Africa.



variability (CV) is generally over 40%). The rainy season lasts not more than two months. Growing season for crops in dryland agriculture is usually 60 days or less. Such areas are agroecologically suited to livestock production, extensive farming or agroforestry systems. Crop

production is possible only with irrigation, but the costs to develop and maintain irrigated agriculture are high: water has to be transported over long distances from high rainfall areas, or ground water has to be developed. Further, irrigated Vertisols in the tropics are susceptible to waterlogging, and saline and alkaline conditions may develop. High input and high technology agriculture can sustain arable crop production in tropical Vertisols and vertic soils occuring in arid climates.

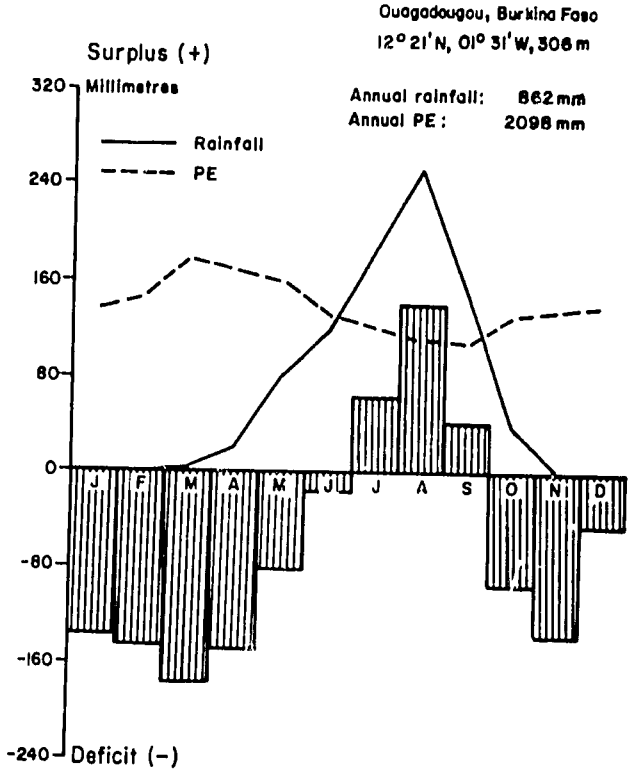
Vertisols and vertic soils of the dry semi-arid tropics in Africa

Vertisols occur in many countries in the dry semi-arid tropics (SAT), including Burkina Faso, Cote d'Ivoire, Ghana, Togo, Benin, Nigeria, Chad, Cameroon, Central African Republic, Sudan, Ethiopia, Kenya, Uganda, Tanzania, Zambia, Zimbabwe, Madagascar and Senegal. In such areas the rainfall is usually unimodal and there are 2.0-4.5 humid months when the monthly rainfall exceeds PE.

In the northern hemisphere, the rainy season generally extends from June through September. July, August and September show a positive water balance (Figure 6), but all the other months have a negative water balance.

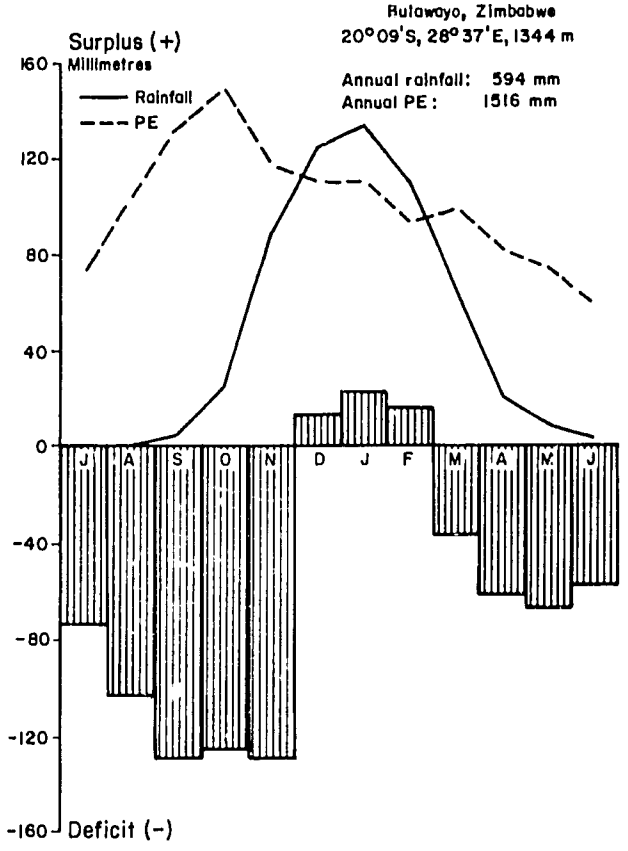
In the southern hemisphere, for example at Bulawayo, Zimbabwe, the rainy season is somewhat longer (Figure 7), and lasts from November through March. Some rain may be received in October, April, and May. The humid months with a positive water balance are usually limited to December, January and February.

Figure 6. Rainfall, potential evapotranspiration (PE) and water balance in a dry semi-arid location in tropical Africa (northern hemisphere).



The dry SAT climatic areas of Africa receive 500-1500 mm rainfall annually, but most areas receive 700-1200 mm. The rainfall CV is 20-30%, and the crop growing season is 60-200 days, but more generally 90-200 days. Such areas are suited for dryland agriculture, and one or two crops can be successfully grown most years. Some

Figure 7. Rainfall, potential evapotranspiration (PE) and water balance in a dry semi-arid Vertisol location in tropical Africa (southern hemisphere).



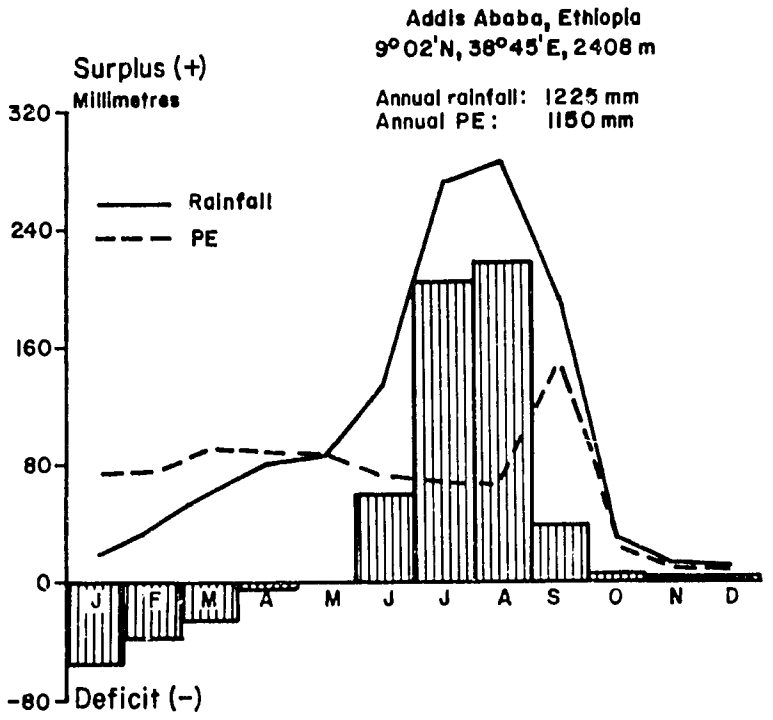
drainage is needed for 2-3 months of the year, and the cost to develop Vertisols and vertic soils for improved management technologies is relatively low. Some 55% or 24 million ha of the Vertisols and vertic soils of tropical Africa occur in dry SAT climates.

Vertisols and vertic soils of the dry/wet semi-arid tropics in Africa

Sudan, Ethiopia, Burundi and Zaire have Vertisol areas in the dry/wet SAT region where the annual rainfall generally exceeds 1000 mm, and there are 4.5-7.0 humid months in a year. A typical example of this climate class is Addis Ababa, Ethiopia, where the annual rainfall is 1225 mm and the annual PE is 1150 mm (Figure 8). Seven months, May through November/December have a positive water balance and can be termed as 'humid months' according to Troll's (1965) definition. April has a small water deficit. The cropping season is May through October for the rainy season crops, and October through February for the cool (cold) post-rainy season crops.

About 25% of the area (10 million ha) of the Vertisols and vertic soils of Africa occur in dry/wet SAT climates, where the annual rainfall is 1000-2000 mm. The variability of the annual rainfall is low (CV 15-20% or less). The rainy season lasts 5-9 months with 4.5-7.0 'humid' months, and the dryland agriculture growing season is 180-300 days or more. Two or more crops can be raised in an intercropping or sequential fashion. This agroclimatic region is suited for agropastoral crop production and for agroforestry. Drainage of excess water is a major constraint to increased crop production. Development of Vertisols for sustained agriculture is fairly expensive in this agroclimatic zone.

Figure 8. Rainfall, potential evapotranspiration (PE) and water balance in a dry/wet SAT Vertisol location in eastern Africa.



ROLE OF SOIL-CLIMATE INTERACTION STUDIES IN AGRICULTURAL DEVELOPMENT

Vertisols are heavy soils with more than 35% clay, are generally deep, and can hold considerable amounts of water (200-300 mm) in the soil profile. To understand the crop environment in the Vertisol regions of Africa, it is imperative that soil and climatic parameters be studied together. Growing

season length in the tropics is closely related to the soil-water balance. The water balance not only determines the plant-available water, but also characterises the runoff and deep drainage components which are the key determinants of soil erosion and nutrient losses.

From the study presented in this paper, it is estimated that out of a total of 43 million ha of tropical Vertisols and associated soils in Africa, some 34 million ha are located in the dry and dry/wet semi-arid climates. Large tracts of this potentially productive agricultural land are found in some 20 countries of the continent. ICRISAT has shown that consistently high crop yields are possible under dryland management of semi-arid tropical Vertisols. At its research centre at Patancheru in Andhra Pradesh, India ($17^{o}27'$ N latitude, annual rainfall 743 mm, PE 1801 mm) over the past 11 years, ICRISAT has harvested yields of over 3 t ha^{-1} of food crops in its Vertisols watersheds, in spite of the usual rainfall variability (CV 30%), through adoption of improved crop production and soil and water conservation methods (Kanwar and Virmani, 1986). ILCA has also recorded three- or four-fold production increases over traditional crop yields by adapting some elements of ICRISAT's improved Vertisols management system to Ethiopian highland Vertisols at Debre Zeit (Jutzi and Mesfin Abebe, 1986).

The tropical climates have a strongly seasonal rainfall character, which is associated with high intensity, high volume storms. The Vertisols under such climatic conditions are susceptible to severe soil erosion. Any improved farming systems suggested to replace the traditional Vertisol management system must incorporate some elements of soil conservation.

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CLASSIFICATION AND MANAGEMENT-RELATED PROPERTIES OF VERTISOLS

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ABSTRACT

Vertisols, as a class of soils, are easily recognised because of their clayey textures, dark colours, and special physical attributes. These soils are very productive if well managed, but present constraints to low-input agriculture.

The classification of Vertisols according to *Soil Taxonomy* is summarised, and management-related properties of the soils are discussed. The surface microvariability of Vertisols, reflected in their internal soil properties, imposes constraints on their use for agronomic research and agriculture in general. Temporal changes in physical attributes of these soils require accurate timing of agricultural practices for efficient use. As the unique mineralogy of Vertisols makes these soils very susceptible to erosion, soil management practices must be geared to reduce soil loss.

INTRODUCTION

In a landscape, soils typically form a continuum, with one soil grading almost imperceptibly into an adjoining soil. Because of the unique mineral and chemical composition of Vertisols, the transition to other soil types is usually clearly defined and can be easily delineated on a soil map.

Although their high natural fertility and positive response to management make Vertisols attractive for agriculture, some of their other properties impose critical limitations on low-input agriculture. The inherent limitations of Vertisols are largely a function of the moisture status of the soils and the narrow range of moisture conditions within which mechanical operations can be conducted. Farmers using traditional methods of agriculture are aware of the high risks associated with the use of these soils.

Even with high-input technologies, risk aversion is difficult since timing of tillage and of other farming operations is critical. As a consequence, the full agricultural potential of Vertisols has not yet been exploited in many parts of the world. This paper explains the classification of Vertisols according to *Soil Taxonomy* (Soil Survey Staff, 1975) and describes management practices that relate to the properties defined in the classification.

CLASSIFICATION

Despite their unique attributes, Vertisols were not recognized as a separate class of soils until the *7th Approximation* (predecessor of *Soil Taxonomy*) was published in 1960 (Soil Survey Staff, 1960). Because Vertisols frequently occupy basin and lower landscape positions, they were referred to as alluvial soils and were differentiated from other similar soils by their dark colours. Soon, terms such as black clays and cracking clays appeared in the scientific literature. Farmers living on or near such soils gave them vernacular names. For example, in south

India, farmers recognize at least four different kinds of Vertisols and use at least four names to connote their surface properties.

The mineral montmorillonite, which belongs to the smectite family of minerals, is responsible for the general attributes of the soils and their vertic properties. Identification of this mineral in the soil was made possible when X-ray diffraction techniques became commercially available in the early 1950s.

Since montmorillonite has the property of swelling and shrinking, the classification concept of Vertisols was based on their shrink-swell potential. This potential is a function of the clay content of the soil and the relative amounts of montmorillonite in the clay fraction. A soil layer 10 cm thick with this property is not a Vertisol. A minimum amount of clay, as well as a specific clay type, must be present in a minimum soil volume to provide the minimum expression. In addition, these soils crack during the dry season; the presence of cracks and the duration of cracking are also included in the definition of the Vertisols.

Each class in *Soil Taxonomy* is identified by a defining property or properties as well as by its position in the key. The definition of each taxon excludes or includes other properties which further define the soil. Although these default attributes are not spelled out in the definition, they are equally important for classification. Since Vertisols are recognized in the key to the orders after the Histosols, Spodosols and Oxisols, they cannot have the defining characteristics of these soils. Their placement in the key before the Aridisols, Ultisols, Mollisols, Alfisols,

Inceptisols and Entisols implies that these soils may have only subordinate vertic properties.

The definition of Vertisols in *Soil Taxonomy* is based on four obligatory properties. Vertisols:

1. do not have a lithic or paralithic contact, petrocalcic horizon, or duripan within 50 cm of the surface;

2. have 30% or more clay in all subhorizons to a depth of 50 cm or more after the soil has been mixed to a depth of 18 cm (for example, by ploughing);

3. have, at some time in most years unless irrigated or cultivated, open cracks at a depth of 50 cm that are at least 1 cm wide and extend upward to the surface or to the base of a plough layer or surface crust; and

4. have one or more of the following:

   a. gilgai;
   b. at some depth between 25 cm and 1 m, slickensides close enough to intersect;
   c. at some depth between 25 cm and 1 m, wedge-shaped natural structural aggregates that have their long axis tilted 10-60° from the horizontal.

Requirement (1) establishes the minimum soil volume, and the definition requires that there is no impermeable layer within 50 cm. Requirement (2) defines the minimum composition of the soil material. Requirements (3) and (4) define the minimum morphological expression of the vertic properties.

The suborder definitions are based on the length of time the cracks remain open or closed during the year, which requires field observations for several years. The four Vertisol suborders, which are defined precisely in *Soil Taxonomy*, are:

Xererts

These soils have a mean annual temperature of less than 22°C, a mean summer-winter temperature difference of less than 5°C, and are moistened during the winter when evapotranspiration is low. These are the Vertisols of the mediterranean areas, which occupy about 0.01% of the world's land surface.

Torrerts

These desert Vertisols have cracks that seldom close or only close about three times in 10 years. Information on these soils, which occupy about 0.001% of the world's land surface, is limited.

Uderts

The cracks in these Vertisols of the humid areas remain open less than 90 cumulative days in a year. It is estimated that they occupy about 0.03% of the world's land surface.

Usterts

These Vertisols of the semi-arid regions or the monsoonal climates occupy the largest area of all the suborders, 2.3 million km^2 or 1.8% of the world's land surface.

The great groups in each suborder are defined by the colour of the upper 30 cm of the soil,

particularly the moist Munsell chroma. The *chrom* great groups have a chroma of >1.5 and the *pell* great groups have a chroma of <1.5. When these definitions were created, it was assumed that the pell great groups were in general more poorly drained than the chrom great groups, but there are contradictory opinions on the relation between soil colour and drainage class (J. Comerma, CENIAP, Venezuela, 1986; personal communication). Nevertheless, there is a consensus to retain this separation at some categoric level, since it is a mappable criterion in the field.

The Vertisol subgroups identify intergrades to other soils or properties and are recognised in the taxon name by an adjective added to the great group name; for example, *Aquic* Chromudert, *Entic* Pellustert and *Chromic* Pelloxerert.

The control section for defining the family category is the section between 25 cm and 1 m depth. Criteria used in the family category are:

- particle-size class,
- mineralogy class,
- temperature class, and
- reaction class (if applicable).

Examples of family names are:

- fine, montmorillonitic, isothermic, Typic Pellustert,
- very-fine, mixed, thermic, Aquic Chromoxerert.

Since the classification of Vertisols in *Soil Taxonomy* was based on a limited number of soils, the International Committee on Vertisols (ICOMERT) is now working to improve the classification.

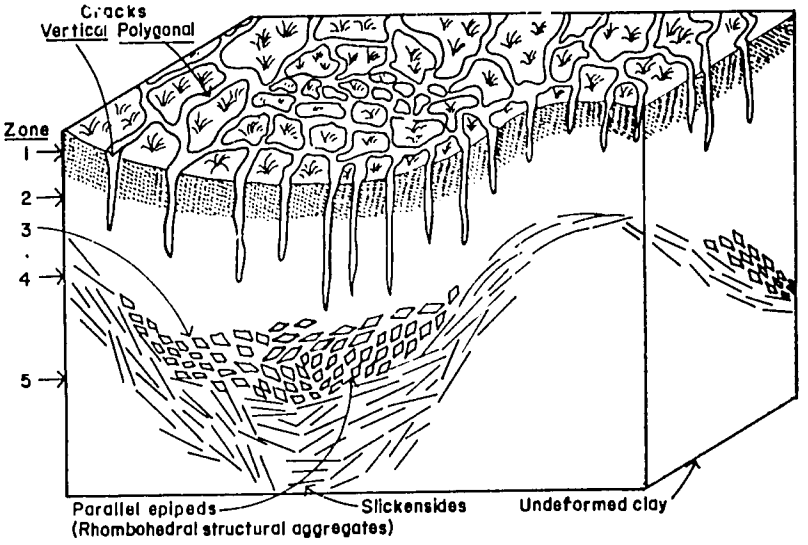
SOIL MORPHOLOGICAL PROPERTIES--MICROVARIABILITY

In order to appreciate the management-related properties of Vertisols, it is necessary to know not only the general soil properties, but also the properties in different parts of the soil. The situation is complicated for Vertisols by the temporal changes of soil properties in different parts of the soil as a function of depth, and the microvariability on the surface.

Figure 1 is a sketch of a pedon, showing gilgai microrelief on the surface and microrelief within the soil. It illustrates the short-range variability in profile characteristics. The amplitude of the gilgai may range from 1 to 10 m, making the soil surface topography highly variable. Cultivation may easily destroy the microrelief, but usually does not change the internal soil properties. Figure 1 illustrates how the surface topographic variations are mirror-imaged in the subsurface layers. Thus, even though the soil is levelled, the subsoil variations remain and will affect the water regime of the soil from point to point. If agronomists conducting field trials are unaware of these variations, they may obtain incorrect experimental results.

In a vertical section (Figure 2), the characteristic zonation of the soil profile is illustrated. The thickness of each zone is critical and partly controls the response to management techniques.

Figure 1. Cross-section of Gilgai microrelief.

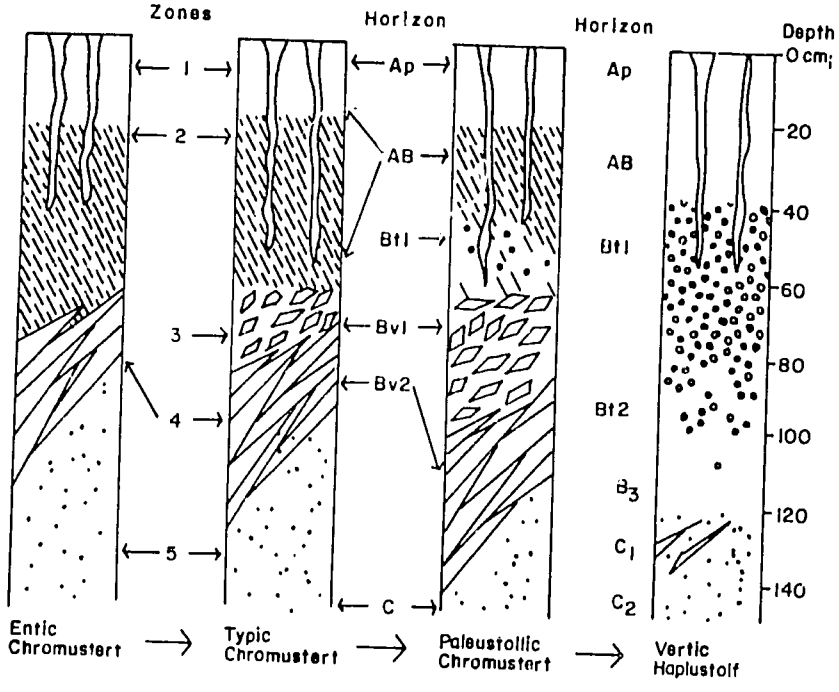


MANAGEMENT-RELATED CONSTRAINTS

Surface structure and consistency

Vertisols are extremely hard when they are dry, but when wet they become extremely plastic, to almost a liquid state, with a very low bearing capacity. Their structure and consistency are generally a direct function of the ratio of clay to sand and the mineral composition of the clay. Vertisols with more than 50% clay and a dominance of montmorillonite have poor rheological characteristics, since montmorillonite has a high

Figure 2. Microphological differentiation of a sequence of soils (generalised).



surface charge and a low Zero Point of Net Charge (ZPNC). At the normal pH of Vertisols (6.0-7.5), the soil is at least three units above the ZPNC, and if water is available, the mineral will be in a dispersed state.

In this situation, interparticle binding forces are minimal and aggregates rupture fast. On drying, the tissue-paper-like sheets of montmorillonite pack against each other to form a very compact, low porosity aggregate. The bulk density (Table 1) changes from about 1.3 g cm^{-3} at 0.03 MPa tension to more than 1.8 g cm^{-3} at oven-dry conditions. Few roots can penetrate a medium

with a bulk density of more than 1.6 g cm^{-3}, and the shrinking force also tends to crush any roots. Tillage, unless high energy machinery is used, is extremely difficult in the dry state. In the moist state, the low bearing capacity and the plastic nature of the material are deterrents. Thus, tillage can only be conducted at a moisture tension close to, but not at, field capacity.

There is no easy solution to this soil surface problem. One technique that mitigates the problem is the surface addition of mulch or non-Vertisol soils, preferably sandy materials. If a nearby source is available, farmers who use traditional cultivation methods could be encouraged to add other soil to the field annually. In south India, farmers add tank silt to Vertisols to build up the surface tilth. In Kenya, trees are planted in holes filled with red Alfisols.

Another technique practised in many countries is to prepare raised broadbeds, some of which are as high as 0.5 m and about 1 m wide. The beds are initially composed of very rough and very hard clods ranging in size from 1 to 10 cm or more. With alternate wetting and drying, the clods break down to a fine tilth. The wetting and drying could be induced or accelerated by controlled sprinkler irrigation or left to the initial rain showers. Once the surface tilth is obtained, the seedbed is smoothed and planted in one operation without additional manipulation. After germination, furrow irrigation provides further moisture. This technology is based directly on the properties of the montmorillonitic clay.

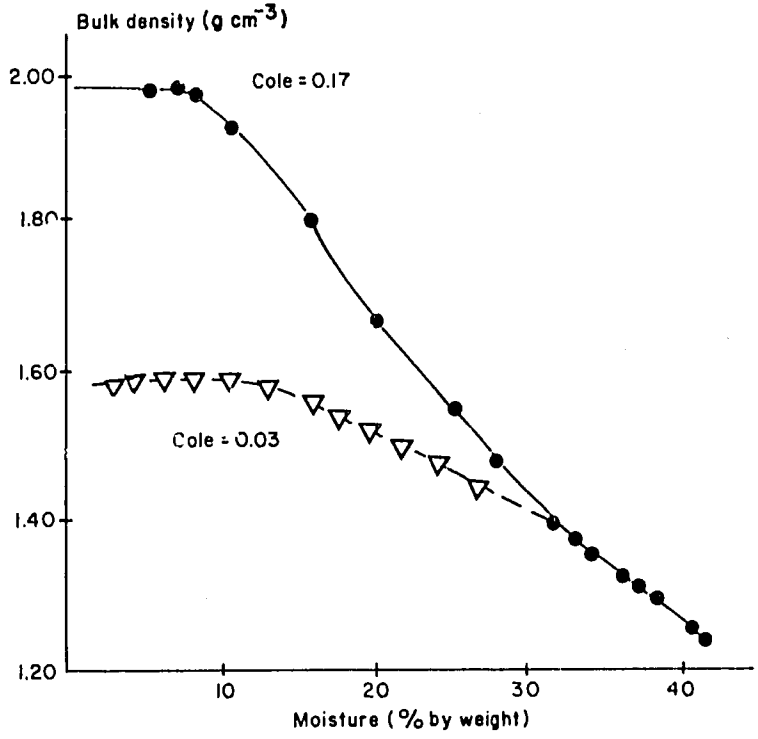
Grossman et al (1985) developed a relationship to estimate the bulk density of

Table 1. Coefficient of linear extensibility (COLE) and bulk densities of selected Vertisols.

Classification	Depth (cm)	COLE ($cm\ cm^{-1}$)	Bulk density ($g\ cm^{-3}$)	
			0.03 MPa	oven-dry
Udic Chromustert	0- 8	0.106	1.34	1.82
	36-76	0.115	1.32	1.84
Entic Chromoxerert	0-13	0.060	1.10	1.83
	13-38	0.174	1.14	1.85
Udic Pellustert	0- 5	0.093	1.14	1.49
	5-15	0.091	1.23	1.60
	15-41	0.126	1.23	1.83
Typic Torrert	5-25	0.124	1.23	1.75
	40-60	0.117	1.12	1.56

Vertisols at any specific moisture content. Figure 3 illustrates this relationship for two situations: one where the soil has a Coefficient of Linear Extensibility (COLE) of 0.03 $cm\ cm^{-1}$, and the other where COLE is 0.17 $cm\ cm^{-1}$. Both situations reach water contents below which shrinkage is near zero; the soil with the lower COLE reaches the equilibrium bulk density at a higher water content. At this bulk density, there is no further shrinkage. The equilibrium bulk density may be used to characterise the soils.

Figure 3. Bulk density and moisture relationships for Vertisols at two COLE values.



Surface cracking

Shrinking of the drying soil mass induces cracks which have a polygonal appearance. The cracks in Vertisols have been grouped into three sets (Grossman et al, 1985):

- Vertically oriented cracks which outline large blocks or prisms at the upper part of the soil. The cracks are wide, about 5-10 mm, and become progressively deeper as the soil dries out.

- Cracks which form angular or blocky elements at the soil surface. These form at high water tensions, perhaps close to the wilting point.

- Cracks which form deeper in the soil and are related to the internal pedoturbation associated with the slickensides.

The first two sets of cracks exhibit properties that are important in land use and management.

Vertisols with a granular surface soil mulch (the first set) tend to have lower bulk densities, perhaps due to a slightly higher organic matter content and to the space between the granules. Soils with angular surface structure (the second set) are easier to till and roots can permeate the spaces and move deeper. In addition, the filled crack spaces are probably the most likely areas for roots to establish during the next season because water flows easily through these areas (Grossman et al, 1985).

Cracks have several indirect effects on crop performance. Because the rhizosphere is dehydrated last, the cracks normally form away from the stubble of the previous crop which sits at the centre of the polygon. In this case, dislodging of the plant is not a problem, but when the rhizosphere also dries out, soil shrinkage could strangle or shred crop roots.

Cracks also retard surface wetting from any off-season rains. At the beginning of the rainy season, much of the water is not available to the plants since the water is rapidly evacuated by the void system. During the initial rain showers, the subsoil below the zone of the cracks is moistened.

Successive rains moisten the top few centimetres of the soil, causing it to swell and seal the surface. Subsequent rains cause ponding, making tillage difficult and initiating erosion.

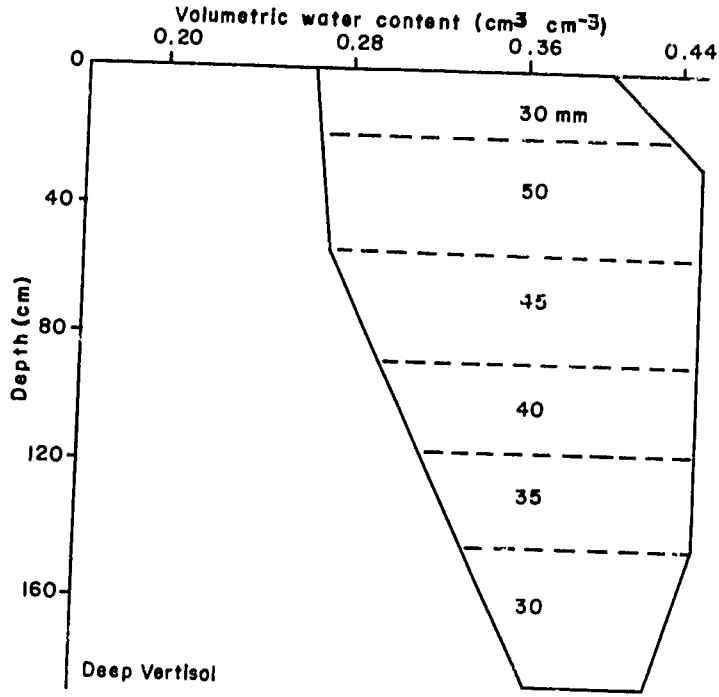
Moisture control

Moisture conservation during the dry season and removal of excess water during the wet season are crucial management practices for Vertisols, which differentiate them from most other soils. As a rule, Vertisols are clayey, and due to the montmorillonitic mineralogy, have a high water-holding capacity (Figure 4), resulting in a very low hydraulic conductivity and a low infiltration rates.

The high amount of available water illustrated in Figure 4 is deceptive, since not all the water is available to the plant. The water retention difference calculated from water retained at 0.03 MPa and 1.5 MPa tensions indicates the potential of the soil. Due to shrinkage and cracking, the water is not readily available to the roots even though there is moisture in the peds.

Conserving the soil moisture while inducing more uniform soil wetting and maintaining a suitable surface tilth requires deep tillage prior to the onset of the rains. Mulching with organic residues and addition of non-Vertisol soils will aid this process considerably. Raised broadbeds have similar advantages. If the precipitation is characterised by high-intensity, short-duration storms, a network of contoured ditches would help channel run-off and keep much of the surface water from causing erosion.

Figure 4. Depth functions of available moisture.



Source: Russell (1978).

At the end of the rainy season, the challenge is to reduce evaportranspiration losses and conserve soil moisture, so that a succeeding crop can be grown from the stored moisture. Surface soil temperatures of the top few centimeters may reach 60°C in the dry season. Mulching, in combination with deep tilth, reduces evaporative losses and surface soil termperatures.

Matching crops to these soil conditions is also a partial solution, but socio-economic considerations do not always make this feasible.

Moisture management on single plots of land is difficult and in some cases impossible. A technically designed drainage and irrigation system for the whole catchment is beneficial and can increase moisture control.

Soil loss

The onset of the rains causes tremendous soil loss through erosion, but subsequent rains are less destructive. Depending on the slope, several management techniques are available and are well documented, particularly in publications of the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) (Kanwar et al, 1982). The propensity to erode is another feature of Vertisols and is related to the high charge and low ZPNC minerals in the colloid fraction.

CONCLUSIONS

The Vertisol definition stresses cracking, pedoturbation, and movement within the soil mass (slickensides). It should be noted, however, that from the management viewpoint, other characteristics appear to be more important: hardness when dry, plasticity when wet, a very low infiltration rate when the surface soil is sealed, very slow saturated hydraulic conductivity, compaction as a result of swelling, available water capacity, presence or absence of surface mulch, sodium saturation, possible salt content, rooting volume, and occurrence of permeable materials in the subsoil.

It is imperative that these characteristics be taken into account, if not in soil classification, then at least for technical

assessments to evaluate the potential of these soils and determine management practices. In the development stages of *Soil Taxonomy*, a distinction was made at the great group level between "grumic" Vertisols that develop a loose, porous, surface mulch of discrete, very hard aggregates, and "mazic" Vertisols that, on the contrary, develop a platy or massive surface crust with uncoated silt or sand grains which persist after drying.

Subsequently, this differentiation was abandoned because it seemed to be influenced more by management and to vary from year to year. In humid areas, however, the crusting phenomenon seems to be frequent and is of importance for the soil water regime: less water intake, more hazards of waterlogging, difficult tillage, and poor seedbed conditions. The relationships between crusting in Vertisols and other soil-forming factors point to an intergrading toward Planosols (Dudal, 1973). In fact, where these soils are not ploughed, a thin albic horizon overlying heavy clay may be found.

While Vertisols make up a relatively homogeneous order in a taxonomic sense, it should be stressed that they show diverse characteristics that are important to their wetting, drying, and suitability for plant growth. The precipitation effectiveness on Vertisols is strongly influenced by water entry, water retention and water removal (when it occurs in excess of uptake capacity). This third factor is of particular importance in subhumid and humid zones for tillage operations and soil aeration during the growing period.

Management practices have been designed to overcome the physical problems of Vertisols. Since subsurface drainage is not feasible because

permeability is slow, special attention has been given to surface drainage. Cambered beds, ridges, furrows, bunding, and broadbanks have been applied in Ghana, India, Indonesia, Trinidad, USA and Venezuela.

For the semi-arid tropics, ICRISAT (Kanwar et al, 1982) has developed a technology which allows Vertisols to be cropped in both the dry and wet seasons. The technology is conditioned by a certain soil depth and quantity of stored available water that covers the moisture requirements of the dry-season crop. Dependable rainfall is needed for seeding when the soil is still dry before the onset of the rains. Elements of this technology also might be applicable in more humid areas where tillage in wet conditions offers particular difficulties. Soil depth and water storage capacity are major factors in determining which components of a technology can be transferred.

Vertisols in subhumid and humid areas have been put to a wide range of uses. A major part is still used as pasture because tillage constraints have prevented these soils from being cultivated in a number of developing countries. Under rainfed conditions, and depending on the temperature regime, Vertisols produce wheat, maize, sorghum, soybeans, cassava, groundnuts and pigeonpeas. Under irrigation, Vertisols grow rice, sugarcane and cotton. Irrigation has to be adjusted to an initially fast infiltration through cracks, and a subsequent slow and rather shallow uptake of water when the cracks are closed.

Weed control is difficult because soil plasticity makes entering fields difficult when these soils are wet. In humid zones, Vertisols

also are used for forestry in Argentina, Ghana, Indonesia, USA and other countries. Large areas of Vertisols are unused and offer a potential to increase agricultural production. While management difficulties of Vertisols deserve attention, their favourable features should be given equal emphasis: their high cation exchange capacity, the high base saturation in a majority of these soils, the high waterholding capacity, a favourable seedbed in the "grumic" soils, a certain stable fertility, and low salinity hazards because of the self-mulching process. With appropriate technologies, additional Vertisol areas can be cultivated, and those already in use can produce higher yields.

The great variability of Vertisols and the wide range of climatic conditions under which they occur should be fully considered when technologies are to be transferred. In addition to technical aspects, socioeconomic conditions should be taken into account. Farm size, cropping systems, labour availability, draught animal power, marketing facilities, and food habits may determine the success or failure of a technical innovation.

Proper management and timing of cultivation practices are critical factors in the efficient use of Vertisols. The shrink-swell characteristics of montmorillonites, which dominate the mineralogy of Vertisols, give the soil special attributes which impose constraints to low-input agriculture. With high energy and high inputs, Vertisols are perhaps the more productive soils. However, the challenge is to develop low-input technologies for Vertisols, such as those of ILCA and ICRISAT, that will enable small farmers in developing countries to achieve sustainable agriculture.

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THE SUB-SAHARAN VERTISOLS--AN OVERVIEW

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ABSTRACT

Vertisols are widely distributed in the subhumid and semi-arid regions of Africa, but are dominant soils in only small parts of their range. Their main features are highly characteristic, but there are great chemical and physical differences among them, some of which are described. These characteristics and differences are important for livestock management because they provide opportunities to increase production, but may constrain the introduction of fodder species, grazing systems and animal traction. To make best use of these dark clays, animal production systems should take account of the other soils with which they are associated.

RESOURCE ASSESSMENT

AGROCLIMATOLOGY

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AGROECOLOGICAL ASSESSMENT OF ETHIOPIAN VERTISOLS

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ABSTRACT

A simple agroecological zonation system developed by the AACM (Australian Agricultural Consulting and Management) Agricultural Advisory Team in the Agricultural Development Department of the Ethiopian Ministry of Agriculture has been used to define the distribution of Vertisols in Ethiopia. Vertisols are found in all but two of the 25 agroecological zones (AEZ). In addition, although Vertisols occur in all eight administrative zones, they predominate (>25% of the arable area) in only three, the central, northwest and southeast zones. Hence, programmes to support adaptive research and extension of improved Vertisol management practices should be centred on these AEZs and administrative zones.

If appropriate surface/subsurface drainage measures were implemented on 25-50% of the Vertisol areas in the main AEZs, then a conservative estimate of potential food grain production would be about 12 million t. This figure highlights the critical need to make better use of these soils in a country which is striving for food self-sufficiency.

INTRODUCTION

The AACM (Australian Agricultural Consulting and Management) Agricultural Advisory Team was attached to the Ethiopian Agricultural Development Department (ADD) of the Ministry of Agriculture in late 1984. The team reviewed past trials and demonstrations conducted by the ADD in order to formulate a new trials programme of improved crop production technologies designed for the peasant sector. One prerequisite for this programme was to develop a suitable agroclimatic zonation system so that past data could be aggregated on a rational basis to provide a framework for selecting new trial sites. The prime requirement was for a simple system which could be readily understood by field officers and be useful to national and regional planning programmes.

The agroecological approach has been used to formulate the framework for a National Field Trials Programme which has been implemented by the ADD. This programme locates adaptive trial sites in the major agroecological zones (AEZ)/soil units of each region so that representative fertilizer and agronomic practices can be developed for extension to peasant farmers.

This paper concentrates on the assessment of Vertisol areas found in the various AEZs and the implications for trials and agricultural production.

METHODS

Several agroecological type zonation systems have been utilised in Ethiopia in the past. The Ministry of Agriculture grouped agricultural areas

according to loosely defined altitude classes (high, medium and low) and soil colour (red or black). An equally broad approach based on three land use classes (high potential cereal cropping, high potential perennial cropping and low potential cropping) was adopted by the Ethiopian Highland Reclamation Study (Cloutier, 1984) and by ILCA (Amare Getahun, 1978; Gryseels and Anderson, 1983). Neither of these systems is sufficiently detailed for planning research, development and extension programmes.

A more realistic approach, based on a combination of altitude, rainfall and soil colour was proposed by Pinto (1984), but it contained too many classes to be practical at a field level. However, the concept was very useful and a similar but more refined approach has been developed by the Land Use Planning and Regulatory Department (LUPRD) of the Ministry of Agriculture for the preparation of land resources maps (Hendrickson et al, 1984). In this approach the major factors considered in assessing land resources are:

- length of growing period (LGP)--a function of rainfall, evapotranspiration, soil water storing capacity and meteorological hazards. The calculation of LGP has been developed by FAO (1978) and although it cannot account for local conditions like runoff during high intensity rains, soil water augmentation from subsurface drainage, variable soil water storage characteristics, etc, it remains a useful concept at regional and national levels.

- thermal zone (TZ)--a function of temperatures prevailing during the growing season and closely related to altitude in Ethiopia.

- landscape units--these combine aspects of the prevailing landform, distribution of slope classes and the major soil types.

Unfortunately the LUPRD land resource classification is based on relatively scant meteorological information and on satellite imagery which has not been fully verified on the ground. However, it remains the most complete and up to date information available for the whole country.

Consequently the land resource maps and supporting documents have been used to define a simple system of agroecological zonation. The length of the growing period and thermal zone were chosen as the basic climatic factors to define the main AEZs. Five classes of LGP and five TZ were selected to define 25 possible AEZs representative of the whole country:

Length of growing period			Thermal zone		
LI	-	<90 days	T1	-	<500 metres
LII	-	91-150 days	T2	-	500-1300 metres
LIII	-	151-210 days	T3	-	1300-2000 metres
LIV	-	211-270 days	T4	-	2000-3000 metres
LV	-	>270 days	T5	-	>3000 metres

Within each AEZ the areas of the various landscape units have been measured, and from these data the areas of the individual soil classes and slope classes have been estimated. From an aggregation of these data, these areas have been calculated:

- gross area--total land area within a given AEZ.

- arable area--area remaining after deduction of the areas of Lithosols, lithic phases, swamps, lakes and land with slopes of >30%.

- weighted area--area calculated by applying a population density factor to highlight those locations already intensively developed for agriculture. (Weighted area (WA) is calculated from arable area (AA) and population density per km^2 (PD) by WA = AA x PD/200.)

- soil classes--total area occupied by given soil classes in each AEZ.

- slope classes--the areas located within each of the four main slope classes (0-8, 8-16, 16-30 and >30%) in each AEZ.

The full details of the system and the results obtained on a regional and national basis have been summarised (AACM, 1987).

RESULTS AND DISCUSSION

Vertisols occupy almost 12 million ha, or nearly 19% of the arable area of Ethiopia and 22% of the weighted area currently being intensively farmed. As the third most common soils after Nitosols and Cambisols, they clearly represent a major soil resource in the country which is vastly underexploited due to management difficulties using the traditional cultivation practices.

Zonal distribution of soil classes

Vertisols occupy more than 10% of the soils in all administrative zones of the country, but are the

most important component (>25%) in the central, northwest and southeast administrative zones (Table 1). Hence, the development of improved management practices for Vertisols will have important implications for increasing crop production in all administrative zones.

Table 1. Areas (expressed in million ha) of the major soil classes in the administrative zones in Ethiopia.

Soil class	Administrative zone[a]							
	CEN	NW	W	S	SE	E	NE	N
Nitosols	0.8	3.7	8.1	1.2	0.4	0.1	0.1	-
Cambisols	1.3	0.8	0.5	3.1	1.8	1.2	1.0	2.3
Vertisols	1.6	2.7	2.0	1.6	1.6	1.2	0.3	0.9
Luvisols	0.4	2.3	0.1	1.3	0.7	0.5	0.1	0.6
Fluvisols	0.2	0.1	1.6	1.4	0.2	1.0	0.2	1.3
Xerosols	-	-	-	0.9	0.9	2.5	-	1.1
Solonchaks	0.1	-	-	0.1	-	-	-	-
Acrisols	-	0.4	1.3	0.1	-	-	-	-
Others	0.2	0.1	0.4	-	0.3	1.3	0.1	-
Total	4.6	10.1	14.0	9.7	6.1	9.0	2.9	7.2
% Vertisol	35	27	14	16	26	13	10	13

a. Zones: CEN - Central (Shewa)
NW - Northwest (Gojam & Gonder)
W - West (Kefa, Ilubabor & Wellega)
S - South (Sidamo & Gamo Gofa)
SE - Southeast (Arsi & Bale)
E - East (Harerge)
NE - Northeast (Wello)
N - North (Eritrea & Tigray)

Agroecological distribution of Vertisols

National arable areas

Vertisols occur in all but two of the AEZs in Ethiopia (Table 2), but tend to be concentrated in four main AEZs:

LII T2	1.89 million ha	LIV T3	1.59 million ha
LIV T4	1.31 million ha	LIII T3	1.28 million ha

These four AEZs contain more than 50% of the total area of Vertisols in the country.

Although these four AEZs are important on the basis of Vertisol area, these soils comprise only 20-40% of the total arable soils in each AEZ (Table 3). Vertisols assume much greater relative significance in the AEZs LII T1, LIII T1, LIV T1 and LV T1, where they occupy 56-79% of the arable area. The total area of these AEZs is relatively small, but proper Vertisol management will be critical to enhanced agricultural production.

Zonal arable areas

When the distribution of Vertisol occurrence in the AEZs of the administrative zones is considered (Table 4), the relative importance of the AEZs containing large areas of Vertisols differs (Table 5).

These are the AEZs which must be considered in each region when assessing the type of improved Vertisol management practices required for future development.

Table 2. Potential arable areas (expressed in thousand ha) of Vertisols in the different agroecological zones.

Thermal zone (TZ)[b]	Length of growing period (LGP)[a]					Total
	LI	LII	LIII	LIV	LV	
T1	230	170	630	690	40	1760
T2	704	1888	613	107	119	3431
T3	182	511	1279	1588	461	4021
T4	-	77	602	1310	634	2623
T5	-	36	15	47	3	101
Total	1116	2682	3139	3742	1257	11936

a. LI - < 90 days
LII - 91 - 150 days
LIII - 151 - 210 days
LIV - 211 - 270 days
LV - > 270 days

b. T1 - < 500 metres
T2 - 500 - 1300 metres
T3 - 1300 - 2000 metres
T4 - 2000 - 3000 metres
T5 - > 3000 metres

Table 3. Vertisols as a percentage of the total arable area in the different agroecological zones.

Thermal zone (TZ)b	Length of growing period (LGP)[a]					Mean
	LI	LII	LIII	LIV	LV	
T1	5.6	63.2	79.4	55.8	62.5	27.2
T2	5.7	29.6	15.5	3.8	8.1	12.7
T3	6.5	12.4	30.0	20.3	10.9	18.7
T4	-	13.3	35.0	41.9	25.3	32.7
T5	-	40.0	4.2	19.9	1.0	12.6
Mean	6.3	23.5	29.0	24.6	14.6	18.7

a. and b. Refer to Table 2 footnotes.

Table 4. Arable area (expressed in thousand ha) of Vertisols in the different agroecological zones.

AEZ[b]		Administrative zone[a]							
		CEN	NW	W	S	SE	E	NE	N
LI	T1				190	40			
	T2				595	26	59	3	21
	T3				46		136		
	T4								
	T5								
LII	T1								108
	T2	1	911	7	71	332	1	5	560
	T3				128	56	120	70	137
	T4							43	34
	T5							36	
LIII	T1			603					
	T2		545	30			34		4
	T3	169	385		85	107	481	52	
	T4	432				58		112	
	T5	11						4	
LIV	T1			653					
	T2			107					
	T3	412	353	319	84	47	373		
	T4	466	478	50		316			
	T5	47							
LV	T1								
	T2			12	107	46			
	T3	27		193	195				
	T4	17		8	68	541			
	T5					3			
Total		1582	2672	1982	1569	1572	1204	325	864

a. Refer to Table 1 footnote.
b. Refer to Table 2 footnotes.

Table 5. Relative importance of the agroecological zones containing large areas of Vertisols.

Administrative zones	Agroecological zones[a]		Percent of Vertisol area in administrative zone
Central	LIV T4	LIII T4	57
Northwest	LII T2	LIII T2	54
West	LIV T1	LIII T1	63
South	LI T2	LV T3	50
Southeast	LV T4	LII T2	56
East	LIII T3	LIV T4	71
Northeast	LIII T4	LII T3	56
North	LII T2		65

a. Refer to Table 2 footnotes.

National weighted areas

Population weighting of the Vertisol areas causes a slight change in emphasis of the respective AEZs (Table 6). In this case the four major AEZs are:

LIV T3 0.57 million ha LIV T4 0.57 million ha

LIII T3 0.30 million ha LIII T4 0.25 million ha

which account for over 68% of the total weighted Vertisol area.

These AEZs represent the areas where most farmers are already attempting to farm Vertisols. Hence, national research and development programmes should concentrate initially on the above four AEZs in order to achieve the maximum immediate benefit from improved Vertisol management and farming practices.

Table 6. Weighted area (expressed in thousand ha) of Vertisols in the different agroecological zones.

Thermal zone (TZ)[b]	Length of growing period (LGP)[a]					Total
	LI	LII	LIII	LIV	LV	
T1	-	7	8	10	-	25
T2	15	165	62	11	12	265
T3	12	72	303	573	183	1143
T4	-	25	253	567	165	1010
T5	-	13	7	-	-	20
Total	27	282	633	1161	360	2463

a and b. Refer to Table 2 footnotes.

Zonal weighted areas

The distribution of the weighted Vertisol areas in the individual zones (Tables 7 and 8) shows only relatively minor divergence from the AEZs identified on a national basis.

Only in the north zone is there a need to address AEZs with shorter growing periods and somewhat lower altitudes.

Table 7. Weighted area (expressed in thousand ha) of Vertisols in the different agroecological zones.

AEZ[b]		Administrative zone[a]							
		CEN	NW	W	S	SE	E	NE	N
LI	T1								
	T2				10	1	2	3	1
	T3				3		9		
	T4								
	T5								
LII	T1								
	T2		101		5	10			7
	T3				12		15	1	48
	T4							18	27
	T5							13	12
LIII	T1			8				13	
	T2		51	3			8		
	T3	69	83		35	22	75	18	1
	T4	179				22	2	50	
	T5	5						2	
LIV	T1			10					
	T2			11					
	T3	226	114	69	68	11	85		
	T4	235	212	12		108			
	T5								
LV	T1								
	T2			2	10				
	T3	30		49	97	6	1		
	T4	22		3	33	106	1		
	T5								
Total		766	561	167	273	286	198	118	96

a. Refer to Table 1 footnote.
b. Refer to Table 2 footnotes.

Table 8. Distribution of weighted Vertisol areas in the individual agroecological zones.

Administrative zones[a]	Agroecological zones		Percentage of Vertisol area in administrative zone
Central	LIV T4	LIV T3	60
Northwest	LIV T4	LIV T3	58
West	LIV T3	LV T3	71
South	LV T3	LIV T3	60
Southeast	LV T4	LIV T4	75
East	LIV T3	LIII T3	81
Northeast	LIII T4	LIII T3	58
North	LII T2	LII T3	78

a. Refer to Table 1 footnote.
b. Refer to Table 2 footnotes.

Thus a national programme to develop and promote improved surface drainage, revised land preparation patterns, more productive cropping patterns, better conservation and erosion control practices and other related soil, water and crop management procedures should be concentrated in four target AEZs (LIV T3, LIV T4, LIII T3 and LIII T4), and three administrative zones (central, northwest and southeast) for maximum immediate impact.

Vertisol-related cropping systems

In order to simplify the types of farming and cropping systems which should be considered when promoting the development of Vertisols in Ethiopia, the broad grouping of relevant agroecological zones shown in Table 9 is useful.

The longer growing period/higher altitude grouping includes the AEZs LIV T3/T4 and LIII T3/T4. It includes 50% of the total area of Vertisols and regions of high population density. Within this grouping, farming systems are based on rainfed production. The major objective is to improve soil surface drainage in order to avoid waterlogging and better exploit the longer growing season.

The second largest grouping, short growing period/low altitude, includes the AEZs LI T1, LI T2, LII T1 and LII T2. This group includes 25% of the Vertisol area, but is located in regions of low population density. In general, most of this group is currently suited to grazing, but with proper surface and subsurface drainage, irrigated cropping is possible, particularly large-scale industrial or import substituting crops, since most Vertisols are associated with the flood plains of the larger rivers.

The third grouping, longer growing periods/low altitude, includes AEZs LIII to LV at T1 and T2, and represents 18% of the Vertisol area. Rainfed cropping predominates in this zone and, with proper soil and water management, a broad range of crops can be grown.

The final group, short growing period/higher altitude, is relatively minor and represents only

Table 9. Grouping of the agroecological zones (AEZ) to simplify the selection of suitable cropping patterns for research and development.

Group	Area (ha x 1000)	Agroecological condition	Farming system/ crops[a]
I	5939	Longer growing period (151- >270 days) Higher altitude (1300- >3000 m)	Rainfed cropping (maize, wheat, barley, teff, oats, haricot, linseed, *noug*, rape, faba)
II	2992	Short growing period (<150 days) Low altitude (<1300 m)	Grazing and irrigated cropping (cotton, kenaf, sugar-cane, sesame, rice, sorghum, maize)
III	2199	Longer growing period (151- >270 days) Low altitude (<1300 m)	Rainfed cropping (maize, sorghum, sesame, cotton, sugar-cane, sunflower)
IV	806	Short growing period (<150 days Higher altitude (1300- >3000 m)	Grazing and irrigated cropping (vegetables, spices, fruit trees, flowers, maize)

a. Cropping assumes that improved surface drainage and land shaping can be achieved.

7% of the total Vertisol area. It includes AEZs with LGPs of LI and LII and thermal zones T3, T4 and T5. These highland valley bottoms are currently mainly used for grazing, but if surface drainage could be improved in the T3 and T4 areas, these could be readily used for the irrigated production of vegetables and other horticultural crops.

In general terms, if 25% of Groups II and IV could be irrigated and 50% of Groups I and III could be brought under improved surface drainage, the following potential food grain production levels could be postulated for Ethiopian Vertisols.

Group I	6 million t (at 2 t ha^{-1})
Group II	3 million t (at 4 t ha^{-1})
Group III	2 million t (at 2 t ha^{-1})
Group IV	0.8 million t (at 4 t ha^{-1})
Total	11.8 million t

Hence, the possible benefits from improving the management of Vertisols in Ethiopia are enormous in a country aiming at food self-sufficiency.

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ASSESSING THE AGROCLIMATIC POTENTIAL OF VERTISOLS

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ABSTRACT

The agroclimatic potential of a soil can be expressed as the net total biomass production grown under a prevailing radiation and moisture regime. The period in which biomass production is possible can be estimated by growing period analysis, and the rate of biomass production by a summary radiation model. While the radiation regime can be assumed to be uniform, the moisture regime can, under the same climatic conditions, differ markedly according to soil type.

It is argued that Vertisols have a lower agroclimatic potential than other soil types because of their limited growing period. The single most important factor that reduces the available growing period below the estimates from climatic data is the waterlogging hazard in areas with concentrated surplus of rainfall over potential evapotranspiration. Improved surface drainage can prevent or alleviate waterlogging but cannot fully recover the growing period that would be available on other soils.

A second factor that reduces the available growing period is the need to sacrifice part of it to land preparation, which might not be possible at other times of the year because of inadequate power or inappropriate soil moisture.

Growing period losses are closely linked to the typical shrink-swell cycles of Vertisols. Deep and wide cracking in dry Vertisols leads to inverse moisture gradients at the beginning of the growing period, which bring topsoil moisture levels in the available range at a later time than in other soils. This necessitates delayed planting and is a limitation of particular relevance in areas with short growing periods.

A quantitative estimate of growing period losses by factors that delay plantings can be made by a comparing potential growing period from the climatic data with the growing periods available for different planting dates.

AGROCLIMATIC DATA ANALYSIS OF SELECTED LOCATIONS IN THE VERTISOLS REGIONS OF ETHIOPIA

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ABSTRACT

Vertisol areas of the Ethiopian highlands constitute about 12% of Ethiopia's total area. Cropped Vertisol areas account for 24% of all cropped land in the Ethiopian highlands. Important crops in these areas are teff, durum wheat, chickpea, lentil, linseed and barley. Crop yields are low but stable. The main reasons for low agricultural production are variability of rainfall, poor management of on-farm water resources, inadequate conservation of soil-water in the rainy season and the adoption of low-input, low-risk technologies.

Data from eight locations in Ethiopia were analysed to evaluate agroclimatic, agrobiological and other environmental variables affecting agriculture, to provide guidelines for obtaining higher, sustained crop production. The SORGF model was used to demonstrate the applications of crop growth simulation.

PHYSICAL PROPERTIES

PHYSICAL PROPERTIES OF ETHIOPIAN VERTISOLS

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ABSTRACT

Vertisols are important to Ethiopian agriculture. They account for 24% of all highland soils that are cropped, but their high yield potential has not been realised. Production constraints are related to the physical properties of Vertisols and their moisture regime. The heavy texture and expanding clay minerals narrow the range between drought stress and excess moisture. Workability of these soils is hampered by their stickiness when wet and hardness when dry, and waterlogging and erosion greatly affect crop production. These soils are important to agricultural production; research priority should be given to realising their production potential.

INTRODUCTION

Vertisols are dark-coloured clays which develop cracks when expanding and contracting with changes in moisture content. They are geographically widespread, but it is only in the past decade or two that they have received scientific attention. Finck and Venkateswarlu (1982) indicated that Vertisols have an enormous yield potential but that this is often not realised.

Vertisols represent a vast crop production resource. It is estimated that there are at least

280 million ha of these montmorillonitic clays in the world, located mainly in Africa, Australia, India and the USA. Many of these soils are underutilised because they are difficult to manage--hard and cloddy when dry, and very sticky when wet (Willcocks and Browning, 1986).

Of the total Vertisol area, 126.5 million ha are found in three developing countries (Sudan, Chad and Ethiopia), where resources, facilities and trained scientific manpower are scarce, and where food is in short supply.

Berhanu Debele (1985) reported that of the 25 FAO/Unesco soil orders, 17 exist in Ethiopia. Lithosols, Cambisols, Nitosols, Vertisols, Xerosols, Solonchaks, Fluvisols and Luvisols cover more than 80% of the country, and are the most important soils. Vertisols cover 12.6 million ha, or 10.3% of the country; 7.6 million ha are found in the highlands. One quarter of these soils are presently cropped--24% of all highland soils cropped in Ethiopia (Jutzi and Mesfin Abebe, 1986)--which indicates their importance in Ethiopian agriculture.

The physical characteristics of Vertisols, coupled with the limited resources of small farmers, limit crop production on these soils.

IMPORTANCE OF VERTISOLS IN ETHIOPIAN AGRICULTURE

The largest Vertisol areas are on the volcanic plateaux, colluvial slopes and side slopes of volcanoes in central Ethiopia; on the colluvial slopes and alluvial plains bordering Sudan; and on the vast limestone plateaux of central Hararge province. Limited areas are found in such varied

sites as the granitic colluvium in basins with seasonal drainage deficiences in southern Sidamo; on sandstone colluvium in valleys in Tigray; on the floodplains of the Wabi Shebele and Fafen rivers in the Ogaden; and in basins in western Ethiopia, where rainfall reaches 2000 mm (FAO/LUPRD, 1984).

Donahue (1972) reported that of 29 randomly sampled pedons in four major agricultural areas of the country (Setit Humera in Gonder, Gambela in Ilubabur, Chilalo in Arsi, and Middle and Lower Awash river basins in Harerge regions), 19 were classified as Vertisol and 10 as Entisol. Some site characterisations of Vertisols are given in Table 1.

Rainfed crops such as teff (*Eragrostis tef*), durum wheat, chickpea, lentils (*Lens culinaris Med*), linseed, noug (*Guizotia abyssinica*), and bread wheat are generally grown on Vertisols. Wherever drainage conditions are favourable, faba bean, field peas and barley are cultivated. In the lowlands, irrigated crops such as cotton, sugarcane, citrus, and some vegetables are grown on these soils. Small farmers grow sorghum, haricot beans, maize and other lowland crops.

Average yields on these soils are low: 500-800 kg ha^{-1} for cereals, 500-700 kg ha^{-1} for highland pulses and 300 kg ha^{-1} for oil crops.

PHYSICAL PROPERTIES OF ETHIOPIAN VERTISOLS

Texture

Vertisols in Ethiopia generally contain more than 40% clay in the surface horizons and close to 75%

Table 1. Site characterisation of some Vertisol areas in Ethiopia.

Site characteristics	Awash	Melka Werer	Wonji	Ambo	Ginchi
Altitude (m)	700-750	750	1540	2060	2240
Physiography	Piedmont plain? Upper terrace?	Alluvial plain (back swamp)	Alluvial plain	Ambo depression	Lava plateau
General slope	3%	<1%	<1%	3-4%	
Local slope	3%	<1%	0.5%	2-3%	0-2%
Erosion	Slight sheet wash	None, there may be deposition from floods	None	Slight sheet wash	Slight sheet and gully erosion
Drainage	Imperfect	Imperfect-poor	Imperfect-poor	Imperfect-poor	Imperfect
Land use	100% grassland (game reserve)	100% cultivated at station	100% cultivated to sugar-cane	100% cultivated to cereals and pulses	Mostly cultivated: wheat, chickpea, teff, noug, lentil, linseed
Parent material	Colluvium/alluvium	Alluvium	Alluvium	Colluvium?	Weathered basalt
Rainfall (mm)	500	540	--	875	±900
FAO class	Pellic Vertisol (sodic phase)	Pellic Vertisol	Pellic Vertisol	Pellic Vertisol	Pellic Vertisol

Source: Morton (1977).

in the middle part of the profiles. The sand fraction is low, often less than 20%, and is found in the bottom and the surface (plough layer) horizons. In the highland Vertisols where soil burning (guie) is practised, the sand fraction is normally high in the surface horizon because the clay bakes into sand-size particles (Table 2, Berhanu Debele, 1985).

Clay mineralogy

In Ethiopian Vertisols the dominant clay minerals belong to the smectite group. Since both the free and total iron contents of Vertisols are high, it is believed that Nontronite is the most prevalent smectite. Berhanu Debele (1985) indicated that illitic minerals also constitute a significant proportion.

Bulk density

Because few data on bulk density of Ethiopian Vertisols are available, it is not possible to characterise bulk densities of very widely distributed Vertisols. Reports from elsewhere show that Vertisol bulk density is usually high, 1.5-1.8 g cm^{-3}, and may reach 2.05-2.1 g cm^{-3} (Murthy et al, 1982). These variations in bulk density are caused by swelling and shrinking with changes in soil moisture content. The soils have high bulk density when dry and low density when wet (Virmani et al, 1982).

Consistency

When dry, Vertisols are hard and impossible to plough with oxen-drawn implements and may even be difficult to cultivate with heavy machinery. Seedbed preparation is therefore difficult; the

Table 2. Particle size distribution in some Ethiopian Vertisols.

Location	pH (H_2O)	Depth (cm)	Sand (2-0.05 mm)	Silt (0.05-0.002 mm)	Clay (<0.002 mm)
Wonji	6.9	0- 10	20.0	3.0	77.0
	7.4	10- 95	17.0	3.0	80.0
	7.5	95-160	17.0	13.0	70.0
	7.6	160-200	18.0	5.0	77.0
Awash	8.2	0- 5			
	8.5	5- 30	26.0	25.0	49.0
	8.6	30- 65			
	8.1	65-100	8.0	42.0	50.0
	8.2	100-170	8.0	42.0	50.0
Melka Werer	7.8	0- 30	15.5	22.5	62.5
	7.8	30- 75	17.5	15.0	67.5
	7.6	75-100	17.5	15.0	67.5
	7.6	100-145	32.5	32.0	34.5
	7.5	145-170	17.5	30.0	52.5
Ginchi	6.8	0- 22	12.0	24.0	64.0
	6.8	22- 50	12.0	20.0	68.0
	7.5	50- 80	10.0	16.0	74.0
	7.7	80-125	14.0	12.0	74.0
	7.6	125-155	13.0	30.0	57.0
	8.0	155-210	25.0	52.0	23.0
Ambo	6.1	0-10/15	13.7	17.5	68.8
	6.1	10/15- 35	11.2	20.0	68.8
	6.5	35- 65	11.2	20.0	68.8
	7.7	65-125	25.0		75.0
	7.7	125-200+	30.0		70.0
Sheno		0- 8	24	42	36
		8- 40	14	22	64
		40- 65	-	-	-
		65-100	14	24	62
		100-130	18	22	60
		130-200	14	25	61
Sheno (guie)	5.6		29	46	25
(no guie)	5.6		18	32	50

Sources: Morton (1977) and IAR (1979).

seedbed is generally rough even after repeated cultivation. When wet these soils become plastic and sticky. Tillage and seedbed preparation are only possible within a narrow soil-moisture range.

Structure

In the dry season, surface horizons are characterised by huge, strongly developed prismatic primary structures separated from each other by deep vertical cracks, of various sizes, at intervals of 20-30 cm. These prisms break into strongly developed, often coarse, angular to sub-angular, secondary aggregates. In the wet season, both primary and secondary structures are almost completely destroyed, reducing the surface horizon to a massive block. At this time only shiny pressure faces and/or well-developed slickensides are visible (Berhanu Debele, 1985).

Pores, except for the cracks developed during the dry season and occasional root channels, are limited. The plant roots are confined to cracks and slickenside faces.

Available water

Vertisols have a relatively high water storage capacity in the root zone because of their depth and high clay content. The available water range has been reported as 110-250 mm for the top 1 m of the soil profile (Virmani et al, 1982). Virgo and Munro, as quoted by Virmani et al (1982), observed that the moisture content in deeper layers of the soil profile is lower, apparently due to compression effects on matric potential.

The high water-storage capacity of Vertisols is important in regions with uncertain rainfall.

The growing season on deep Vertisols is usually longer than on other soils; on the highland Vertisols, wheat, lentil, chickpea and vetch grow to maturity entirely on residual soil moisture after establishment at the end of the rainy season. Farmers practise late-season planting to avoid the serious drainage problems characteristic of these soils during the rainy season.

PROBLEMS

Cultivation and seedbed preparation

Ethiopian Vertisols have a high content of clay, particularly expanding lattice clays. High clay content, type of clay mineral, unfavourable consistency and absence of pores make them difficult to work in both dry and wet conditions. A substantial amount of rainfall is needed to wet a dry Vertisol. The rain tends to move into cracks rapidly and wets the deeper layers of the soil profile, leaving the surface relatively dry. Achieving optimum moisture conditions for cultivation is difficult under present management practices. Once the rainy season starts and the surface is wet, cultivation is virtually impossible.

To overcome cultivation difficulties, seedbed preparation for all crops in the Ethiopian highlands starts with two ploughings during the short rainy season (March/April), when workability is relatively good. Up to six passes are made to prepare a seedbed for teff and durum wheat. It is not always possible to prepare a fine seedbed. Even after repeated cultivations the seedbed is rough. For the other crops, two or three passes are considered sufficient.

Drainage

The highland Vertisol areas are generally characterised by smallholder mixed cereal-livestock farming systems with a marked subsistence orientation. Land cultivation is almost exclusively done using oxen-drawn implements. The area is characterised by high rainfall (>900 mm year^{-1}) and low evaporative demand due to moderate temperatures, which vary widely with altitude, but might average 15°C annually. As a result, most vertic soils are severely waterlogged (estimated at 2.5 million ha, especially vertic Cambisols and vertic Luvisols) (Jutzi and Mesfin Abebe, 1986).

As the result of poor drainage, crops sown in early June suffer from prolonged waterlogging--they are stunted and show signs of poor aeration and nutrient deficiency. Grain yields are low.

Erosion

Vertisols in Ethiopia are located on either relatively flat or slightly sloping land. Erosion is a serious problem under present management, especially on fallow cultivated during the rainy season and on some sloping land in the highlands.

RESEARCH RESULTS

Research on black clay soils at two Institute of Agricultural Research (IAR) sub-centers (Ginchi and Sheno) showed that drainage and fertilizer application increase yields.

Soil burning practised in the highlands can be replaced by adequate drainage through deeper

ploughing with a tractor or planting on cambered beds. The advantages of cambered beds or ploughing with a mouldboard plough are more pronounced if high levels of fertilizer (60 kg N and 26 kg P ha^{-1}) are applied.

These recommendations are not within the reach of small farmers and have not resulted in the expected impact. Farmers still practise traditional methods of improving the drainage of Vertisols.

The Vertisols management project for the Ethiopian highlands, a joint project of ILCA, ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), IAR, Alemaya University of Agriculture, the Ministry of Agriculture and Addis Ababa University, is developing technologies within the reach of the traditional farmer to drain excess moisture, improve soil fertility and develop a sustainable farming system.

CONCLUSIONS

The need for more intensive and applied research on Vertisols is apparent. Any research geared towards increasing productivity should start with a clear understanding of the physical characteristics of Vertisols. Research should address two important soil physical issues: workability and drainage.

Aspects that require urgent research attention include:

- identification and characterisation of Vertisols;

- tillage and land configuration: surface drainage and seedbed preparation;
- water management and use: rainfall pattern and probability studies, and water harvesting from catchments; and
- soil conservation: design and development of conservation structures and practices.

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SOIL BURNING IN ETHIOPIA: SOME EFFECTS ON SOIL FERTILITY AND PHYSICS

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ABSTRACT

In the central highlands of Ethiopia, a unique soil management system, known locally as *guie* (soil burning), is practised. The physical and chemical changes resulting from soil burning were studied and analysed in the laboratory.

It was found that soil burning changed soil colours to redder hues, fused clay into sand-sized particles, decreased the organic matter content and increased the soil pH. Total N was lost in the burnt layer of the guie heap, but increased in other layers. Available P increased with higher temperatures. The cation exchange capacity, and exchangeable Ca and Mg, decreased, while K increased. In the burnt layer, the Fe content increased, whereas the Mn content decreased; Cu and Zn contents decreased with more heat.

The most favourable effects were found to be the increase in P, the increase in available N and the change to a coarser soil texture. An obvious disadvantage was the loss of organic matter.

THE ROLE OF SOIL SPACIAL VARIABILITY INVESTIGATIONS IN THE MANAGEMENT OF THE CHAD BASIN VERTISOLS OF NORTHEAST NIGERIA

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ABSTRACT

The Chad Basin of northeast Nigeria has a vast Vertisol area. These soils are not only rich in plant nutrients, but also have a high water-holding capacity, and are therefore capable of supporting large-scale production of food and forage crops. The ability of the soils to support large-scale cultivation of forage crops is particularly significant in the northeast since this area is the leading producer of livestock in Nigeria.

Prediction of soil behaviour and crop productivity is conventionally based on soil test results. Soil samples collected from a field must be representative if test results are to be valid. A procedure to obtain representative soil samples, based on an adequate assessment of the soil spatial variability, is presented.

Surface (0-15 cm) soil samples were collected from 100 locations spaced at 2-m intervals on a transect in the middle of a 2-ha field in the Chad Basin of northeast Nigeria. The samples were analysed for exchangeable cations, saturation extract electrical conductivity, particle size distribution, bulk density, organic carbon and pH.

All the soil properties investigated were normally distributed. Estimated sample autocorrelograms and semivariograms suggested that the soil properties were spatially independent. The implication of the spatial independence of these soil properties in selecting an appropriate soil sampling plan is discussed.

Sample size calculations revealed that while it requires only one sample to estimate the mean values of clay content and pH within ±10% of the population means of these properties at the 95% confidence level, 695 samples would be required to estimate the mean value of exchangeable Mg for the study area at the same level of precision. The implications of these estimates of sample number requirements to obtain reliable soil test results for improved management and enhanced productivity of Vertisols are discussed.

EFFECTS OF ADSORBED CATIONS ON THE PHYSICAL PROPERTIES OF VERTISOLS IN THE LAKE CHAD BASIN OF NORTHEAST NIGERIA

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ABSTRACT

The physical properties of Vertisols from the Lake Chad Basin of Nigeria depend on the nature of the predominant cations in the exchange complex. The percentage of water-stable aggregates and the hydraulic conductivity are drastically reduced by Na and to a lesser extent by K, whereas Ca and Mg increase these two properties. Addition of phosphogypsum has no significant effect on water retention, plasticity and aggregate stability, but it decreases the degree of dispersion and effectively prevents a sharp decline in the hydraulic conductivity compared with the control.

Some implications for land use, long-term irrigation and reclamation of these Vertisols are discussed. The potential for large-scale sustained grain production under extensive irrigation in the area appears to be very high because good quality water is available from Lake Chad and boreholes. Increased availability of

crop residues to be used as feed will enhance the integration of livestock and arable crops in farming this area. Poor drainage is currently constraining the agricultural productivity of these soils. Physical surface drainage and the addition of gypsum can alleviate this constraint.

SOIL WATER AND NUTRIENTS

SOIL WATER MEASUREMENT AND MANAGEMENT ON VERTISOLS IN QUEENSLAND, AUSTRALIA

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ABSTRACT

Measuring and interpreting profile soil water changes, infiltration and runoff under ponded and rainfall conditions, and evaporation and deep drainage in Vertisols, are discussed. Measurement of soil water parameters/processes in Vertisols is usually no more difficult than in rigid soils. However, there is more to be understood about rainfall infiltration into Vertisols, and its quantitative prediction.

Of the 50 million ha of Vertisols in Queensland, 1.2 million ha are used for dryland grain production in areas receiving less than 500 mm rainfall per year. Research at the Soil Conservation Research Branch of the Department of Primary Industries in Queensland is concentrated on stabilising grain yield, either by catchment water management practices or by matching cropping pattern to soil water supply and rainfall reliability, and on decreasing soil erosion and managing peak storm runoff rates from cropped areas.

Three techniques of soil water management are considered: fallowing, opportunity cropping and optimising crop-soil-climate combinations using modeling. The rainfall pattern in Queensland makes summer fallowing on Vertisols very inefficient because most of the rain is lost as evaporation (about 65%) and runoff (about 17%). Rather, opportunity cropping, using the rain as it falls, is better, but this approach is not economically successful in all cropping areas of Queensland. It is suggested that it is only through crop growth models that the interaction of soil water storage, climate, crop type and planting date on grain yield can be sensibly judged, using long-term (>80 years) simulations of crop yield from rainfall data, to incorporate the effects of a highly variable rainfall pattern. Results from such a model are presented.

INTRODUCTION

Water supply to crops is the major constraint to grain yield on the 1.2 million ha of Vertisols used for dryland (and irrigated) cropping in Queensland. Dryland research concentrates on cropping strategies, such as matching planting date to soil water and rainfall reliability, with appropriate surface soil management strategies to increase soil water storage and reduce erosion. In irrigated areas, irrigation frequency, transient surface waterlogging and water quality in relation to profile permeability are studied. In both types of cropping environment, soil water parameters and processes such as soil evaporation and deep drainage must be measured. The unique characteristic of Vertisols is their volume change with changes in moisture content, which influences these soil water processes.

A convenient framework to consider soil water behaviour is the catchment water balance equation:

Infiltration = rainfall + irrigation - runoff

= change in soil water store
+ drainage below root zone
+ evaporation + transpiration.

SOIL WATER CONTENT

Change in soil water content

Volumetric soil water content, θv (volume of water per unit volume of soil), is one of the fundamental descriptors of the water status of a soil. It is numerically equal to the depth of stored water per unit depth of soil. The gravimetric soil water content, θg, is expressed in terms of the weight of water per unit weight of soil. For a non-swelling field soil, the change in profile soil water content, ΔS, over a given time interval, may be calculated as:

$$\Delta S = \sum_{i=1}^{n} \frac{(\Delta\theta g_i) * \overline{BD}_i * Z}{\rho H_2O} \text{ units of cm or mm} \quad (1)$$

where:

Z = the depth of the sampling increment--usually 10 cm.

$\overline{BD}_i$ = the average bulk density of depth increment i

$\Delta\theta g_i$ = the difference in gravimetric moisture content between any two sampling times for the i-th depth increment

n = the number of depth increments, each of length Z

ρH_2O = the density of water.

For swelling soils, there are a number of apparent difficulties in the application of equation 1:

- o variation in bulk density with water content; and
- o difficulty in measuring bulk density accurately on cracked soil, because the cracks must be representatively sampled.

However, Gardner (1978), Bridge and Ross (1984) and Yule (1984) have shown that because bulk density variations are exactly compensated by soil height changes, and because cracks are essentially closed at maximum field water content (θgmax), equation 1 can be used in swelling soils if the bulk density at θgmax is used:

$$\Delta S = \frac{(\theta gmax - \theta g_x)}{\rho H_2O} * BD_{\theta gmax} * 10 \qquad (2)$$

where:

θg_x = gravimetric water content at the indicated depth at time x

10 = the depth (cm) of the soil sampling interval at the reference wetness state.

The change in soil water storage is simply the difference in gravimetric water content between any two sampling occasions multiplied by the bulk density at the (fully wet) reference wetness state. The difficulties are in the measurement of bulk density.

Measurement of bulk density

Bulk density is:

$$BD = \frac{1 - \varepsilon}{\frac{1}{AD} + \frac{hg}{\rho H_2O}} \qquad (3)$$

where:

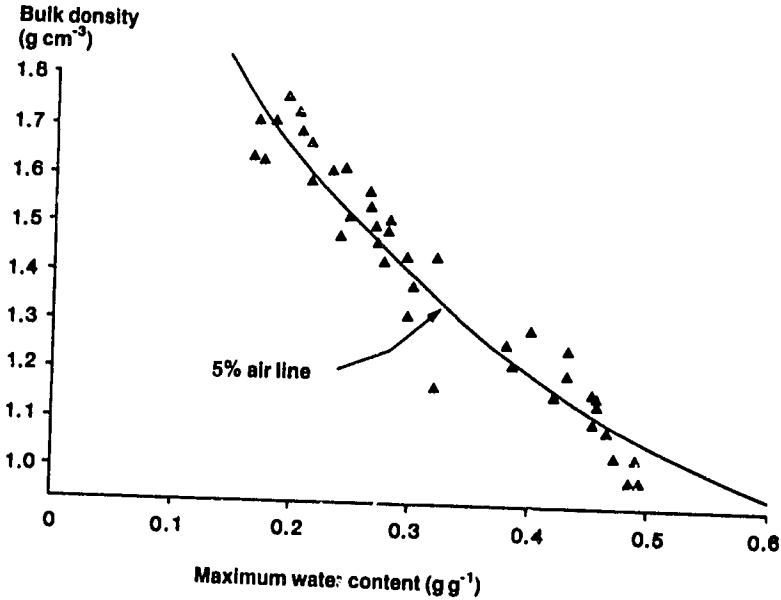
AD = the absolute density of the soil solids (about 2.65 g cm^{-3})

ε = the volumetric concentration of soil air (cm^3 cm^{-3}).

For swelling soils our experience is that ε at maximum field water content is approximately 0.05 cm^3 cm^{-3}. Hence, if θgmax is known, bulk density can be calculated. For example, 2 days after flood irrigation of a black earth soil in Queensland θg measured 0.5 g g^{-1}. From equation 3, $BD_{\theta gmax}$ can be evaluated as 1.08 g cm^{-3}.

If this gravimetric sampling and calculation procedure is repeated for a range of swelling soils in which θgmax varies (due to changes in clay content and/or mineralogy), pairs of $BD_{(\theta gmax)}$ and θgmax values can be plotted (Figure 1).

Figure 1. Relationship between field bulk density and maximum water content for a range of Vertisols in Queensland.



The effect of error in the assumed ε values is not large. For example, if the true ε = 0.10 cm^3 cm^{-3}, and assumed ε = 0.05 cm^3 cm^{-3}, then for θgmax = 0.50 g g^{-1}, calculated bulk density reduces from 1.08 to 1.03 g cm^{-3}. This is an error of les than 5%.

Equations 2 and 3 show that the calculation of soil water changes in Vertisols is almost as straightforward as that for rigid soils. Moreover, provided the soil profile is fully wet (ie, at θgmax) the bulk density of a sample taken with a hand auger can be calculated using equation 3.

Low ε values at θgmax infer a restricted aeration status of Vertisols in their fully wet

state. An exception is the surface 10 cm of irrigated raised beds (Yule et al, 1984).

Measurement of soil water using the gravimetric method

A fundamental problem in gravimetric sampling is that uncertainty in measurement (ie, the variance) at each sampling occasion is additive when differences in θg are sought. The problem is partially resolved if the same locations can be monitored at each sampling occasion to take advantage of the reduction in error due to covariance.

Measuring soil water using the neutron moisture meter in Vertisols

The neutron moisture meter (NMM) is the obvious instrument to exploit the advantage of sampling at the same location. However, there are still errors arising from imprecision in the calibration equation (θv vs fractional count rate, C_f); instrument error in measuring a random radioactive process; and heterogeneous water distribution over sites, which is the major source of random error in any neutron meter measurement. Williams and Sinclair (1981) presented a comprehensive analysis of statistical errors associated with using an NMM. They stressed that the minimum variance associated with NMM use is set by the precision of the calibration equation. A highly precise field calibration equation is clearly important.

When using an NMM there are potential bias problems introduced by bulk density effects, bound water, slow neutron absorbers, high organic matter content and sharp water/soil or soil/air boundaries (Greacen et al, 1987). These apply

both to Vertisols and rigid soils. In Vertisols, NMM calibration poses special problems because bulk densities of dry, cracked soil are required, while the cracking pattern of the calibration bay must approximate that of the field. A simple method is to take large cores (100 mm diameter, 100 mm long) from an uncracked, fully wet soil profile (at θg_{max}) and monitor height and weight changes as the cores dry slowly in the laboratory (Yule and Ritchie, 1980). These data allow unique BD vs θg relationships to be established which are then applied to the field θg vs C_f data.

Alternatively, a mode of shrinkage can be assumed, such as three-dimensional, normal volume change, and bulk density at any θg is then calculated from an analytical expression given by Fox (1964). Failure to allow for shrinkage cracks in BD samplings/calculations can cause a negative bias of up to 30% in estimates of $\Delta\theta v$, although a high precision in the calibration equation is still possible (Greacen and Hignett, 1979).

Shrinkage cracking inevitably occurs around the NMM access tube, but, provided the tube-air-soil-air-soil geometry is the same in the calibration bay as it is in the field plot, these geometry effects are 'calibrated out'. Preferential water movement down the crack formed between the access tube and the dry soil can occur, allowing infiltration through horizontal soil surfaces. This may cause pockets of dry soil to occur in the middle of the soil matrix between the shrinkage cracks. Consequently, θv estimated from an NMM calibration equation established on a drying soil may overestimate the true average θv in a wetting soil until the vertical wetting fronts link up.

Finally, when calculating profile moisture changes using an NMM, allowance must be made for the different profile heights (due to shrinkage) between any two sampling occasions. Failure to allow for this can introduce a relative error of 10-15% in the maximum ΔS (Gardner, 1985).

PLANT AVAILABLE WATER CAPACITY

Plant available water capacity (PAWC) is a second fundamental soil hydrological parameter because:

- it sets the upper limit on the size of the plant soil water store;
- it acts as the water supply buffer between rainfall events during crop growth; and
- it determines irrigation frequency, which influences water use efficiency, distribution canal capacity, and surface waterlogging.

Following Gardner et al (1984), PAWC can be defined as:

$$PAWC = \sum_{i=1}^{n} \frac{(USL - LSL)_i * BD_i * \Delta Z}{\rho H_2O} \qquad (4)$$

where:

USL = the upper storage limit, the gravimetric water content of the wet soil after downward drainage is negligible.

LSL = the lower storage limit, the gravimetric water content after plant water extraction in the field.

RD = the rooting depth.

BD = the bulk density at the USL.

ΔZ = the depth interval considered.

ρH_2O = the density of water.

i = subscript referring to any one of n soil layers

$$n = \frac{RD}{\Delta Z}$$

PAWC may vary with crop, growth stage, stress level, root development restrictions, extent of soil water recharge, etc, but when measured using management appropriate for the intended application, it has proved an extremely useful concept for comparisons among soils (Shaw and Yule, 1978; Gardner and Coughlan, 1982). We measured PAWC in the field using 25 m^2 mini-bays with an indicator crop and found that drainage becomes negligible 2-3 days after irrigation.

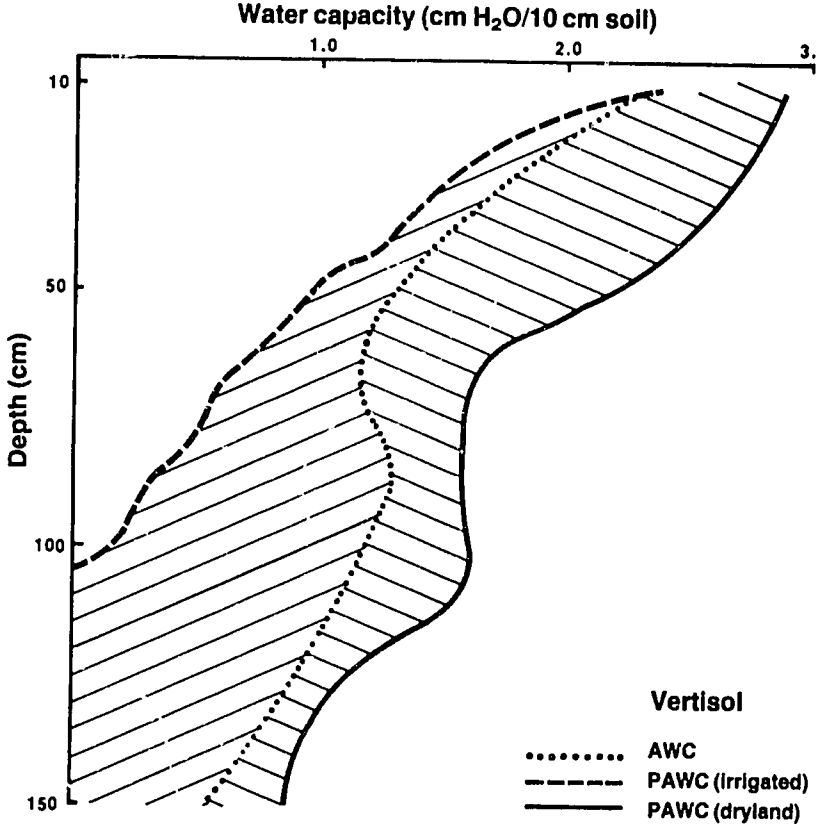
Hence, provided there is complete subsoil wetting, the USL is synonymous with $\theta gmax$. The LSL depends on soil depth and the level of drought stress we use to define the end of plant water extraction. In irrigated areas, this is visible plant stress for 2-3 consecutive days, while in dryland areas, it corresponds to the minimum θg measured during the crop cycle. Rooting depth varies with crop growth, the stress levels imposed, and between Vertisols: it is defined as the deepest soil depth of significant decrease in soil moisture between irrigations, or between wet and dry profiles in dryland crops.

Field determinations of PAWC on a wide range of Vertisols in Queensland have given values of 100-130 mm for mildly-stressed conditions to 70-140 mm in severely-stressed sorghum. Differences in PAWC were caused mainly by differences in rooting depth (50-120 cm) between soils (Gardner and Coughlan, 1982; Shaw and Yule, 1978). Differences in the volumetric available water capacity (AWC) per unit soil depth had a second order effect with values ranging from 15-22 mm 100 mm^{-1}.

Differing PAWC responses to extreme drying cycles have been observed in a number of irrigated Vertisols. The increased PAWC response to extreme drying cycles is caused by increased rooting depth and activity. An extreme example is a strongly self-mulching Typic Pellustert where the PAWC for mildly-stressed, irrigated sorghum is 120 mm, increasing to 290 mm for dryland ratoon sorghum with a stress level causing leaf death (Figure 2). For comparison, the AWC profile using the -15 bar θg as an estimate of the LSL is also shown. Summing the AWC profile over 150 cm soil depth gives 200 mm of available soil water. The soil properties allowing these rooting depth/activity-PAWC responses to plant stress are uncertain, but the response appears greatest in Vertisols with strong, very fine (<5 mm) to fine (5-10 mm) subangular, blocky soil structure with a well-developed, secondary structure of large (500 mm x 200 mm) lenticular peds. Subsoil aeration effects are hence strongly implicated.

In dryland experiments causing high plant stress levels, PAWCs of 200 mm in 180 cm of rooting depth are common in self-mulching clays, reducing to 120-130 mm in shallow soils (<80 cm) and in those Entic Chromusterts of low potential

Figure 2. Distribution with soil depth of the Available Water Capacity (AWC) and the Plant Available Water Capcity (PAWC) at two levels of plant stess for a Typic Pellustert.



volume change and poor self-mulching ability. Methods of predicting USL, LSL, and RD from more easily-measured soil properties, such as -15 bar θg, are being studied.

INFILTRATION

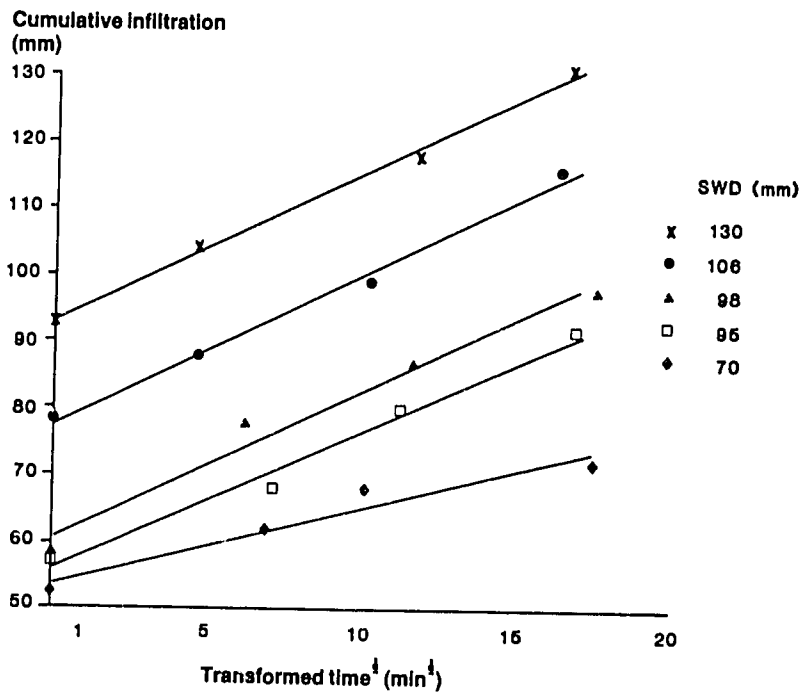
Information on the infiltration process and rates is of importance in irrigation layout design, to assess likely waterlogging hazards, to understand the effects of surface management treatments on soil water accumulation, and for use in models which simulate the water balance using lengthy data sets (>80 years). Infiltration can be separated into ponded and rainfall conditions.

Ponded

The classic, buffered infiltrometer ring method to study ponded infiltration is a complete failure on Vertisols, because water in the inner ring moves away laterally into the interconnecting shrinkage crack network.

As an alternative, we built 25 m^2 mini-bays with a continuous, thin metal wall buried to about 120 cm, resulting in a water-tight, undisturbed, non-weighing lysimeter. The bays allowed a representative cracking pattern under row crop conditions to be sampled. Details on construction and measurement are given in Shaw and Yule (1978) and Gardner (1978). Infiltration was measured at different antecedent moisture contents by rapidly flooding the bay and thereafter maintaining fully-ponded conditions for 5-24 hours. In a wide range of Vertisols, two-thirds of the total net water addition was instantly taken by the soil to fill the crack volume. An example of this infiltration behaviour is shown in Figure 3, where cumulative infiltration is plotted as a function of the square root of elapsed pondage time. The Y axis intercept is the crack volume, while the slope of the line equals the sorptivity (S) (Philip, 1969).

Figure 3. Relationship between cumulative infiltration and the square root of time for a Typic Pellustert under ponded conditions for a range of antecedent soil water deficits.



As the net water addition equated closely with the independently-measured initial soil water deficit (SWD), the cumulative infiltration (I) behaviour can be described by the equation:

$$I_{(t)} = 2/3 * SWD + St^{0.5} \qquad (5)$$

where S varies with both antecedent soil water content and crack wall surface area (Gardner, 1978). Because the infiltration rate at the end of 5 hours was only to about 4 mm h^{-1}, with a

further reduction to about 1.5 mm h^{-1} after 24 hours of ponding, extended irrigation times added little water to these soils.

This variation in 'saturated' infiltration rate over time is consistent with saturated water flow through macrovoids, which swell shut slowly (Ritchie et al, 1972). Other studies on Vertisols in Queensland have established a 10-fold reduction in infiltration as ponding time increased from 24 hours to 7 days. This behaviour has implications for assessing the incidence of surface waterlogging and deep percolation under paddy rice (Gardner and Coughlan, 1982).

Rainfall

Measuring and describing infiltration behaviour under rainfall (a flux-controlled boundary condition) is much more difficult, requiring, among other things, the prediction of time to ponding as affected by variation in rainfall intensity and antecedent soil water deficits. Complications are caused by the formation of surface seals of large hydraulic resistance and layered soil hydraulic properties. Tilled Vertisols combine all these characteristics. Because of the above problems, attempts have been made to collect empirical infiltration data using rainfall simulators (McKay and Lock, 1978; Glanville, 1984).

Instrumented catchments can also be used to obtain information on rainfall infiltration on either a storm or short-time basis. A common difficulty with the latter approach is that the generation of excess rainfall rate (R) is not time-synchronised with the measured runoff rate (Q), because the depth of ponded water on the soil

surface must continuously adjust to allow for varying rates of surface runoff. Only in a steady state condition does R = Q. Rose (1985) solved this problem for simple rectangular catchments. He showed, for specified times (t), how $R_{(t)}$ could be calculated from $Q_{(t)}$ data which, when combined with measured rainfall rate data, $P_{(t)}$, allowed infiltration rate, $i_{(t)}$, to be calculated:

$$i_{(t)} = P_{(t)} - R_{(t)} \qquad (6)$$

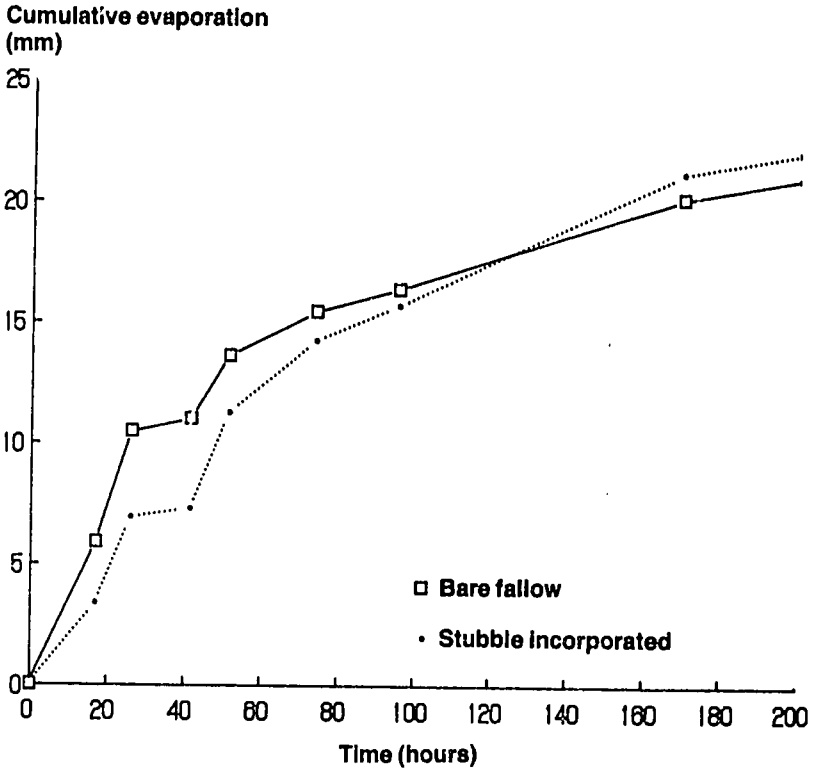
The task of describing these experimental data by physically-based infiltration equations appropriate to Vertisols, which both crack and surface seal, remains unresolved.

EVAPORATION

The effect of summer fallowing on evaporation is of interest because data from southeast Queensland indicate that some 65% of fallow rainfall (of about 450 mm) is repartitioned into soil evaporation (Freebairn et al, 1986a). Evaporation rates also may be responsive to levels of surface cover (Bond and Willis, 1969) and tillage.

Weighing lysimeters 570 mm diameter x 400 mm long were used to evaluate evaporation losses in relation to surface cover and simulated tillage (Freebairn et al, 1986b). After 3 days there was little effect of stubble on evaporation from a repacked black earth (Figure 4). Assessing evaporation response to simulated tillage practices and soil compaction by planting press wheels presents some difficulty in these small experimental units. However, weighing is the only practical way to capture the short-term evaporation behaviour.

Figure 4. Relationship between cumulative evaporation and cumulative time for a Typic Pellustert under bare surface and stubble mulch (4 t ha^{-1}) conditions. Data were obtained from small weighing lysimeters.



DRAINAGE

Drainage estimates below the root zone are important to 'close' the catchment water balance; to assess the effect of a cultural practice, such

as irrigation for paddy rice raising the regional water table; and to determine the suitability of saline water for irrigation (Shaw and Thorburn, 1985a).

Drainage can be measured directly or by inference from analyses of tracers. Direct measurement can be of two types:

- measurement of changes in profile water content; or

- calculation of flux rates using the measured soil hydraulic gradient (by tensiometers) and knowledge of the relationship between unsaturated hydraulic conductivity (K), and volumetric water content (θv).

The first method can be used only when the 'wetting front' is above the maximum depth of measurement, while the second method, often called the flux-gradient technique, is difficult to maintain for extended periods of time. Additional difficulty occurs in Vertisols because the maximum drainage rate, K_s, is small while the amount of water stored above field capacity is usually less than 0.02 cm^3 cm^{-3} (Hodnett and Bell, 1981).

Because recharge in Vertisols is episodic, isotopic tracer techniques, which integrate long-term drainage behaviour, are an option. Despite their success (Allison and Hughes, 1978), the measurements are time-consuming and expensive.

An alternative tracer is the salt introduced by rainfall (Eriksson and Khunakasem, 1969), because under equilibrium conditions, salt flux into a soil equals salt flux out. By definition, salt flux equals a solute concentration (measured

by electrical conductivity, EC) multiplied by a depth of water (either average yearly infiltration, I, or drainage, D). By assuming I equal to average yearly rainfall, P_g, Shaw and Thorburn (1985b) were able to establish a set of regression equations of the form:

$$LF_r = \frac{D}{I} = \frac{EC_r}{EC_s} = \frac{a * P_g}{ESP^c} + b \qquad (7)$$

where:

LF = leaching fraction

r = rainfall

s = a soil depth below the active root zone

ESP = exchangeable sodium percentage of the soil (at 90 cm)

a,b,c = regression coefficients.

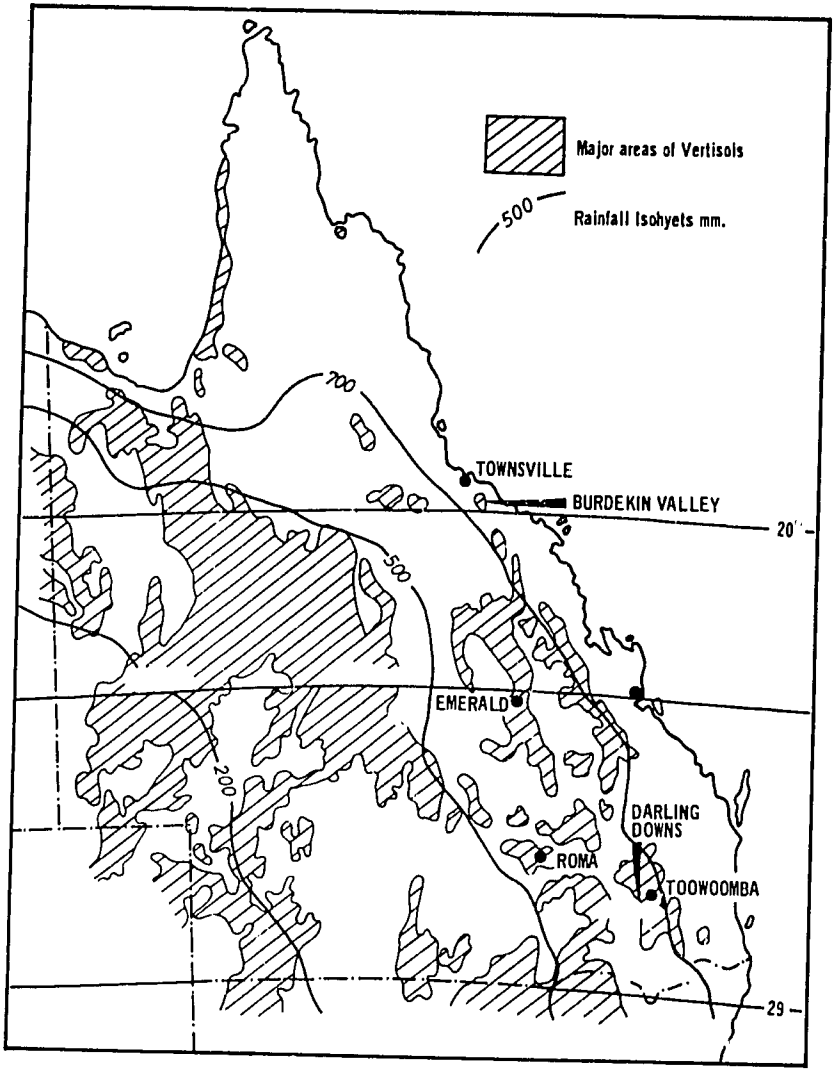
Shaw and Thorburn (1985b) tested the validity of their predictions by comparing predicted LF (from equation 7) with measured LF of Vertisols in three irrigation areas. Measured LF values varied from 0.01 (drainage = 1% of water applied) to 0.3, and agreement was good.

MANAGEMENT PRACTICES

Background

Cropping on Vertisols in Queensland for wet-land grain production occupies 1.5 million ha in the 500-700 mm rainfall zone (Figure 5). Soil water

Figure 5. Map of Queensland showing the distribution of Vertisols and mean annual rainfall isohyets.



is a major constraint and farmers have responded by growing one crop per year and fallow for water storage during the other season.

Water management methods in dryland cropping have one or more of the following objectives:

- o increasing fallow moisture accumulation by decreasing soil evaporation and storm runoff;
- o using rain when it falls by opportunity cropping irrespective of season;
- o matching cropping strategies to PAWC and climate.

Fallow moisture storage

The major methods used to manipulate fallow moisture accumulation are tillage and crop residue management practices. Results from tillage-surface cover trials in Queensland have shown that the ΔS response is variable. The summer fallow moisture efficiency (ΔS divided by fallow rainfall) for a southeast Queensland area over a 5-year period averages only 20-25% (Wildermuth et al, 1986). Through stubble mulch and tillage, reduced runoff was found to improve the moisture storage from 18 to 24% but the tillage and crop residue management had no effect on evaporation, with 65 and 66% evaporation from bare fallow and stubble mulch/zero tilled plots, respectively (Freebairn et al, 1986). The reasons for such high evaporative losses are a combination of relatively small storms (20-80 mm), storms spaced at intervals of several weeks, and the relatively large amount of water (30-40 mm) held between air dry and $\theta gmax$ in the surface 10-15 cm of Vertisols. Thus, soil water deficits (SWD) due

to evaporation often approximate storm size, and it is only when average yearly rainfall is greater than soil water deficit that 'excess' water is available for subsoil recharge, as in central Queensland, where substantial moisture accumulation only occurs if storm sizes are >30 mm (Table 1).

Table 1. Soil water accumulation during fallows as related to rainfall amount and storm size at Emerald, central Queensland.

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

Source: Shaw and Thorburn (1985b).

Because evaporation is not easily modified by the stubble levels that we can generate (about 4 t ha^{-1}), positive ΔS responses can most likely be achieved by reducing fallow runoff. However, average annual runoff from a Typic Pellustert for

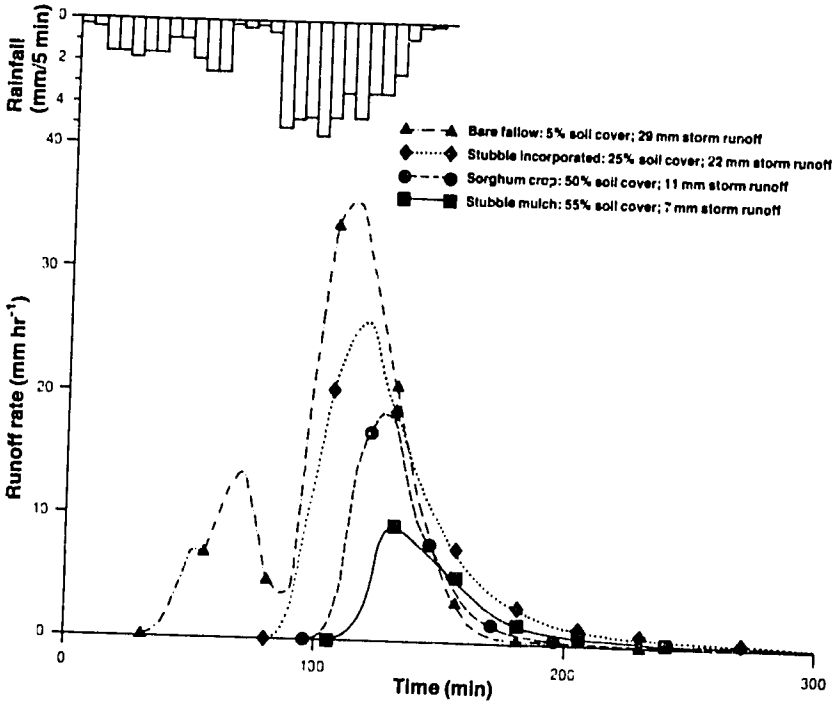
a bare fallow with stubble burnt was reported to be only 89 mm from 780 mm of annual rainfall, most of which occurred in the summer fallow (Freebairn et al, 1986a). Stubble mulch reduced runoff by 30 mm, but although much of this 30 mm difference is repartitioned into ΔS, the effect on wheat yield was small (<200 kg ha^{-1}).

One possible reason for difficulties in reducing runoff is that, unlike the monsoons of India and parts of Africa, rain during the Queensland summer falls in small (<70 mm), well-spaced storms, which allows the shrinkage cracks to swell shut near the surface. Consequently, during the latter half of the fallow, much of the rainfall must infiltrate vertically through the soil matrix, and it is under these conditions that runoff responses to surface cover and surface roughness are observed (Freebairn and Wockner, 1986). Surface cover serves an important secondary role in reducing peak storm runoff rates, which has obvious implications to the design ratings of hydraulic structures. Figure 6, taken from Freebairn et al (1986c), shows an example of this response.

Opportunity cropping

Opportunity cropping is defined as planting a crop whenever surface moisture conditions are satisfactory for seedling emergence, provided the soil profile moisture store equals or exceeds some specified fraction of PAWC (for example, water store >0.2 PAWC). The rationale behind this approach is to redirect evaporation from fallow land into biomass-producing transpiration. Depending on the amount and reliability of rainfall, this strategy involves either winter or summer or double cropping each year.

Figure 6. Rainfall and runoff for four surface cover conditions for a Typic Pellustert in southeast Queensland. Rainfall is 62 mm.



Source: Freebairn et al (1986c).

The success and adoption of this approach depends on soil type, amount and variability of summer rainfall, and average grain yields from the winter crop. Results from eastern areas of southeast Queensland (Freebairn et al, 1986c) indicate that double cropping (summer sorghum-winter wheat) has a small effect on annual runoff and erosion, but an additional 2 t ha^{-1} of grain

is produced each year. The practice is not widely used by farmers because high average wheat yields (3 t ha^{-1}) remove the economic urgency of accepting the management inconvenience of two crops per year.

Similarly, double cropping is not often used in western areas of southeast Queensland (for example, in Roma) because unreliable summer rainfall, relatively small PAWC (about 130 mm), and high evaporation rates combine to make summer cropping unacceptably risky (Berndt and White, 1976; Lloyd and Hamilton, 1984). Rather, it is better to fallow the land during the summer in order to maximise soil water store for the winter wheat crop, which averages 1.6 t ha^{-1}.

Opportunity cropping is practised in central Queensland (for example, in Emerald) with grain crops planted from December to May and again from August to September. The success of this cropping system in Emerald compared with Roma may be due to more summer rain (445 mm vs 360 mm), a smaller spacing between summer storms (ie, PAWC buffer is not emptied before rain), and a smaller incidence of winter frosts which increases the flexibility of wheat planting dates. Time to flowering is an important determinant of wheat yield, because the timing of drought stress and frost hazard combinations can cause a variation from 0.8 to 2.0 t ha^{-1} in simulated wheat yield for identical planting soil moisture conditions (Woodruff, 1985).

Matching cropping to PAWC and climate

The cropping strategies used in the different climatic zones of Queensland have evolved by a process of trial and error. This is usually a

very expensive learning process. To better understand how soils and climate interact to affect grain yield (and erosion) we are developing cropping models, initially for wheat, which explore the effect of PAWC, rainfall, planting profile water content, plant variety and frost hazard on the probability distribution of grain yield. There are two aspects to PAWC-climate-yield analysis: the probability of achieving high yields and the chances of avoiding low yields resulting in a monetary loss (ie, risk aversion).

A simple form of this analysis is shown in Figure 7 where simulated wheat yield probabilities for two locations in Queensland are compared for two PAWC values. Wheat variety and planting date were held constant. A rainfall record of 80 years was considered.

For a PAWC of 100 mm, the median yield (yield at 50% probability of exceedence) at Greenmount (eastern southeast Queensland) was 1600 kg ha^{-1} compared with 1300 kg ha^{-1} for Roma (western southeast Queensland). The yield difference is not large although median growing season rainfall was 250 mm and 195 mm, respectively. However, if PAWC is 200 mm, median wheat at Greenmount increases dramatically to 2400 kg ha^{-1}, while at Roma the increased yield is only 1600 kg ha^{-1}. The reason is that the probability of actually filling the 200 mm PAWC profile at Roma during a summer fallow is much less than at Greenmount. Median profile water stores at planting were 180 and 135 mm (data not shown). Thus soils with large PAWC may confer only a small yield advantage in dry areas because they are rarely filled to capacity. Similarly, in areas (or years) of high growing-season rainfall, large PAWC values will also confer little yield advantage.

Figure 7. Probability distribution of simulated wheat yields on a Typic Pellustert for two Plant Available Water Capacity (PAWC) values (100 mm and 200 mm) at two locations in southeast Queensland. Period used in the simulation was 80 years. Average annual rainfalls are 571 mm (Roma) and 735 mm (Greenmount).

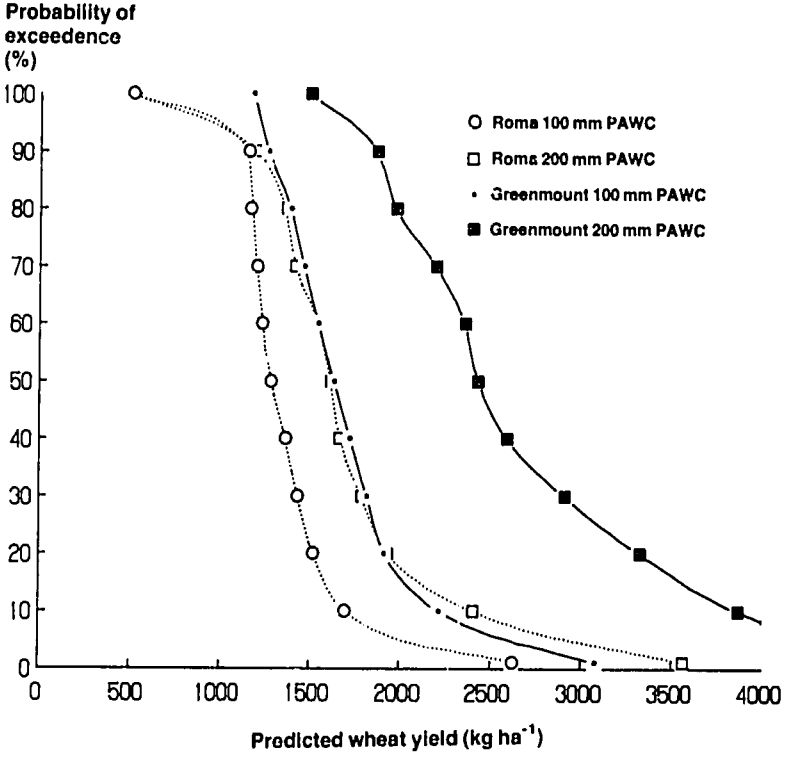


Figure 7 may also be used to determine risk aversion. Assuming the wheat yield to break even is 1400 kg ha^{-1}, this may be achieved 80% of the time at Roma for a PAWC of 200 mm. The converse is that, in 1 year out of 5, the farmer will make a loss. However, if PAWC equals 100 mm, this risk

increases to 6 years in 10. Clearly, large PAWC values are an advantage in reducing the risk of monetary loss in low rainfall areas. At Greenmount, the probability of losing money is negligible because the Typic Pellusterts there have PAWCs >200 mm (Freebairn et al, 1986a).

These simulated wheat yields are dominated by the relative transpiration rate at or near anthesis, which can be reduced by small leaf area and/or a low soil water store at this time (Woodruff and Tonks, 1983). In contrast, pasture has no yield-sensitive growth stages. Consequently, large differences in PAWC have much less influence on simulated yield (McCown, 1973).

CONCLUSIONS

Measuring and predicting the components of the catchment water balance is not an easy task for any type of soil or cropping system. The measurement of soil water parameters and processes in Vertisols is generally not much more difficult than in rigid soils. However, to make sensible comments on the long-term consequences of adopting various surface management treatments and cropping systems in a climate with highly variable (both in time and space) rainfall patterns, physically-based simulation models are required.

These models require both a sound physical understanding of how hydrological processes respond to management treatments, and the expression of this understanding by quantitative equations. The level of understanding of rainfall infiltration into Vertisols in the Queensland context is inadequate.

Similarly, a better understanding of why relatively subtle differences in climate and soil cause the success or failure of opportunity cropping techniques is necessary. It is likely that this understanding will require, in part, a closer examination of the soil physics of the upper 20 cm of the soil profile, since the water balance of this layer determines opportunities to plant crops, which, in turn, strongly influence the probability of drought stress at flowering (and, hence, crop yield).

Although a large PAWC does not ensure high crop yields unless sufficient fallow and growing season rain occurs, its value is still an important variable in any cropping model. There is a need to understand those soil properties which allow (or prevent) deep and active subsoil rooting, which overwhelming determines PAWC in Vertisols.

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IRRIGATION WATER MANAGEMENT FOR COTTON ON VERTISOLS IN THE MIDDLE AWASH REGION OF ETHIOPIA

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ABSTRACT

Improved water management practices for cotton, planted on Vertisols in the Middle Awash region of Ethiopia, were developed at Melka Werer Research Centre of the Institute of Agricultural Research.

The optimum irrigation furrow length on Vertisols is 200 m. The optimum initial stream flow rate for a furrow of this length with a slope range of 0.005-0.008% is 3.5 litres sec^{-1} with a cut-back stream flow rate of 1.5 litres sec^{-1}: for a slope of about 0.015%, the optimum initial stream flow rate is 2.13 litres sec^{-1} and cut-back stream flow rate 1.61 litres sec^{-1}.

The recommended irrigation schedule for cotton includes irrigations of 75 mm at 2-week intervals or 125 mm at 3-week intervals. However, according to a computed irrigation schedule for cotton planted on 15 May on Vertisols (available water: 220 mm m^{-1}), the crop needs one irrigation of 60 mm at establishment, two irrigations of 75 mm each at 12-day intervals during the vegetative stage, four irrigations of 105-110 mm each at 2-week intervals during yield formation, and one irrigation of 140 mm towards ripening, in addition to 150 mm at planting. For maximum crop production, 75-mm irrigations should be applied at 2-week intervals in addition to 200 mm at planting.

To optimise production per unit of water applied, three irrigations, one of 200 mm at planting, followed by two of 150 mm each at flowering and boll formation, are adequate to obtain a yield similar to that obtained with 75-mm irrigations at 2-week intervals, provided rainfall is normal and well distributed during the season. This will save 40-50% of the irrigation water. Cotton can extract considerably more water from the lower soil depths when irrigated at 4-week intervals than when irrigated at 2-week intervals.

INTRODUCTION

The Middle Awash region of Ethiopia is in the semi-arid climatic zone with a long hot summer and a short mild winter. Annual rainfall amounts to 200-500 mm. Irrigation is therefore vital to ensure crop production.

Accurate information on soils in the area is sparse. However, a soil survey of 200 ha at the farm in Melka Werer Research Centre showed that Vertisols constitute about 70% of the farm area.

In this area, cotton is the main crop and is grown on about 13 000 ha, but wheat is gaining popularity. Soil, water and climatic conditions are suitable for growing many other lowland crops such as maize, groundnut, sesame, kenaf, fruits and vegetables.

Mismanagement of irrigation on poorly drained Vertisols under semi-arid conditions could lead to waterlogging and soil salinisation. These problems have resulted in 30% of the 3500-ha Melka Sadi State Farm being seriously affected by waterlogging and salinity after only 15-20 years.

Melka Werer Research Centre (MWRC) of the Institute of Agricultural Research (IAR) has been engaged in research to develop improved water management practices. Research topics include evaluation of stream size in relation to furrow length, determination of optimum irrigation frequency and irrigation depth, soil moisture extraction patterns by different crops, and evaluation of the effect of drought stress on growth and yield of important crops. This paper summarises the results of some of the experiments conducted at MWRC for developing efficient water management practices for cotton grown on Vertisols in the Middle Awash region of Ethiopia.

MATERIALS AND METHODS

Chemical and physical characteristics of Vertisols

To determine chemical and physical characteristics of Vertisols, a representative soil profile to 2 m was described and soil samples taken. The infiltration rate of the soil was measured near the sampling site using the standard double ring method. Field capacity and permanent wilting point were determined using a pressure membrane apparatus.

Soil moisture samples were taken separately from 19 different locations representing Vertisols at the MWRC and the Amibara Irrigation Project. Field capacity and permanent wilting point of each sample were determined. Soil density measurements were taken at each of the 19 sites and available soil moisture was calculated. Regression analyses of clay content on field capacity on permanent wilting point were carried out.

Stream flow rate and furrow length evaluation

Six alternate furrows, each 250 m long, were selected on Vertisols at MWRC, Melka Sadi and Amibara State Farms. Furrow spacing was 80-90 cm, depth was 25-40 cm, field slope was 0.005-0.015%.

Furrows were staked at 25-cm intervals along the entire 250-m length. Six stream flow rates ranging from 0.60 to 4.42 litres sec^{-1} were tested. Flow rates were calibrated and measured volumetrically before the test. As water was led into each furrow, the time taken for the water to reach each station was recorded, and Parshall flumes were used to measure flow during the test. Each furrow was inspected for overflow or erosion, out-flow at the end of each furrow was observed, and excess flow was cut back and the cut-back flow rate recorded. At the end of the test, the time for the water to recede at each station was recorded. Forty-eight hours after the test, water distribution at the upper, middle and lower end of each furrow was estimated from soil samples.

Quantities of water needed to refill the soil moisture reservoir to field capacity were computed, and the time necessary to refill the soil moisture reservoir was determined using the water intake rate measured at each site. Stream advance time and total irrigation time were determined. From the advance rate, optimum stream flow rate and optimum furrow length for each stream flow rate were determined. Water distribution and irrigation application efficiency were recorded.

Irrigation frequency and depth

Cotton varieties Acala 1517/70 and Acala 1517/70C were planted as test crops. Different irrigation

frequencies and irrigation depths were studied. Two or three irrigations during the crop establishment stage were common to all treatments, after which differential irrigation frequencies and depths were applied to the respective treatments. Each treatment was replicated at least four times. Irrigation applied was supplemented to rainfall during the season (Table 1). Each irrigation application was measured and seasonal irrigation applications and rainfall were recorded. All other cultural practices were standard and common to all treatments. The characteristics of the Awash river water used for irrigation are given in Table 2.

Computed irrigation schedule

The irrigation schedule for cotton planted on Vertisols (available water: 220 mm m^{-1}) in the Middle Awash area was calculated for 15 May planting. Growth stages, root depth and distribution, crop water requirements, and irrigation application at 60% depletion of available soil moisture were considered.

Drought stress vs yield

Six previously screened stress-tolerant cotton varieties were tested during 1983-1986. Different levels of drought stress were imposed by the four treatments:

A. One 200-mm irrigation at planting;
B. One 200-mm irrigation at planting and a second irrigation of 150 mm at peak flowering;
C. One 200-mm irrigation at planting and two subsequent irrigations of 150 mm each at peak flowering and boll formation; and

Table 1. Rainfall during cotton growing season.

Month	Rainfall (mm)						
	1968	1969	1974	1975	1983	1984	1986
May 15-30	1.0	17.8	25.6	0.0	30.9	70.3	53.1
June	55.8	6.1	53.8	57.0	17.8	33.7	59.1
July	130.7	75.0	151.1	186.0	107.5	144.6	107.4
August	145.8	84.6	28.8	169.0	149.2	63.3	67.1
September	46.4	18.0	72.8	57.4	24.4	70.0	114.6
October	12.0	0.4	4.2	4.0	12.2	0.0	5.2
November	53.1	0.8	0.0	0.0	0.0	2.0	0.0
Total	444.8	202.7	336.3	473.4	342.0	383.9	406.5
Effective rainfall (70%)	311.4	141.9	235.4	331.4	239.4	268.7	284.6

Table 2. Characteristics of Awash river water at Melka Werer (1985).

Time of sampling	pH	EC (mmhos cm^{-1})	CO_3^{2-}	HCO_3^-	Cl^-	Ca^{2+} and Mg^{2+}	Na^+	K^+	SAR
July	8.1	0.20	0.24	0.24	0.22	0.46	1.09	0.15	2.27
October	8.5	0.70	0.40	0.76	1.34	0.58	6.03	0.31	11.17

D. One 200-mm irrigation at planting and nine subsequent irrigations of 75 mm each at 2-week intervals up to 126 days after planting (control treatment).

These four treatments were replicated four times in a randomised complete block design. Irrigation applied was supplemental to rainfall during the season (Table 1). All other cultural practices were standard and common to all treatments.

RESULTS AND DISCUSSION

Physical and chemical characteristics of Vertisols

A typical Vertisol is characterised in Table 3. From data in Table 4, the regression analysis of clay content (C) on field capacity (FC) on permanent wilting point (PWP) gave the following equations:

$$FC = 35.74 + 0.37\ C, \quad r = 0.76$$

$$PWP = 12.42 + 0.41\ C, \quad r = 0.74$$

The predicted and measured values matched reasonably well. The above regression equations are valid under the following limiting conditions:

- clay content of 40-84%,
- textural group of clay loam to clay, and
- negligible organic matter content.

Table 3. Chemical and physical characteristics of a Vertisol.

Depth (cm)	pH	ECe (mmhos cm^{-1})	Colour	Clay (%)	Structure	Water content FC[a] (%)	Water content PWP[b] (%)	Bulk density (g cm^{-3})	Available water (mm m^{-1})
0-32	8.5	1.8	10YR 3/2	69.5	Sub-angular blocky	53.9	36.4	1.31	229.9
32-48	8.2	1.7	10YR 4/2	65.5	Sub-angular blocky	56.5	35.1	1.44	308.6
48-83	8.1	1.2	7.5YR 3/2	67.5	Prismatic	55.5	35.8	1.38	271.9
83-140	8.0	3.5	10YR 2/2	63.5	Sub-angular blocky	53.3	35.2	1.45	262.0
140-200	7.3	4.5	10YR 6.3	47.5	Massive	48.4	32.1	1.27	207.1

a. Field capacity.

b. Permanent wilting point.

Source: G. Haider, Endale Bekele and Tilahun Hordofa (IAR, Addis Ababa, Ethiopia, unpublished data).

Table 4. Moisture characteristics of 19 Vertisols.

Soil No.	Clay (%)	Bulk density ($g\ cm^{-3}$)	Water content FC[a] (%)	Water content PWP[b] (%)	Available water ($mm\ m^{-1}$)
1.	64	1.2	56.53	34.24	222.9
2.	48	1.3	53.89	32.42	214.7
3.	40	1.3	51.26	28.61	226.5
4.	76	1.15	65.64	43.53	221.1
5.	80	1.15	64.20	41.52	226.8
6.	54	1.25	60.40	40.64	197.6
7.	60	1.25	65.98	47.04	189.4
8.	52	1.25	55.48	32.73	227.5
9.	58	1.25	62.89	42.01	200.8
10.	48	1.30	52.53	29.38	231.5
11.	38	1.35	42.46	20.95	213.1
12.	56	1.25	53.76	33.63	201.3
13.	78	1.15	65.04	40.88	241.6
14.	72	1.15	56.44	35.48	209.6
15.	56	1.25	52.36	32.30	200.6
16.	46	1.30	58.01	35.58	224.3
17.	52	1.25	57.56	37.33	202.3
18.	62	1.20	52.66	31.25	214.1
19.	84	1.15	68.23	53.50	247.3

a. Field capacity.
b. Permanent wilting point.

Source: Kandiah, IAR, Addis Ababa, unpublished data.

Stream flow rate and furrow length

Soil moisture characteristics at three selected sites are given in Table 5. Optimal stream flow

rates and furrow lengths at three sites are given in Table 6. In general:

- a furrow length of 200 m is optimum for Vertisols;
- with a furrow slope range of 0.005-0.008%, the optimum initial stream flow rate for a 200-m long furrow is 3.5 litres sec^{-1} with a cut-back stream flow rate of 1.5 litres sec^{-1};
- for a field slope of about 0.015%, the optimum initial stream flow rate is 2.13 litres sec^{-1} with a cut-back stream flow rate of 1.61 litres sec^{-1}; and
- the application efficiency is around 70% (Kandiah, 1981).

Irrigation frequency and irrigation depth

The first irrigation frequency trials were conducted during 1968 and 1969. The crop was irrigated at 2-, 3- and 4-week intervals. There were no significant differences in yield among the irrigation interval treatments (Table 7). However, a consistently higher yield (combined seed and fibre) was obtained when the crop was irrigated every 2 weeks. The higher yield levels for 1968 could be due to higher rainfall and a better rainfall distribution (Table 1). Plants that were irrigated at 4-week intervals had deeper roots that extracted considerably more water from the lower soil depths than plants that were irrigated at 2-week intervals (Table 8) (MWRS, 1968; 1969).

A second trial was carried out in 1974 and 1975. Four irrigation frequencies (2-, 3-, 4-,

Table 5. Soil moisture characteristics of selected Vertisol sites.

Characteristics	Location I	Location II	Location III
Slope (%)	0.008	0.015	0.005
Water content at field capacity (%)	42.0	42.0	42.0
Bulk density (g cm^{-3})	1.2	1.2	1.2
Average initial soil moisture (%)	27.6	27.34	27.44
Water required to refill 75 cm of root zone (cm)	12.06	13.20	13.10
Refill time (hours)	3.99	3.62	4.65
Stream advance time (hours)	1.00	0.90	1.16
Total irrigation time (hours)	4.99	4.52	5.81

Table 6. Optimum stream flow rates and furrow lengths.

Characteristics	Location I	Location II	Location III
Optimum initial stream flow rate (litres sec^{-1})	3.44	2.34	3.50
Cut-back stream flow rate (litres sec^{-1})	0.72	1.72	1.42
Optimum furrow length (m)	205.00	190.00	210.00
Application efficiency (%)	97.00	78.00	62.00

Table 7. Cotton yield (combined seed and fibre) for different irrigation intervals.

Irrigation interval (week)	Yield (t ha^{-1})	
	1968	1969
2	2.15	1.72
3	2.02	1.68
4	1.94	1.57

None of the values were significant at the P=0.05 level.

Table 8. Soil moisture extraction pattern.

Soil depth (cm)	Percent moisture depletion			
	2-week intervals		4-week intervals	
	1968	1969	1968	1969
0-30	64.5	60.8	46.5	44.1
30-60	20.7	23.2	30.0	29.7
60-90	14.8	16.0	23.5	26.2

Source: IAR/MWRS (1968; 1969).

and 5-week intervals) and three amounts of irrigation water (75, 125 and 175 mm) were replicated four times in a split-plot design. Irrigation at 2-week intervals during 1974 gave a significantly higher yield than irrigation at 3-,

4- and 5-week intervals (Table 9). The difference in yield between 4- and 5-week intervals was not significant. During 1975, irrigating every 2 or 3 weeks resulted in significantly higher yields than irrigating at 4- or 5- week intervals. In 1974 plants that received 175-mm irrigations gave higher yields than plants which received 125- and 75-mm irrigations (Table 9). In 1975, irrigation depth had no significant effect on yield. Interaction between irrigation frequency and irrigation depth was not significant in either year. However, water use efficiency was greatest when a 75-mm irrigation was applied at 2-week intervals or when a 125-mm irrigation was applied at 2- or 3-week intervals.

The higher yields in 1975 could have been due to well-distributed higher rainfall (Table 1), which could also be responsible for the lack of yield differences among the treatments during 1975 (IAR/MWRS 1974; 1975).

Effective rainfall during any irrigation interval should be deducted from the irrigation quantity in the computed schedule shown in Table 10 (Haider, IAR/MWRC, Addis Ababa, unpublished data).

Drought stress vs yield

Cotton yield was affected significantly by different drought stress treatments. Yields from treatments C and D were significantly higher than from treatments A and B (P=0.05) (Table 11). Differences in yields from treatments C and D were non-significant in two out of the three seasons. Treatment A gave a significantly lower yield than the other treatments except in 1987 when the differences in yield from treatments A and B were

Table 9. Effect of irrigation interval and depth on cotton yield.

Year	Mean cotton yield (t ha^{-1})						
	Irrigation interval (weeks)[a]				Irrigation depth (mm)[a]		
	2	3	4	5	75	125	175
1974	5.70a	4.97b	3.64c	3.43c	3.73a	4.41b	5.16c
1975	6.41a	6.42a	6.06b	6.19b	6.39a	6.12a	5.90a

a. Within factors and years, values followed by the same letter are not significant at the P=0.05 level.

Table 10. Computed irrigation scheme for different growth stages of cotton. Total quantity of irrigation water is 930 mm.

	Planting	Establishment	Vegetative stage		Yield formation stage				Ripening
Irrigation interval (days)	0	21	12	12	14	14	14	14	25
Cumulative days after planting	0	21	33	45	59	73	87	101	126
Irrigation quantity (mm)	150	60	75	75	110	110	105	105	140

Source: Haider, IAR/MWRC, Addis Ababa, unpublished data.

Table 11. Cotton yield for different treatments.

Treat-ment	Number of irrigations	Mean cotton yield (t ha^{-1})[a]		
		1983	1985	1987
A	1	0.91c	0.47d	3.56b
B	2	1.83b	0.72c	3.88b
C	3	2.83a	1.11b	4.26a
D	10	3.13a	3.87a	4.32a

a. Values in the same column followed by the same letter are not sigificantly different at the P=0.05 level.

Source: IAR/MWRC, Addis Ababa, Ethiopia, unpublished data.

not significant. Higher yields in 1987 could have been due to higher and better distributed rainfall during the season. Treatments C and D consistently used water more efficiently than treatments A and B.

To maximise cotton yield, nine irrigations of 75 mm each should be applied at 2-week intervals up to 126 days after planting, in addition to one 200-mm irrigation at planting. However, if irrigation water is inadequate, three irrigations of 200, 150 and 150 mm at planting, peak flowering and boll formation are enough to obtain reasonably good yields. If rainfall is well distributed during the season, then yields comparable to the treatment of 10 irrigations can be expected from the three irrigations, in addition to reducing water use by 40% (IAR/MWRC, Addis Ababa, Ethiopia, unpublished data).

CONCLUSIONS

The clay content of Vertisols in the Middle Awash area is 40-84% with an available soil moisture range of 180-250 mm m^{-1}. There are positive relationships between soil clay content and field capacity and permanent wilting point.

The optimum irrigation furrow length for Vertisols is 200 m, with an optimum initial stream flow rate for a slope range of 0.005-0.008% of 3.5 litres sec^{-1}, with a cut-back stream flow rate of 1.5 litres sec^{-1}. For a furrow slope of about 0.015%, the optimum initial stream flow rate is 2.13 litres sec^{-1} with a cut-back stream flow rate of 1.61 litres sec^{-1}.

The recommended irrigation schedules for cotton in the Middle Awash region are: 75-mm irrigations at 2-week intervals, or 125-mm irrigations at 3-week intervals.

According to the computed irrigation schedule, the crop needs one irrigation of 60 mm during the crop establishment stage, two irrigations of 75 mm each, 12-days apart, during the vegetative stage, four irrigations of 105-110 mm each at 2-week intervals during yield formation, and one irrigation of 140 mm towards the ripening stage.

For maximum production, cotton should be irrigated at 2-week intervals with 75 mm of water. However, to optimise the production per unit of water, three irrigations, one of 200 mm at planting, followed by two of 150 mm each at flowering and boll formation, are adequate to obtain a reasonably good yield. This yield would be similar to that from 75-mm irrigation applications at 2-week intervals, provided

rainfall is normal and well distributed during the growing season, and will also save 40% of the irrigation water.

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SOIL MOISTURE RELATED PROPERTIES OF VERTISOLS IN THE ETHIOPIAN HIGHLANDS

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ABSTRACT

The influence of soil moisture on the consistency and bulk density of Vertisols in the Ethiopian highlands was investigated. A moisture content of 29-39% at the plastic limit was found to be the optimum for ploughing 18 Vertisols studied. The practical implications of consistency limits on tillage and other uses of the Vertisols in the Ethiopian highlands are discussed. Curvilinear relationships were found between moisture content and bulk density. The problems of field determinations of bulk density for volumetric moisture content calculations are highlighted. A simple correction procedure for the reduction in soil core volume in the determination of bulk density for volumetric moisture content calculations is presented.

INTRODUCTION

Soil moisture has a major influence on the behaviour of Vertisols during tillage and weeding, and at harvest. While interest in estimating soil moisture has been strong, the relationship between soil moisture content and other soil properties

that affect management and use has received little attention, particularly in sub-Saharan African soils.

Soil consistency is closely related to soil moisture. The moisture content affects the ability to work the soil, and the consistency is an index of that ability. The indices are important for tillage operations, and traffic by farm animals, farm implements and humans. Soil consistency has also been related to shrinking and swelling of clays, compressibility, strength and soil permeability, and has been used as a guide to when to begin soil manipulation (Sowers, 1965).

In addition to clay and critical moisture content, Nayak and Christensen (1971) concluded that the swelling potential of expansive soils was a function of the plasticity index. Paul (1982) used the consistency at the plastic limit to recommend a moisture content of 25-30% for tillage operations for shrinking and swelling clay soils in Guyana.

The consistency of abrasive and adhesive clay soils in Alabama was used to develop tillage equipment that allowed soil tillage over an extended moisture range, and hence increased the possibility of growing two crops in one growing season (Johnson et al, 1982). In Ethiopia, Berhanu Debele (1985) considered the consistency of Vertisols to be unfavourable and a limit to their ability to be worked productively, and to need investigation.

Knowledge of volumetric moisture content is required to assess the storage capacity of soils and for water balance studies. Bulk density is one property required to obtain volumetric

moisture content. The shrinking and swelling of Vertisols alters their bulk density and hence their volumetric moisture content. Several researchers (Yule, 1984; Smith, 1984) have shown that errors in volumetric moisture calculation result when the bulk density is not determined at the right moisture content. Yule (1984), following Fox (1964), suggested the determination and use of the shrinkage curve for volumetric calculations. The generalised curve (Yule, 1984), estimated after Yule and Ritchie (1980a), contains both the swelling and shrinkage limits and can be constructed, indirectly, from cation exchange capacity, bulk density at the swelling limit, and the water content at the swelling limit. However, there can be errors in the estimates of both bulk density and water content at the swelling limit.

Yule (1984) used a soil cube as a working model to establish a relationship between moisture content and vertical shrinkage. Although such models help to establish and explain some of the concepts, there have always been practical limitations in their application.

Satisfactory sampling for bulk density at the swelling limit (Yule, 1984) requires determination of the structural water loss, swelling limit, and shrinkage limit of the Vertisol. The subsequent correction procedure proposed by Yule (1984) is only accurate for a dry profile with constant water depth, and consequently has practical limitations for application to Uderts.

The bulk density/soil moisture relationships and the moisture content at which bulk density values are taken have not been calculated for Vertisols in sub-Saharan Africa.

Reports of the extent and characteristics of shrinking and swelling in Vertisols, and their relationship with moisture content, are scarce. This paper reports on the influence of moisture content on the consistency limits, and on bulk density and its implications in volumetric determination of soil moisture for Vertisols in the Ethiopian highlands.

MATERIALS AND METHODS

Sites and soils

The sites for this investigation were on ILCA Vertisol research and outreach project sites in the Ethiopian highlands. Some physical and chemical properties of the soils have been reported elsewhere (Kamara and Haque, 1987a).

Consistency limits

The consistency limits at the plastic and sticky points were determined according to the procedures described by Sowers (1965).

Bulk density and soil moisture

Field studies

The bulk densities of Vertisols were determined during the 1986 dry season at the ILCA Shola research site (SH/1/86) and at the ILCA Debre Zeit research station (DZ/4/86) in the Ethiopian highlands (Kamara and Haque, 1987b). At each location, 2.5 x 2.5-m plots were established by enclosing the plots with metal sheets extending 10 cm into the ground and 15 cm above the soil surface. The plots were flooded, covered with a

plastic sheet and sampled periodically with an Edelman auger to determine bulk density and gravimetric moisture content.

Laboratory studies

Moisture content and bulk densities of soils from the SH/1/86 site were determined for disturbed and undisturbed samples. Known amounts of water were added to air-dried sieved (2-mm mesh) samples from each layer, and the samples were repacked into cores 8 cm in diameter and 5 cm deep. The cores (four for each layer) were then oven-dried for 48 hours to determine moisture content and reduction in volume of the soil core. Four undisturbed cores taken at each layer from profile SH/1/86 were oven-dried, and moisture content and volume reduction were also measured.

RESULTS AND DISCUSSION

Soil consistency

Moisture content at the plastic and sticky consistency limits for 18 surface Vertisols are given in Table 1. Relative proportions of sand, silt and clay differ between the soils and are also shown to indicate the effect of the particles on consistency limits. Moisture content for all the soils varied from 29 to 39% at the plastic limit, and from 39 to 53% at the sticky point limit. Johnson et al (1982), Cooper and Georges (1982) and Paul (1982) have reported moisture contents of 28-40% for the plastic limit and 32-46% for the sticky limit for Vertisols and some clay soils elsewhere.

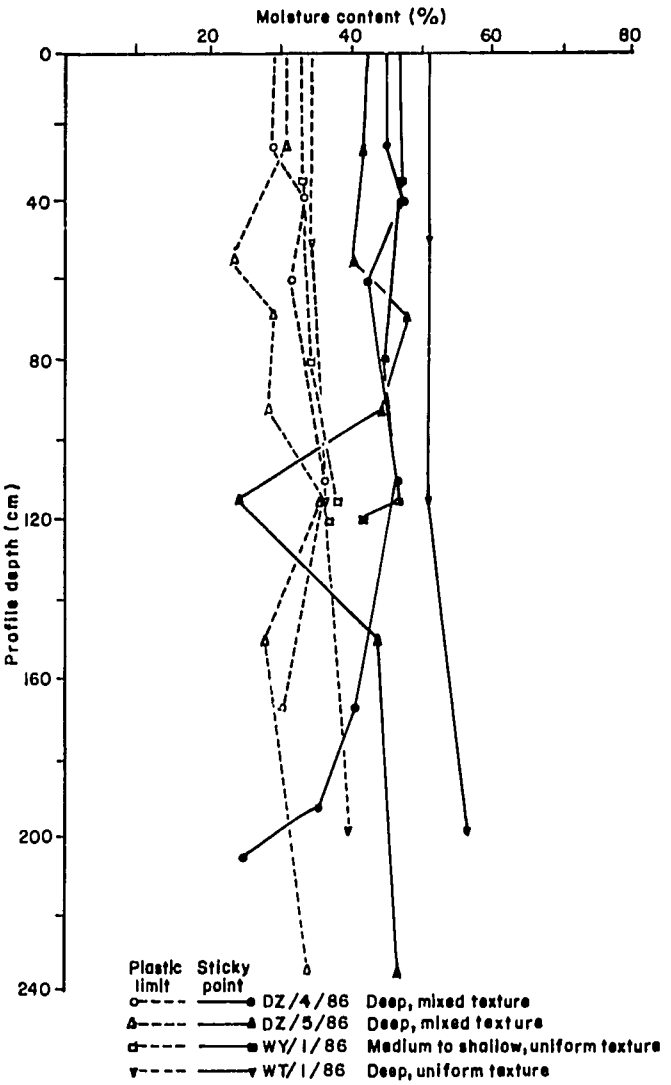
Table 1. Particle size analysis and moisture content at the plastic limit and sticky point limit for surface Vertisols from the Ethiopian highlands.

Profile	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Moisture content: Sticky point (%)	Moisture content: Plastic limit (%)	Plasticity index (%)
NR/1/86	0-70	20	20	60	47±1.3	33±0.8	14
NR/2/86	0-52	18	20	62	49±2.0	38±1.3	11
NR/3/86	0-78	20	18	62	51±0.7	36±1.0	15
DZ/4/86	0-25	19	22	59	45±0.7	29±1.3	16
DZ/5/86	0-26	14	34	52	42±0.6	31±2.5	11
SH/1/86	0-23	19	21	60	50±0.8	36±1.0	14
SH/2/86	0-20	23	24	53	52±1.0	37±0.7	15
WY/1/86	0-34	15	21	64	48±0.6	33±1.2	15
WY/2/86	0-38	19	21	60	45±0.5	31±1.3	14
WT/1/86	0-49	18	17	65	51±0.5	34±0.4	17
WT/2/86	0-37	18	21	61	53±1.1	35±0.8	18
MW/2/86[a]	0-41	16	42	42	42±0.6	36±1.4	6
SM/2/86	0-50	24	9	67	52±0.9	37±1.4	15
WG/1/86	0-40	15	21	64	50±0.8	38±5.0	12
DZ/3/86	0-22	11	39	50	39±2.0	30±0.8	9
DB/2/86[a]	0-60	15	33	52	52±0.8	37±1.8	15
SD/2/86[a]	0-26	27	4	28	49±1.4	39±0.7	10

a. Buried Vertisols (Kamara and Haque, 1987a).

Profile moisture distribution at the sticky point and plastic limit for deep uniform-textured, medium to shallow uniform-textured and deep mixed-textured Vertisols are shown in Figure 1. Moisture content is higher and more uniform for the profiles with a uniform texture than for those with a mixed texture. This is attributed to the different proportions of clay (Table 1) in the

Figure 1. Profile moisture distribution at the plastic and sticky point limits for Vertisols in the Ethiopian highlands.



profiles (Kamara and Haque, 1987a). Consistency limits in Table 1 can be taken as surface values for determining land preparation requirements. Consistency limits at lower depths (Figure 1) should provide a basis for estimating and evaluating--indirectly--the subsoil water-holding capacity, permeability, strength of subsoil material to support farm buildings or roads, and subsoil shrinking and swelling.

Soils with a low sticky point, such as DZ/4/86 and DZ/5/86, are not strong enough to support farm buildings and roads. For both surface (Table 1) and subsoil (Figure 1), the high sticky point consistency of WT/1/86 will hold more moisture than the low sticky point consistency and low plastic limit soil at WY/1/86 site. Soil from the lowest layer of the DZ/4/86 profile (Figure 1) failed the plastic limit test because of the coarseness of the material in that layer (Kamara and Haque, 1987a) .

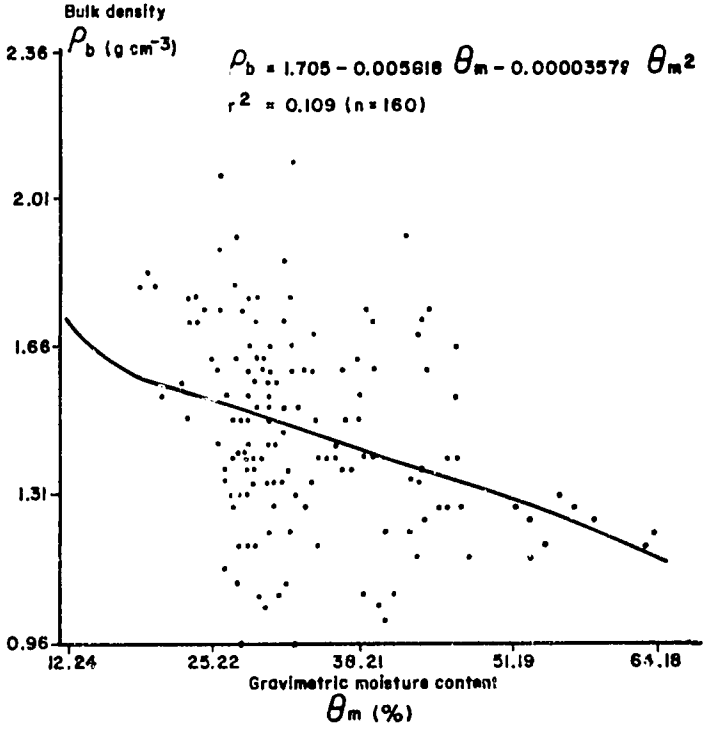
Bulk density and soil moisture

Field studies

Regression analysis was employed to establish and study the relationship between moisture content and bulk density of Vertisols at two sites in the Ethiopian highlands. Figures 2 and 3 show the relationship between gravimetric moisture content (θ_m) and bulk density for the two sites. The relationships are curvilinear and significant at P=0.05.

From about 18% θ_m the relationships are linear with increased moisture content. For swelling and shrinking clay soils, the linear part of the curve supports the normal one-dimensional

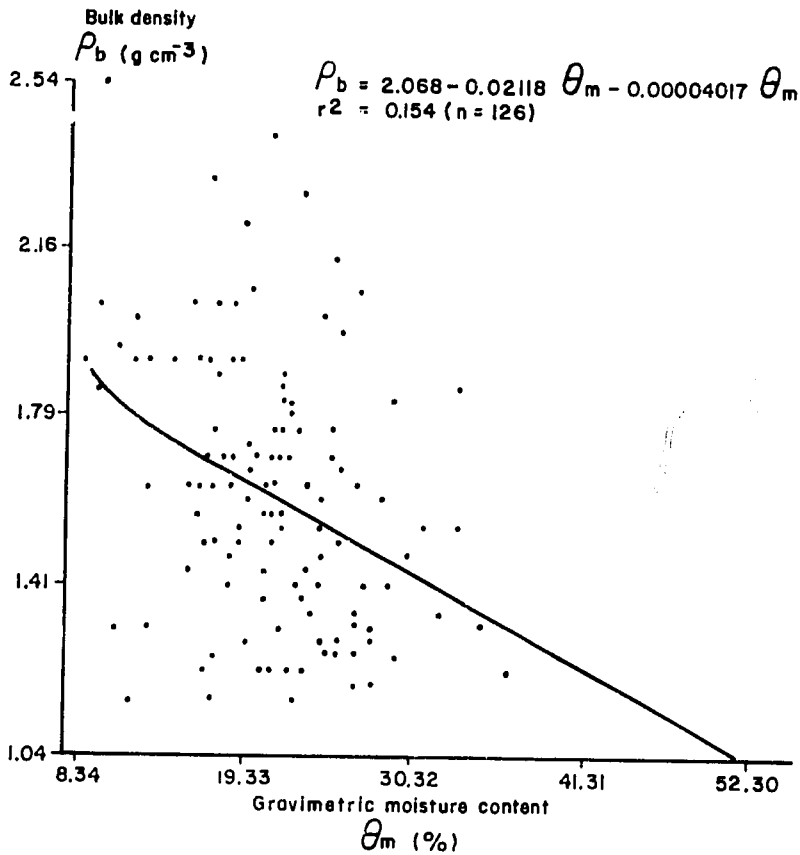
Figure 2. Relationship between gravimetric moisture content and bulk density for a Vertisol (SH/1/86) at Shola, Ethiopia.



shrinkage concept while the other part is three-dimensional (Fox, 1964; Berndt and Coughlan, 1977; Yule and Ritchie, 1980a and 1980b; McIntyre, 1984).

For black earth soils from Australia, Fox (1964) found that for undisturbed soil cores the transition point between one-dimensional and three-dimensional shrinkage was at about 45%

Figure 3. Relationship between gravimetric moisture content and bulk density for a Vertisol (DZ/4/86) at Debre Zeit, Ethiopia.



moisture content. The differences in the transition points in the Shola and Debre Zeit Vertisols and the black earth soil in Australia may be due to differences in the composition of the soils (McIntyre, 1984).

Laboratory studies

The volume of a Vertisol core is reduced by oven drying for bulk density and moisture content determinations. Consequently, the volume of the cylindrical core used to determine soil bulk density does not represent the core volume as assumed for non-shrinking soils.

The relationships between moisture content and reduction in soil volume in the disturbed cores after oven-drying, and r^2 values, for the SH/1/86 profile in the Ethiopian highlands are given in Table 2.

The reduction in soil volume of undisturbed cores taken from five layers of the SH/1/86 profile, the bulk density corrected for the reduction in soil core volume, and the uncorrected densities, are shown in Table 3. The cores were taken on 9 June 1987 after the onset of the main rainy season to allow crack closure and profile moisture recharge.

Table 2. Regression equations and r^2 values of soil core volume reduction (V_r in %) as a function of percentage soil moisture (θ_m) of a Vertisol profile (SH/1/86) in Ethiopia.

Depth (cm)	Regression equation	r^2
0-23	$V_r = -4.5440 + 0.6592\ \theta m - 0.002862\ \theta m^2$	0.954[a]
23-100	$V_r = 5.0000 + 0.2363\ \theta m + 0.001680\ \theta m^2$	0.984[a]
100-127	$V_r = 0.1279 + 0.6467\ \theta m - 0.001651\ \theta m^2$	0.980[a]
127-164	$V_r = 3.2630 + 0.3310\ \theta m + 0.001011\ \theta m^2$	0.983[a]
164-200	$V_r = -3.9440 + 0.6162\ \theta m - 0.000847\ \theta m^2$	0.992[a]

a. Significant at P=0.05.

The gravimetric moisture content that influenced soil core volume in the bulk density determination is included in Table 3. The soil moisture content at sampling was significantly different for some of the layers within the profile, and therefore the correction procedures suggested by Yule (1984) are inappropriate. The consequent volume reduction also differs between layers, which makes it necessary to ascertain the volume reduction for each Vertisol profile layer when determining bulk density.

The regression equations in Table 2 were used to predict the reduction in soil core volume for each layer in profile SH/1/86. The predicted bulk densities calculated for corrected and uncorrected soil core volumes are included in Table 3. The measured bulk densities from the undisturbed cores that were corrected for the reduction in volume were not statistically different from those predicted using disturbed cores. The disturbed core sample approach used in this investigation can therefore represent field conditions.

Oven-drying reduced the soil core volume of the Shola Vertisol by 52-72 cm^3, which resulted in an underestimation of the bulk density by 21-27%. The volume reduction for each layer in the profile was different because the moisture content within layers differed at sampling time. However the reduction in volume cannot be explained entirely by the moisture content because high moisture content did not always produce correspondingly high volume reductions.

High clay content is generally associated with high shrinkage, and hence reduced volume upon drying. The clay content in this profile increased with depth and ranged from 60 to 74%

Table 3. Measured and predicted bulk density values for the Shola profile (SH/1/86)[a].

	Soil profile depth (cm)				
	0-23	23-100	100-127	127-164	164-200
Gravimetric moisture content (%)	46±2.4a	51±1.3b	53±1.8bc	47±1.7a	47±1.5a
Oven-dry weight of soil core	275.2±7.1	271.9±3.9	269.1±5.3	279.7±3.4	279.4±11
Volume reduction (cm^3)					
measured	72±4.4a	71±4.2a	52±7.1b	65±5.9ac	66±2.8ac
predicted	54	54	75	53	58
Uncorrected bulk density ($g\ cm^{-3}$)					
measured	1.09±0.03	1.08±0.02	1.07±0.02	1.11±0.01	1.11±0.04
predicted	1.09	1.08	1.07	1.11	1.11
Corrected bulk density ($g\ cm^{-3}$)					
measured[b]	1.52±0.02	1.51±0.02	1.35±0.05	1.51±0.03	1.51±0.03
predicted[b]	1.39	1.38	1.52	1.41	1.45

a. Figures within rows followed by the same letters are not significantly different at P=0.05.

b. Values are not significantly different at P=0.05 (t. test comparison, Snedecor and Cochran, 1967).

(Kamara and Haque, 1987a). The volume reduction should have shown a trend similar to the clay content if the clay content was a primary factor. Clay mineralogy and organic matter content might also be important. The mineralogy of this profile has not been investigated but profile organic matter has been reported to range from 5.25% at the surface to 0.09% at a depth of 2.0 m (Kamara and Haque, 1987a).

The reduced volume and the calculated bulk densities for both the corrected and the uncorrected soil core volume reduction were used to calculate volumetric moisture content. This calculation was used to assess the magnitude of the underestimation when the reduced volume is not accounted for in the volumetric moisture calculations (Table 4).

Table 4. Calculated volumetric moisture content from uncorrected and corrected soil core volume for the Shola profile (SH/1/86).

	Measured	Measured		Predicted	
Profile depth (cm)	Uncorrected volumetric moisture content (g cm^{-3})	Corrected volumetric moisture content (g cm^{-3})	Under-estimation (%)	Corrected volumetric moisture content (g cm^{-3})	Under-estimation (%)
0-23	0.501	0.699	28.32	0.639	21.59
23-100	0.551	0.770	28.44	0.704	21.73
100-127	0.567	0.716	20.81	0.806	29.65
127-164	0.522	0.710	26.47	0.663	21.26
164-200	0.522	0.710	26.47	0.682	23.46

Determination of field bulk density is always required for volumetric moisture calculations. Sampling for bulk density in Vertisols at maximum swelling limit (Yule, 1984) requires estimation of the various limits in the shrinkage curve and is hence time consuming, expensive, and impossible in areas where facilities are limited. The established relationships between moisture content and volume reduction (Table 2) for the SH/1/86 profile allow for quick estimation of a correction factor that can be used to determine the actual bulk density of the Vertisols. The advantages of this approach are that: sampling for bulk density can be done at any time during the year, as in non-swelling and non-shrinking soils; and that sampling depths can be varied.

ACKNOWLEDGEMENTS

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SOIL MOISTURE STORAGE ALONG A TOPOSEQUENCE IN ETHIOPIAN VERTISOLS

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ABSTRACT

Soil moisture was measured for 53 weeks during 1986/87 at five sites along a toposequence in the Ethiopian highlands to determine the soil moisture storage capacity for improved cropping systems.

The major soils in the area are Alfisols in the uplands, Vertisols at the lower elevations, and soils with vertic properties between the two. The Alfisols never fully recharge to field capacity to a depth of 50 cm throughout the season, but Vertisols recharge above field capacity, with the adjacent soils receiving excess water only at 1 m depth. During the general vegetative, reproductive and maturation stages of crops in the area, the Vertisols stored 16, 19 and 37% more moisture, respectively, than the Alfisols. The Vertisols can be cultivated during the post-rainy season if the top 50 cm are irrigated to maximum recharge.

INTRODUCTION

Large-scale improved management of specific soils is usually directed towards stabilising and

sustaining crop production as a means to improve living standards. In general, participating farmers hold parcels of land with soils that might be different from those selected for improvement. In the Ethiopian highlands poorly drained Vertisols occur at the bottom of the toposequence, while well-drained upland soils are used for buildings, farmsteads, grazing, and food crop production. Development of production packages for other soils in the area along with the Vertisols will augment the adoption of the Vertisol packages (Jutzi et al, 1987). Such production packages should include characterisation of the soil moisture storage capacity necessary to maintain the stability of all soils within the area for crop production (Haque and Tothill, 1987).

The main purpose of characterising crop production constraints such as soil moisture storage capacity is to enable prediction of crop yields for specific soils under a given climate. For soils along a toposequence, the emphasis has been on predicting soil moisture patterns from some topography characteristics. Employing Horton's (1941) sheet erosion model, Burt and Butcher (1985) developed a topographic index for non-linear hillslopes that relates depth of moisture saturation to the area upslope (a) and the local hillslope gradient (s). Similar area-based indices had been employed to predict the area contributing to surface runoff (Beven and Kirkby, 1979), and distribution of soil moisture deficits within a subcatchment area (Beven and Wood, 1983). Anderson and Kneale (1982) observed that the a/s index was less accurate for shallow slopes because soil properties other than runoff from the upper part of the slope become important. This shortcoming of the relationship between a/s

index and soil moisture distribution pattern is applicable to most of the lower slopes in the Ethiopian highlands where Vertisols occur.

Quantified shapes along slopes have been related to soil moisture patterns (Evans, 1980), and the problems of quantifying the shapes were discussed by Anderson and Burt (1980). Burt and Butcher (1985) compared the a/s index and the quantified shape aspects of the hillslopes for predicting soil moisture patterns along a toposequence in south Devonshire, England, but found the combined area base and shape index to be satisfactory only during wet periods.

Under a ustic soil moisture regime at Kathrine in Australia, Williams et al (1983) estimated that a profile moisture store of less than 100 mm had a less than 30% probability of meeting the moisture requirement of a sorghum crop, and even 200 mm had only a 70% probability of meeting the requirement. In the semi-arid areas of Australia, Williams and Probert (1983) reported fairly accurate prediction of dry-matter yield of *Stylosanthes humilis* using profile water store, rainfall, evaporation and temperature.

Rainfall amount, evaporation, air temperature, and soil type and position within the landscape are major considerations when assessing soil moisture storage capacity along a toposequence. Such assessment can lead to more efficient water management for crops, particularly in areas where the landscape is predominantly undulating and water can be limiting.

The major objectives of this study were to determine the soil moisture storage capacity in various soil types along a toposequence, and to

determine and correlate periods of excess, adequate and deficit soil moisture to appropriate cropping systems for each soil.

MATERIALS AND METHODS

Site and soils

This investigation was carried out at the ILCA Debre Zeit research station, located at latitude 8°44' N, longitude 38°58' E, and 1850 m altitude. The soils are classified as Alfisols in the upland region, Vertisols in lower-lying areas and an intermediate group with vertic properties in between. A detailed description of the pedon and physico-chemical properties of three profiles representing the Vertisols, Alfisols and the intermediate soils with vertic properties is reported elsewhere (Kamara and Haque, 1987).

Experimental procedures

On the toposequence with slopes ranging from 1 to 10%, five sites were selected based on soil type and slope length. At each site, three access tubes were installed 30 m apart across the slope (Figure 1).

Weekly soil moisture measurements were made from 1 July 1986 to 1 July 1987: with a neutron probe from 20 cm depth at 10 cm increments; and gravimetrically, using an 8-cm diameter, 5-cm long, core, from 0-10 cm depth. The area around each access tube was uncropped and kept free of weeds throughout the period. Monthly rainfall, evaporation and temperature for the experimental period were recorded at the ILCA Debre Zeit weather station (Table 1).

Figure 1. Diagram of the toposequence showing major soils and positions of access tubes.

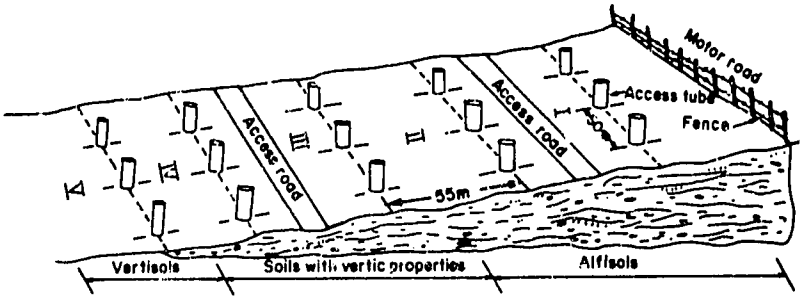


Table 1. Monthly rainfall, evaporation and temperature at the ILCA station, Debre Zeit, during the experimental period.

	1986							1987					
	J[a]	J	A	S	O	N	D	J	F	M	A	M	J
Rainfall (mm)	174	112	193	111	12	0	0	0	20	219	84	172	61
Evap. (mm)	139	134	149	138	243	269	270	357	273	174	201	205	153
Temp. (°C)													
max.	25	24	25	25	26	27	27	27	29	30	29	30	30
min.	10	10	9	8	6	6	7	8	8	11	10	10	9

a. Soil moisture measurements were taken from 1 July 1986 to 1 July 1987. However, as soil moisture values are affected by weather prior to measurement, June 1986 figures are also shown.

RESULTS AND DISCUSSION

Soil moistura storage limits

Table 2 shows soil moisture variation with depth at each of the five sites at maximum layer recharge (maximum) and at the driest layer condition (minimum). The maximum moisture recharge from the rains is an indication of the apparent maximum storage capacity of the soils at any depth and site. The magnitude of such a maximum store is affected by the soil texture and structure, which regulate the water transmission characteristics, the position of the site in the landscape, and the amount of rainfall. The top of the toposequence (site I) had a sandy loam texture at about 80 cm, while sites II to V had clay to loam-clay textures (Table 3) throughout the top 1 m, but the differences in the transmission of soil moisture down the profile cannot be attributed entirely to texture.

Maximum soil moisture recharge to an 80-cm depth was reached at sites I to III during September. Sites IV and V reached maximum moisture recharge to the 120-cm depth between July and September because these two sites received the runoff from sites I, II and III. Maximum moisture recharge should have been reached much earlier, but the delay might have been due to slow water movement through the heavy clay soil. The presence of cracks that could have allowed rapid water entry may be responsible for some of the lower depths reaching maximum recharge earlier than some upper layers.

The rate at which the minimum soil moisture was reached varied widely. Both the Alfisol (site I) and Vertisol (site V) appeared to dry

Table 2. Dynamics of annual maximum (max.) and minimum (min.) moisture status ($cm^3\ cm^{-3}$) at various depths along the toposequence.

Depth (cm)	Site I				Site II				Site III			
	Max.	Date	Min.	Date	Max.	Date	Min.	Date	Max.	Date	Min.	Date
0-10	0.401	16/09/86	0.030	30/01/87	0.454	09/09/86	0.033	27/11/86	0.401	16/09/86	0.030	30/01/87
10-20	0.415	16/09/86	0.010	13/01/87	0.373	16/09/86	0.048	18/11/86	0.560	09/09/86	0.056	10/02/87
20	0.483	16/09/86	0.165	12/08/86	0.378	16/09/86	0.087	10/02/87	0.497	09/09/86	0.224	17/02/87
30	0.593	16/09/86	0.281	06/01/87	0.433	8/07/86	0.212	24/02/87	0.527	23/09/86	0.331	12/05/87
40	0.544	16/09/86	0.147	20/01/87	0.458	16/09/86	0.300	16/06/87	0.519	09/09/86	0.343	12/05/87
50	0.481	16/09/86	0.320	24/02/87	0.476	16/09/86	0.277	12/03/87	0.501	23/09/86	0.340	26/05/87
60	0.415	30/09/86	0.297	12/05/87	0.439	16/09/86	0.331	30/06/87	0.492	23/09/86	0.314	19/05/87
70	0.411	09/09/86	0.201	19/08/86	0.361	16/09/86	0.314	16/06/87	0.495	16/09/86	0.379	03/06/87
80	0.234	16/09/86	0.126	12/05/87	0.359	16/09/86	0.322	30/06/87	0.495	23/09/86	0.329	03/06/87
90	0.190	04/11/86	0.135	22/07/86	0.378	22/07/86	0.217	30/06/87	0.478	23/09/86	0.307	03/06/87
100	0.164	02/09/86	0.143	25/03/87	0.427	22/07/86	0.309	30/06/87	0.423	23/09/86	0.291	03/06/87
110	0.173	11/11/86	0.144	04/03/87	0.465	23/09/86	0.384	12/05/87	0.388	21/10/86	0.275	03/06/87
120					0.474	30/09/86	0.353	06/01/87	0.410	10/02/87	0.255	03/06/87

Depth (cm)	Site IV				Site V			
	Max.	Date	Min.	Date	Max.	Date	Min.	Date
0-10	0.370	16/09/86	0.039	10/02/87	0.524	16/09/86	0.043	27/01/87
10-20	0.360	16/09/86	0.040	04/03/87	0.560	09/09/86	0.065	18/11/86
20	0.405	01/07/86	0.097	17/05/87	0.547	09/09/86	0.076	03/02/87
30	0.457	22/07/86	0.151	13/01/87	0.563	16/09/86	0.163	04/03/87
40	0.488	29/07/86	0.270	25/06/87	0.574	09/09/86	0.262	04/03/87
50	0.506	23/07/36	0.285	20/01/87	0.597	16/09/86	0.358	04/03/87
60	0.441	07/10/86	0.310	01/07/86	0.605	23/09/86	0.373	24/02/87
70	0.403	04/11/86	0.299	15/04/87	0.606	12/08/86	0.371	24/02/87
80	0.419	19/08/86	0.373	01/07/86	0.601	23/09/86	0.396	30/01/87
90	0.478	19/08/86	0.405	08/07/86	0.572	12/08/86	0.431	24/02/87
100	0.524	19/08/86	0.465	19/05/87	0.585	23/09/86	0.459	06/01/87
110	0.580	30/09/86	0.470	19/05/87	0.598	23/09/86	0.479	17/02/87
120					0.599	29/07/86	0.490	24/02/87

Table 3. Particle size distribution and textural class for various depths along the toposequence.

Site	Depth (cm)	Sand (%)	Silt (%)	Clay (%)	Textural class
I	0-20	43	22	35	Gravelly clay loam
	20-40	27	24	49	Gravelly clay
	40-60	32	26	42	Gravelly clay
	60-80	46	30	24	Loam
	80-100	64	22	14	Sandy loam
II	0-20	40	28	32	Clay loam
	20-40	34	28	38	Clay loam
	40-60	34	26	40	Clay
	60-80	30	26	44	Clay
	80-100	26	24	50	Clay
III	0-20	36	26	38	Clay loam
	20-40	33	36	31	Clay loam
	40-60	28	32	40	Clay loam
	60-80	27	30	43	Clay
	80-100	29	16	55	Clay
IV	0-20	30	35	35	Clay loam
	20-40	33	36	45	Clay
	40-60	32	31	37	Clay loam
	60-80	24	27	49	Clay
	80-100	24	25	51	Clay
VI	0-20	11	42	47	Silty clay
	20-40	31	31	37	Clay loam
	40-60	33	28	39	Clay loam
	60-80	22	39	39	Clay loam
	80-100	27	24	49	Clay

faster than the intermediate soils (Table 2). The period during which this minimum occurred is critical to some crops. The extent of drying, expressed as a percentage of the maximum moisture at the 20-, 50- and 100-cm depths for the five sites, is given in Table 4. The Vertisol (site V) lost more moisture at the 20-cm depth, but its high moisture reserve at maximum recharge gave a much lower drying effect at the 50- and 100-cm depths.

Table 4. Extent of drying (%) along the toposequence[a].

Depth (cm)	Sites				
	I	II	III	IV	V
20	66	77	55	76	86
50	33	42	32	44	40
100	17	28	31	11	22

a. Derived from Table 2 and expressed as a percent of the maximum moisture recharge.

The lower elevation Vertisols will be able to support deep-rooted crops. Because of the excessively dry top 20 cm, these soils will require supplemental irrigation to support an existing crop with deep roots or double cropping with shallow-rooting crops.

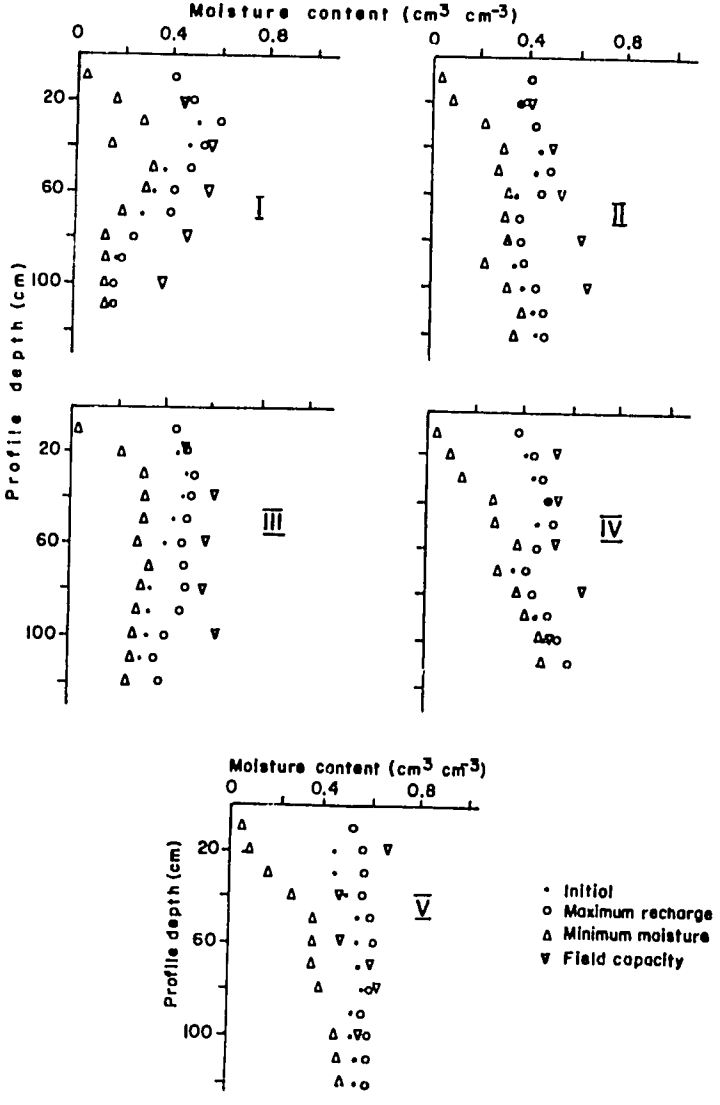
Supplementary irrigation for post-rainy season crop production in Vertisols is necessary, as suggested by Kanwar et al (1982) and Haque et al (1986). Using data from Table 2 for site V at the 0-1 m depth, the maximum recharge was

calculated as 578 mm, while the minimum moisture in the profile was 271 mm. For the top 50 cm of the profile, the maximum moisture was 279 mm and the minimum was 75 mm, while at the 50-100 cm depth the maximum was 298 mm and the minimum was 196 mm. While the top 1 m of the soil profile was depleted by 47%, the top 50 cm was depleted by 73%, and the 50-100 cm layer was depleted by only 25%. It is the top 50 cm that shows the greatest need for supplementary irrigation: to bring this top layer to maximum moisture-holding capacity, the top 20 cm will require 98 mm of water, the 20-40 cm layer 79 mm, and the 40-50 cm depth 28 mm. Drying is greatest at the 0-40 cm depth and is attributed to the depth of cracks--up to 45 cm--(Kamara and Haque, unpublished data).

Field capacity along the toposequence was determined by the pressure plate technique at 0.03 MPa (Figure 2). A fully recharged profile is one in which the recharge from the rain is equal to the moisture content at field capacity. The soils on the upper slopes (sites I, II and III) were never fully recharged to a depth of 50 cm, which implies that crops with roots of 50 cm or longer would need more moisture. Crops with roots less than 50 cm long would be suitable in this part of the landscape. The moisture recharge of the Vertisol (site V) was above field capacity at the 20-120 cm depth. Crop production under such conditions requires either crops that are not susceptible to waterlogging, or removal of excess water through drainage.

Alternatively, since the water above field capacity at the 50-cm depth for site V can be 63% more than that lost by drying, supplemental irrigation applied to the top 50 cm at the time of minimum soil moisture (Table 2) will support a

Figure 2. Soil moisture status at sites along the toposequence.



double cropping system on this part of the toposequence. The soils with vertic properties that are adjacent to the Vertisols were in general fully recharged, and had excess water only at the 1-m depth.

Seasonal moisture dynamics

Profile moisture status at the five sites along the toposequence was plotted for the weeks beginning 12 August 1986 (week 7), 28 October 1986 (week 18), 9 December 1986 (week 24), and 16 June 1987 (week 51) (Figure 3). The dates roughly represent the vegetative growth, reproductive and maturity stages of crops, and the fallow period/planting time for the area, respectively.

The highest moisture store was recorded during the vegetative growth stage: for site I, 0.52 cm^3 cm^{-3} at 30 cm; site II, 0.43 cm^3 cm^{-3} at 40 cm; site III, 0.50 cm^3 cm^{-3} at 30 cm; site V, 0.61 cm^3 cm^{-3} at 50 cm. The area received 42 mm of rainfall during week 7, which partly explains the values during that period; the other periods had no rain at sampling time (Figures 4a and 4b). At site IV, the highest moisture content of 0.52 cm^3 cm^{-3} at 60 cm was recorded during week 18.

Russell (1978) measured the moisture profiles of an uncropped deep Vertisol at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), India, during the rainy season (14 June to September 1977) and during the post-rainy season (6 October 1977 to 11 April 1978). The highest moisture contents recorded were 0.45 cm^3 cm^{-3} at 1.0 m on 7 September during the rainy season and 0.50 cm^3 cm^{-3} at 1.2 m on 6 October during the post-rainy season. Russell (1978) did not report on the moisture profiles for the

Figure 3. Moisture profiles at various times at sites along the toposequence.

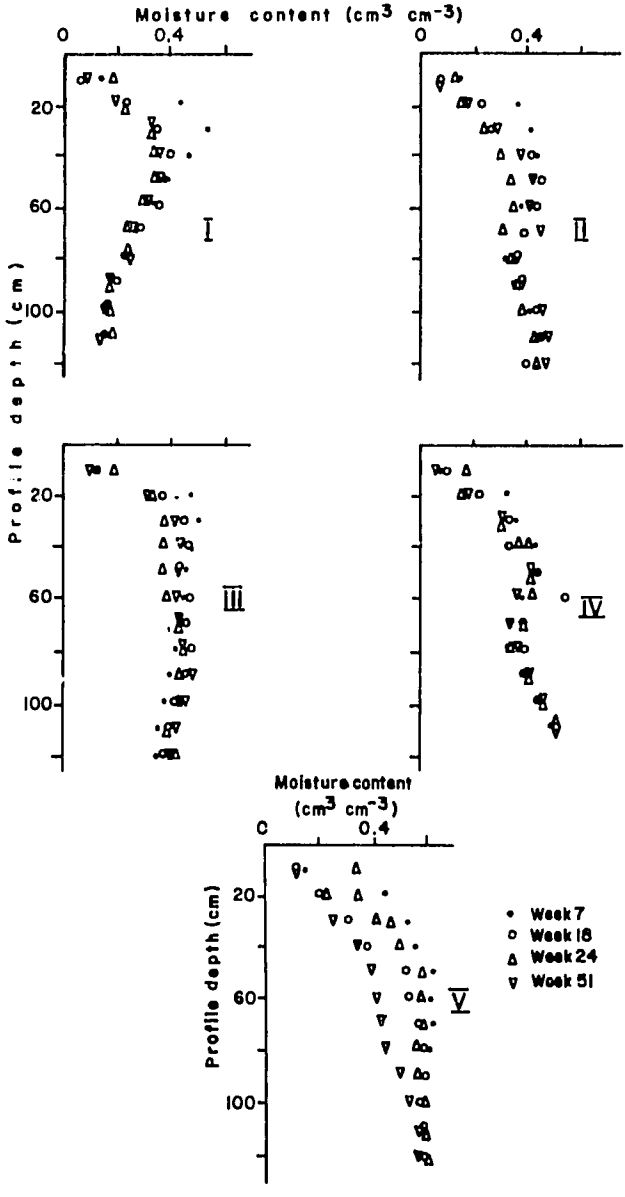


Figure 4a. Dynamics of soil moisture storage at three depths at sites along the toposequence during the vegetative growth stage (A), and during the reproductive stage (B).

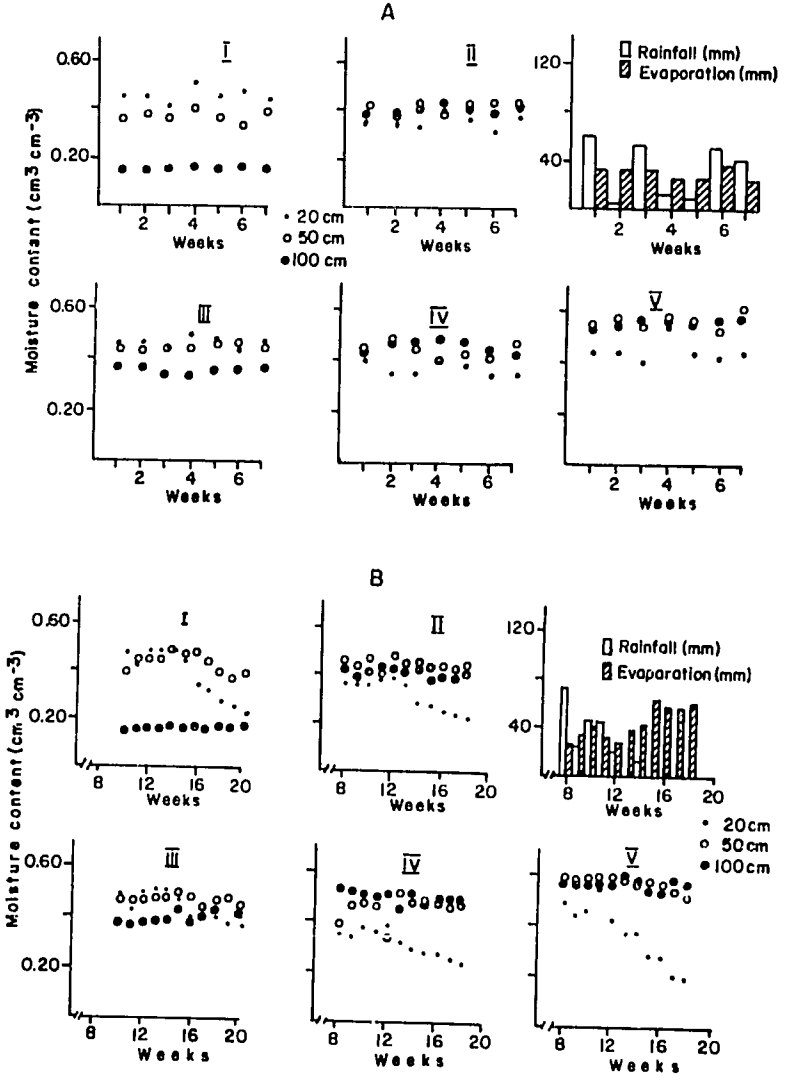
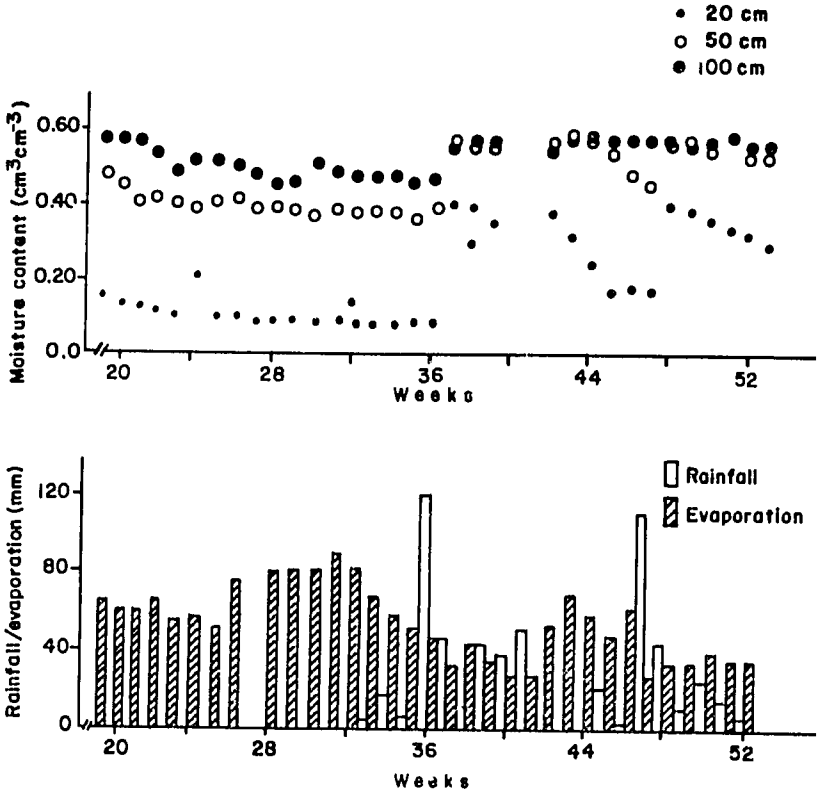


Figure 4b. Dynamics of soil moisture storage at three depths at site V on the toposequence during the maturity/ harvest or fallow stage.



associated Alfisols in the area, but concluded that an adequate agronomic description of a soil moisture profile must indicate when, where and how much water is available in the soil throughout the growing season.

The dry fallow period (week 24) and wetting (planting time week 52) period were characteristic for the Vertisols (site V). The drying effect was

distinct down to 1 m and thereafter the wetting and drying effect were not discernable.

The presence of cracks enhanced the deep wetting and drying in the Vertisols, which remained wet at 1 m and below with a moisture content of >0.60 cm^3 cm^{-3} (Figures 2 and 3).

At 1 m during the vegetative stage, site I had 0.16, site II 0.39, site III 0.41, and site IV 0.50 cm^3 cm^{-3}. These moisture storage differences along the toposequence are important for agronomic assessment of the soils.

Annual soil moisture dynamics

The annual soil moisture measurements were divided and linked with general crop production stages in the area. Three stages were identified: vegetative growth stage (mid-June to mid-August), reproductive stage (mid-August to mid-September) and maturity/harvest stage and fallow (mid-September to mid-June).

Vegetative growth stage

Figure 4a(A) shows soil moisture status at three depths for the five sites during the vegetative growth stage, along with rainfall and pan evaporation for the same period. Most crops are planted from mid-June; crops such as maize reach their maximum growth stage around mid-August.

Weekly water input was 3-60 mm with a potential apparent loss of 26-37 mm. Average weekly rainfall and evaporation were respectively 32.9 and 30.7 mm. These weekly values are important because they influence the soil water store available for crop growth at each depth.

Total soil moisture store within the top 1 m can be estimated by the minimum and maximum soil moisture at 20, 50 and 100 cm: the range of stored soil moisture within the top 1 m was 0.15-0.51 cm^3 cm^{-3} for site I and 0.40-0.61 cm^3 cm^{-3} for the Vertisol at site V, which stored 16% more moisture than the Alfisol. The range for each depth and site indicates the soil moisture regime under which a specific crop can grow (Table 5). Crops in site V will have 3 times more moisture available to them than crops at site I.

Soil moisture at the 20-cm depth in site I was always higher than at the 50- and 100-cm depths. In site IV, the 50- and 100-cm depths were always wetter than the 20-cm depth. At site V, soil moisture will move primarily down the profile, while in site I movement will be largely lateral in the form of runoff, which will leave little water to percolate into the profile. The patterns at sites II, III and IV were intermediate.

Reproductive stage

This period marked the decline of soil moisture at all sites, particularly at the 20-cm depth (Figure 4a(B). The Alfisol site remained dry. As a result of increased evaporation and no rainfall during week 12, the 20-cm depth dried much more rapidly than the 50- and 100-cm depths.

The rate of soil moisture loss was higher at sites I and V than at sites II, III and IV. Sites I and V lost 0.04 cm^3 cm^{-3} per week compared to 0.023-0.028 cm^3 cm^{-3} in sites II, III and IV. The high soil moisture loss at the 20-cm depth in site V could have been caused by the development of cracks. Because of this rapid and large soil

Table 5. Variability of soil moisture (cm^3 cm^{-3}) during three periods at three depths along the toposequence.

Depth (cm)	Sites				
	I	II	III	IV	V
			Vegetative stage		
20	0.444-0.511	0.313-0.460	0.438-0.490	0.340-0.400	0.399-0.535
50	0.342-0.400	0.372-0.426	0.435-0.460	0.395-0.480	0.524-0.608
100	0.149-0.161	0.377-0.427	0.338-0.359	0.467-0.529	0.537-0.572
			Reproductive stage		
20	0.271-0.483	0.223-0.378	0.362-0.497	0.230-0.381	0.189-0.547
50	0.365-0.481	0.425-0.476	0.433-0.501	0.344-0.506	0.505-0.597
100	0.148-0.164	0.381-0.411	0.350-0.423	0.454-0.524	0.545-0.585
			Maturity stage/harvest/fallow		
20	0.165-0.340	0.087-0.274	0.241-0.424	0.097-0.289	0.076-0.405
50	0.320-0.367	0.277-0.425	0.340-0.443	0.285-0.483	0.358-0.575
100	0.143-0.187	0.353-0.469	0.291-0.429	0.465-0.522	0.421-0.582

moisture loss, crops with a shallow root system will experience a sudden moisture deficit that can cause wilting, premature ripening and quality loss. Moisture at the 50-cm and 100-cm depths was 0.55-0.60 cm^3 cm^{-3} at site V and <0.55 cm^3 cm^{-3} at the other sites. The Vertisol (site V) stored 19% more moisture than site I (Table 5).

Maturity/harvest or fallow

The decline in soil moisture during the reproductive period continued during the maturity/

fallow period. The 20-cm depth reached minimum soil moisture during weeks 33-35 for site V (Figure 4b). Site V had the driest soil at 20 cm (Table 5). There was a fourfold increase in soil moisture at 20 cm due to 120-mm rainfall during week 36 and 110-mm rainfall during week 48. However, these rains only slightly increased moisture levels at 50 cm and 100 cm. These are the small rains (Daniel Gamachu, 1977) for this area.

While soil moisture at 50 cm and 100 cm in site V was 0.36-0.58 cm^3 cm^{-3} during the period, site I had soil moisture of 0.19-0.37 cm^3 cm^{-3}; the Vertisol of site V stored 37% more moisture than site I (Table 5). The larger amount of stored moisture during this fallow period has important implications for systems such as double cropping and alley cropping. The moisture at these depths during this period is similar to the other periods when there was rainfall (Figure 3).

These measurements indicate that the Vertisols remain moist or wet throughout the year at 50 and 100 cm. The influence of cracks (which can be up to 45 cm deep) on soil moisture depletion during the fallow period is negligible at the 50-100 cm depth (Figure 4b). The soils should be able to support a second crop if the top 20 cm can be wetted to maximum recharge (98 mm) with supplemental irrigation.

The low soil moisture content in site I, particularly at 100 cm, provides little insurance during a dry year or erratic dry spells. While early planting on the Vertisol at site V may be promising, even during a dry year, early planting would be unwise in the Alfisols at the top of the toposequence since they store little soil

moisture. A scaling of the intermediate soils based on stored soil moisture will provide a useful guide for cropping along the toposequence by making maximum use of the soil moisture at each site to improve crop yields.

ACKNOWLEDGEMENTS

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SOIL FERTILITY RESEARCH ON SOME ETHIOPIAN VERTISOLS

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ABSTRACT

Vertisols are important agricultural soils in Ethiopia. These soils generally have high clay content and consequently a high moisture storage capacity. The pH is slightly acidic to neutral. These soils have high yield potential, but require proper fertility management. Experimental results from NP fertilizer trials on various field crops showed that grain yields could be substantially improved with the application of N and P fertilizers. A similar response was also observed on forage crops.

INTRODUCTION

In Ethiopia, Vertisols cover 12.6 million ha, or about 10% of the country. In addition, there are 2.5 million ha of soils with vertic properties. About 70% of these soils are in the highlands, and about 25% (1.93 million ha) of the highland Vertisols are cropped (Berhanu Debele, 1985).

Vertisols are extensively found in Setit Humera, Gambela, Chilalo and Amibara. These soils occur in the lowlands (<1500 m), at intermediate altitudes (1500-1800 m) and in highland areas (2000 m or higher).

This paper reviews soil fertility studies on Vertisols and indicates future direction for research.

CHARACTERISTICS

Vertisols are naturally fertile soils, but poor drainage and difficult workability limit nutrient availability. The most important characteristic of Vertisols is their high water-holding capacity (commonly 60-70%), a consequence of the deep profile and high content of montmorillonitic clay. Because of waterlogging, these soils remain unused during part of the rainy season, and many highland crops such as teff, barley, durum wheat, chickpea, lentil, noug and vetch are grown on residual moisture at the end of the rains.

The available information on the chemical properties of Vertisols is very limited. Analytical results from selected sites on Vertisol areas are shown on Table 1. Available P in these soils is generally higher than 20 ppm. Berhanu Debele (1985) reported that in 70% of the cases available P is below 5 ppm. In the surface horizons (0-30 cm) most of the Vertisols contain about 3-10% organic matter. Generally soil organic matter is related to texture, increasing with higher clay contents. Total N contents vary from 0.08 to 0.22% and the C:N ratio is about 11-18. The wide range in C:N ratio is attributed to increased nitrification and loss of N, as the Ca and moisture status are very favourable to increased microbial activity (Krishnamoorthy), 1971). The loss of nitrogen might also be caused by denitrification resulting from poor drainage.

Table 1. Chemical characteristics of Pellic Vertisols at selected sites.

Location	pH	C:N	Total N %	Avail. P (ppm) (Olsen)	Exchangeable cations meq/100 g soil K	Ca	Mg	CEC
Holetta	6.7	10	0.16	69.5	1.7	8.0	4.0	22.6
Ginchi	6.4	13	0.15	20.0	1.5	23.5	11.0	42.3
Debre Zeit	6.9	-	0.14	50.0	1.3	24.9	4.5	34.8
Sheno	6.2	11	0.22	53.0	1.2	19.0	8.2	30.0
Melka Werer	8.6	18	0.08	151.0	2.3	29.0	6.2	37.3
Mai Mekden	8.7	11	0.19	33.0	0.45	40.2	2.5	37.3

Source: Desta Beyene (1982).

The pH of Vertisols increases with depth, the topsoil being neutral or weakly acid. According to Berhanu Debele (1985), about 61% of the Vertisols have pH values of 5.5-6.7, 21% have pH values of 6.7-7.3, and 9% have pH values of more than 8. He stated that nearly all of the Vertisols of Ethiopia have CEC of 35-70 meq/100 g soil. In Table 1, however, CEC values range from 22 to 42 meq/100 g soil.

The clay fraction is dominated by smectites. The predominant exchangeable cation, which accounts for up to 80% of the exchange complex, is Ca, followed by Mg: K and Na contribute nearly equal proportions (Berhanu Debele, 1985). In the highlands, base saturation, even in the presence of calcium carbonate nodules, is rarely greater than 80-90%. These nodules are largely crystalline, hard, chemically inactive, and have practically no effect either on the pH or on the base saturation of the soil.

FERTILITY MANAGEMENT

Attempts have been made to improve the productivity of Ethiopian Vertisols through N and P fertilization. Series of experiments have been carried out on Vertisols to study the effects of N and P fertilizers on crop yield.

Response to nitrogen

The response to N at various locations is given in Table 2. There was a marked N response in most of the crops tested (IAR, 1972, 1976 and 1977; Desta Beyene, 1986). Maximum barley yields at Sheno, maximum grain yields for noug, linseed, teff, and bread wheat at Ginchi, and maximum grain yields of wheat, barley and faba bean at Holetta, were all obtained with 90 kg N ha^{-1}. Similar results were found for teff grown at Debre Zeit, Akaki, Chefe Donsa, and Denkaka (AAU, 1983). Durum wheat grown at Debre Zeit gave maximum grain yield when 46 kg N ha^{-1} was applied. Fertilizer trials carried out at Tefki, Inewari and Bichena also showed significant yield increases in bread wheat, durum wheat, teff and faba beans as a result of N fertilizer application (Adugna Haile and Hiruy Belayneh, 1986). For the forage grasses (*Guinea* and *Phalaris*) studied at Holetta, maximum forage yield was found when 46 kg N ha^{-1} was applied.

The high response to N is understandable because total N in most Vertisols is low. Because of rapid nitrification, most of the N added as fertilizer containing NH_4 or NH_2 is subject to leaching or denitrification soon after application. Ammonia fixation also affects fertilizer efficiency in heavy Vertisols (Finck and Venkateswarlu, 1982). Therefore, the application of 90 kg N ha^{-1} for most crops may be

Table 2. Response of rainfed field crops to N fertilizer in Vertisols of Ethiopia.

Location	Crop	Applied N (kg ha^{-1}) 0	30	46	60	90	Sources
		Grain yield (kg ha^{-1})					
Ginchi	Noug	750		860		880	1
"	Linseed	800		960		970	1
"	Teff	720		730		1120	1
"	Bread wheat	1690		2320		2790	1
Holetta	Coloured Guinea[a]	673		1920		1827	2
"	Phalaris[a]	3794		4216		3630	2
"	Bread wheat	2900	3410		3540	4110	2
"	Barley	3000	2960		3200	3480	2
"	Faba bean	1360	1830		1790	2020	3
Sheno	Barley	1448	1716		2018	2164	4

a. Forage yield

Sources: 1. IAR (1977).
2. IAR (1976).
3. Desta Beyene (1986); IAR (1976).
4. IAR (1972).

justified under such conditions since the maximum yield for grain crops was found at this fertilizer level. The efficiency of the N fertilizer applied could be improved through the use of nitrate forms of fertilizer and the deep placement of split application of the ammonium forms of fertilizer.

Response to phosphorus

Responses to P fertilization are given in Table 3. For most crops there was a marked response (AAU, 1983; IAR, 1972, 1976, 1977; Desta Beyene, 1986). At Sheno, barley reached a peak yield of 2057 kg ha^{-1} with the application of 13 kg P ha^{-1}, but

Table 3. Response of field crops to P fertilizer in Vertisols of Ethiopia.

Location	Crop	Applied P (kg ha^{-1}) 0	13	20	26	40	53	Sources
		Grain yield (kg ha^{-1})						
Ginchi	Noug	670		900		920		1
"	Linseed	750		1010		960		1
"	Teff	380		970		1220		1
"	Bread wheat	1690		2590		2250		1
Holetta	Coloured Guinea[a]	673		1434		2767		2
"	Phalaris[a]	3794		4610		4570		2
"	Bread wheat	2870	3420		3730	3960		2
"	Faba bean	1500	1690		1910	1890		3
"	Barley	2560	2900		3590	3560		2
Debre Zeit	Chickpea	1910	1470		2120	1930		4
"	Lentil	513	515		472	576		4
Sheno	Barley	1748	2057		1856	1843	1678	5

a. Forage yield

Sources: 1. IAR (1977).
2. IAR (1976).
3. Desta Beyene (1986); IAR (1976).
4. AAU (1983).
5. IAR (1972).

higher concentration of fertilizer produced lower yields. Significant P responses were observed for teff and bread wheat at Ginchi. For teff the maximum yield was obtained with 40 kg P ha^{-1}, and for wheat 20 kg P ha^{-1} gave the highest yield. The largest yield increment for bread wheat at Holleta and barley at Sheno was observed with the lowest rate of 13 kg P ha^{-1}. For faba bean maximum yield was obtained at 26 kg P ha^{-1}. Trials at Tefki, Inawari and Bichena showed that P was necessary for bread wheat, durum wheat, teff,

and faba beans (Adugna Haile and Hiruy Belayney, 1986). Oilseeds and pulses showed little response to P. Two forage grasses (*Guinea* and *Phalaris*) at Holetta gave high yields with 40 kg P ha^{-1}.

Variation in P response among crops at the same site is mainly due to the complexity of soil P. There are four important soil factors that affect the availability of applied P (Finck and Venkateswarlu, 1982); soil moisture, native available P, nature of the clay, and the amount of clay. Because Ca is the dominant cation in the CEC complex of the Vertisols, added P is usually transformed to calcium phosphate.

Other nutrients

Because K deficiency is uncommon in the country, studies on K fertilizer have not been carried out. Also, little work has been done on secondary nutrients and micronutrients, as these are not considered as factors limiting yield on Vertisols.

CONCLUSIONS

Research efforts on Vertisols should concentrate on improving drainage and tilth. Once drainage has been improved, these soils are among the most fertile, and can produce high yields. Improved management will not only give higher yields, but will also reduce soil erosion.

Biological nitrogen fixation (BNF) is a field that requires special attention. Since N is the most limiting nutrient on Vertisols, the use of forage and grain legumes should be encouraged. Increased N fixation by these legume crops will lead to increased productivity of cereal crops.

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PHOSPHORUS STATUS OF SOME ETHIOPIAN HIGHLAND VERTISOLS

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ABSTRACT

The phosphorus status of some Ethiopian highland Vertisols (15 surface and 37 profile samples) was investigated by determining P sorption capacity, P fractions and available P. Generally, the soils exhibited some differences in their P status. The content of organic P decreased within the soil profiles similar to the organic matter content, while the distribution of the other P fractions within the soil profiles had no consistent trend. Available P was generally limited, reflecting the low content of the active P forms (Ca-P, Fe-P and Al-P) in the soil profiles.

INTRODUCTION

Vertisols cover 10.3% (about 12.7 million ha) of the Ethiopian land mass and are the fourth most abundant soils after Histosols, Cambisols and Nitosols. Vertisols may be found in the 0-8% slope range, but are more abundant in the 0-2% range (Berhanu Debele, 1985).

It is estimated that Vertisols comprise about 24% of all cropped highland soils (Jutzi and Haque, 1985). Vertisols are potentially among the most productive soils of sub-Saharan Africa, but they are agriculturally underutilised within the traditional farming practices due to excess soil moisture from waterlogging during the heavy rains.

Nitrogen and P are the two most important elements which are relatively low in Vertisols (Dudal, 1965; Hubble, 1984). With P, the problem is more of unavailability than of total quantity present in the soil.

The Ethiopian soils, similar to the other agricultural soils of the tropics, are generally low in N and P. Several authors have reported independently that 70-75% of some Ethiopian agricultural soils are deficient in P (Desta Beyene, 1982; Pulschen, 1987; Tekalign and Haque, unpublished data 2). However, very little detailed work has been done on the P status of Ethiopian soils and most of the studies on these soils have been concerned with crop productivity. The characterisation and the distribution of the different chemical forms of P have received little attention. This study presents the results of investigations on the relative distribution of the various P forms, P fixing capacity and available P status of some Ethiopian highland Vertisols.

MATERIALS AND METHODS

Soil sampling analysis

Fifteen soil samples from the plough layer and 37 soil profile samples were collected from various sites (see Table 1). Soil samples were air-

Table 1. Sampling locations and site characteristics.

Soil No.	Location	Longitude (E)	Latitude (N)	Altitude (m)
1614	Debre Zeit (ILCA substation)	38° 58'	8° 44'	1830
1615	Shola (ILCA station)	38° 45'	9° 00'	2380
2295	Suke (ESCRP site)[a]	40° 59'	9° 07'	1980
2297	Tis Abay Falls	37° 35'	11° 29'	1600
2298	Fogera Plains	37° 25'	13° 36'	1802
2299	Debre Birhan (ILCA substation)	39° 38'	9° 36'	2780
2301	Debre Birhan (ILCA substation)[b]	39° 38'	9° 36'	2780
2307	Robe	39° 52'	7° 38'	1700
3669	Wereta[c]	37° 10'	10° 50'	1800
3672	Wereta[c]	37° 10'	10° 50'	1800
3732	Enewari[c]	39° 15'	9° 40'	2600
3749	Wereilu[c]	39° 31'	10° 36'	2600
3753	Wereilu[c]	39° 31'	10° 36'	2600
4454	Wejel[c]	38° 00'	10° 00'	1800
4059	Mega/Sidamo (ILCA Rangelands)	38° 18'	4° 03'	2215

a. ESCRP = Ethiopian Soil Conservation Research Project.
b. Vertisol with overlying colluvial deposit.
c. ILCA Vertisols Project site.

dried in the laboratory, crushed, passed through a 2-mm sieve and stored for physico-chemical analysis. Particle size analysis was carried out by the method of Bouyoucos (1951). Organic matter was determined by the method of Walkley and Black (1934), and pH measured in 1:1 soil:water and 1:2.5 soil:$CaCl_2$ ratios. Extractable Fe and Al

were determined by the method of Mehra and Jackson (1960) and the contents read on an atomic absorption spectrophotometer.

Phosphorus estimation

Total P was determined by $HClO_4$ digestion (Jackson, 1964) and organic P was estimated by the difference between extractable inorganic P before and after ignition by the method of Legg and Black (1955). Inorganic P was fractionated by the method of Chang and Jackson (1957) as modified by Peterson and Corey (1966). Available P was estimated by extraction with acid fluoride (Bray and Kurtz, 1945), and by Olsen's $NaHCO_3$ method (Olsen et al, 1954). Phosphorus in all extracts was determined colorimetrically by the molybdenum blue colour method of Murphy and Riley (1962). Phosphorus sorption was studied using the method of Fox and Kamprath (1970).

RESULTS AND DISCUSSION

Physico-chemical properties

The data in Table 2 show the general properties of the surface (0 to 15 cm) soils used in this study. As would be expected, all the soils except one were of clay texture, containing an average of 62.6% clay. Soil 2301 had the lowest clay content since it represents a buried Vertisol with overlying colluvial deposits. The pH (in soil: water) of the Vertisols varied between 4.80 and 7.72 with a mean value of 5.88. Organic matter and total N contents were also within the ranges reported by earlier workers (Kamara and Haque, 1987).

Table 2. Some physico-chemical characteristics of the soils studied.

Soil No.	Sand (%)	Silt (%)	Clay (%)	Organic matter (%)	Total N (%)	pH (1:2.5)		DCB[a] Extractable (mg g^{-1})	
						H_2O	$CaCl_2$	Fe	Al
1614	26	15	59	2.35	0.10	6.89	6.06	9.3	0.8
1615	24	14	62	3.69	0.12	6.30	6.28	13.9	1.8
2295	22	14	64	3.29	0.14	4.80	4.25	22.5	0.3
2297	16	10	74	2.08	0.09	6.10	5.60	20.1	1.3
2298	18	16	66	4.39	0.21	5.85	5.50	37.4	2.6
2299	19	19	62	6.73	0.33	5.10	4.40	18.2	5.3
2301	37	26	37	4.03	0.21	5.40	5.15	18.1	3.8
2307	24	29	46	8.64	0.23	5.60	5.25	9.5	0.3
3669	18	17	65	1.75	0.09	6.05	5.03	38.8	1.4
3672	18	21	61	2.56	0.15	5.22	4.17	9.6	0.4
3732	20	19	61	2.87	0.11	5.89	4.93	7.7	0.4
3749	15	21	64	2.48	0.13	5.18	4.10	7.2	0.5
3753	19	21	60	1.50	0.06	6.22	4.89	8.5	0.3
4059	24	8	66	2.97	0.11	7.72	6.59	2.9	0.8
4454	15	21	64	3.39	0.15	5.40	4.44	8.3	0.2
Mean[b]	19.9	17.5	62.6	3.48	0.14	5.88	5.11	15.3	1.2

a. Dithionite-citrate-bicarbonate.
b. Excludes soil 2301.

The distribution within the soil profiles of the physical and chemical properties for eight of the Vertisols is shown in Table 3. The percentage clay of sometimes increased with depth, sometimes decreased, and sometimes did not change significantly below the surface horizon. The variation seems to be the result of differences in the weathering of the parent materials and soil forming processes. The pH of the Vertisols increased with depth except in soil 4059 where a slight decrease was noted. Similar trends were also reviewed by Ahmad (1986) and Dudal (1965). Total N (Table 3) and organic matter (Figure 1) contents also followed a decreasing pattern with increasing profile depth. The C:N ratios for the surface soils varied between 7.7 and 11.8 and the trend was variable with depth.

Total phosphorus

Data on total P and other forms of P are presented in Tables 4 and 5. From Table 4, it is clear that soil 3732 contains the minimum amount of total P at the surface. The mean total P content for the surface samples of the 15 Vertisols is 453 ppm. The majority of the surface samples had values greater than 200 ppm which is the value indicated by Olsen and Engelstad (1972) as the maximum total P value for highly weathered tropical soils. On the other hand, the values are of the same order of magnitude as those in other tropical soils of lesser degree of weathering.

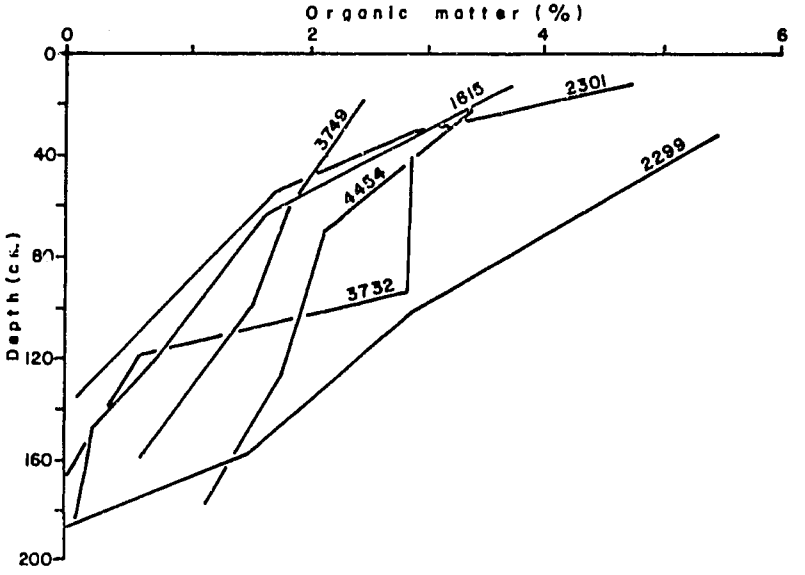
The lowest profile total P was observed in soil 1615 (Table 5) which also has the lowest available P (Bray II and Olsen) (Table 4).

Soil samples from profile 1615 and 4059 have profile total P values similar to the values

Table 3. Distribution of clay, pH, N and P in the soil profiles of some of the Vertisols.

Soil No.	Depth (cm)	pH (1:2.5) H_2O	pH (1:2.5) $CaCl_2$	Clay (%)	N (%)	C:N	C:P	Avail. P Bray II (ppm)
1614	0-25	6.27	5.20	59	0.08	10.8	66.5	18.1
	25-39	6.37	5.29	53	0.07	11.7	74.2	11.2
	39-60	6.59	5.55	49	0.06	13.5	90.2	9.3
	60-112	7.31	6.01	54	0.05	10.5	65.6	0.1
	112-167	7.75	6.34	24	0.02	11.6	58.1	39.8
	167-192	8.03	6.38	17	0.01	9.2	30.7	124.1
	192-205	8.21	6.32	6	0.01	9.0	30.7	191.2
1615	0-23	5.52	4.48	60	0.21	11.0	202.9	0.3
	23-100	5.63	4.65	66	0.07	10.3	119.9	0.1
	100-127	6.05	4.88	72	0.03	12.0	71.9	5.5
	127-164	6.34	5.16	74	0.01	9.6	32.2	7.5
	164-200	6.43	5.29	74	0.01	7.9	39.5	12.9
2299	0-60	4.98	3.92	52	0.25	9.6	50.9	0.8
	60-140	5.90	4.38	60	0.10	12.8	67.2	0.5
	140-170	6.58	4.88	54	0.07	9.8	45.9	35.0
	170-200	6.38	4.66	52	0.01	0.9	3.7	49.7
2301	0-20	5.95	4.25	28	0.27	7.7	83.5	1.2
	20-38	5.85	4.40	44	0.13	14.1	98.3	0.04
	38-67	6.14	5.10	48	0.09	5.8	59.1	60.3
	67-200	6.23	4.70	20	0.01	3.1	17.1	3.3
3732	0-78	5.89	4.93	62	0.11	11.4	103.2	0.6
	78-105	6.12	5.05	62	0.12	10.5	75.8	1.4
	105-128	7.48	6.52	30	0.03	8.8	49.7	9.6
	128-200	7.43	6.37	30	0.01	3.0	10.6	55.0
3749	0-34	5.18	4.10	64	0.13	8.4	49.4	0.8
	34-80	5.35	4.25	66	0.09	9.0	50.7	0.2
	80-115	6.00	4.87	68	0.08	8.4	60.9	0.1
	115-200	6.29	5.00	48	0.03	9.1	52.3	1.5
4059	0-50	7.72	6.55	67	0.11	11.8	128.9	3.6
	50-90	7.74	6.49	69	0.09	13.1	159.4	4.2
	90-115	7.51	6.53	71	0.07	13.9	152.1	16.8
	115-175	7.34	6.54	67	0.02	8.8	92.3	20.6
	175-200	7.26	6.48	75	0.02	5.5	78.3	10.5
4454	0-40	5.42	4.46	64	0.15	9.9	74.3	2.6
	40-95	5.30	4.32	72	0.10	9.4	46.0	0.1
	95-152	5.21	4.22	74	0.09	8.8	62.5	2.0
	152-200	6.39	5.49	74	0.05	10.4	65.5	192.3

Figure 1. Distribution of organic matter within the soil profiles of some of the Vertisols.



reported by Piccolo and Gobena Huluka (1986) as the profile average of two Ethiopian Vertisols from Awasa (170 ppm) and Ginchi (200 ppm).

From on-going studies on some Ethiopian soils, Tekalign and Haque (unpublished data 1), found that soils derived from basaltic rocks/volcanic materials contained the highest amounts of total P. For example, a total P content of 1981 ppm was found in a volcanic ash soil from Debre Sina. This soil also had high contents of Fe_2O_3 and Al_2O_3, which have a high capacity to occlude P (Chang and Jackson, 1957), although an additional suitable explanation could be found from the contribution to total P of the high quantity of organic P present in the same

Table 4. Available, fixed, organic, total and inorganic P fraction values (ppm) in the surface soils of the Vertisols.

Soil No.	Available P			Fixed P	Organic P	Total P	Inorganic P fractions		
	Bray I	Bray II	Olsen				Al-P	Fe-P	Ca-P
1614	3.1	21.5	5.8	105	124	368	12	27	98
1615	0.4	0.8	0.1	240	109	185	4	25	14
2295	0.7	17.3	3.6	220	320	818	11	48	260
2297	0.5	3.4	2.4	245	141	322	7	54	17
2298	1.5	4.0	21.5	400	367	981	24	234	54
2299	1.0	3.1	5.4	600	270	610	14	165	53
2301	6.1	12.2	18.5	125	299	640	60	145	40
2307	1.3	2.7	2.2	220	266	415	7	88	11
3669	1.6	34.7	25.3	385	356	311	15	138	44
3672	1.4	28.8	4.1	198	171	767	14	46	16
3732	6.8	37.3	14.6	112	130	141	15	25	23
3749	1.0	23.8	10.9	210	179	350	12	40	18
3753	0.3	23.3	5.1	180	99	326	15	18	20
4059	0.2	93.9	24.1	87	103	196	19	23	37
4454	3.8	70.9	22.1	178	291	376	26	66	37

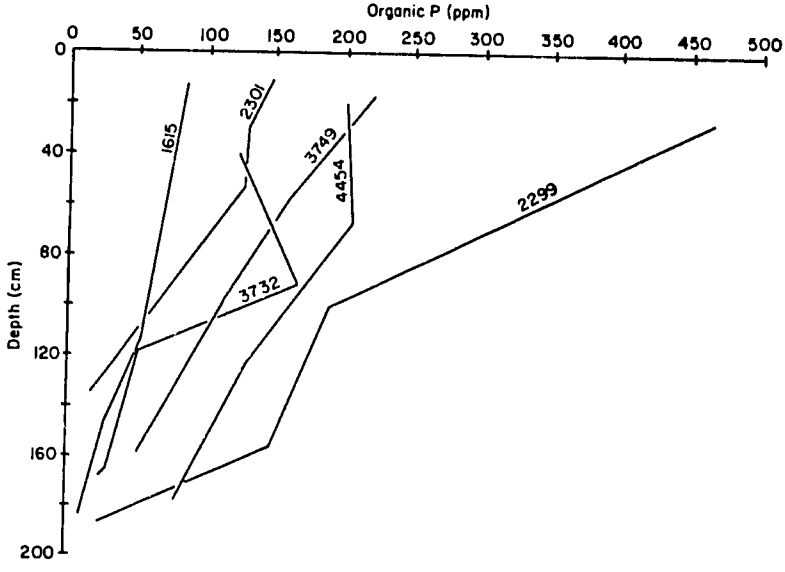
soil. According to the review by Ahmad (1986), total P contents of Vertisols derived from basic rocks/volcanic materials in the USA, India and the Caribbean are only about 50% of those of comparable Ethiopian soils.

Table 5. Total P values and the percentage distribution of active P forms in some of the profiles.

Soil No.	Depth (cm)	Total P (ppm)	Al-P[a] (%)	Fe-P[a] (%)	Ca-P[a] (%)
	0-25	359	9.4	12.5	78.1
	25-39	524	8.2	5.1	86.7
	39-60	443	13.9	36.0	51.8
1614	60-112	327	11.4	11.4	77.3
	112-167	708	0.9	12.1	87.0
	167-192	735	0.8	4.6	94.6
	192-205	795	0.5	2.6	96.9
	0-23	161	14.1	70.5	15.4
	23-100	76	4.8	85.5	9.6
1615	100-127	123	2.5	56.8	40.7
	127-164	110	2.6	62.1	35.3
	164-200	104	9.9	12.7	77.5
	0-60	972	13.4	51.3	35.3
2299	60-140	365	19.2	47.7	33.3
	140-170	561	93.6	69.2	57.7
	170-200	338	29.4	11.8	58.8
	0-20	493	4.9	74.3	20.8
	20-38	250	12.2	69.4	18.4
2301	38-67	551	3.0	2.5	94.5
	67-200	265	0.1	0.5	99.3
	0-78	141	10.9	60.0	29.1
	78-105	188	18.5	38.5	43.1
3732	105-128	925	0.6	0.4	99.0
	128-200	1426	0.9	0.3	98.8
	0-34	350	26.7	60.0	13.3
	34-80	262	32.3	58.1	9.7
3749	80-115	190	31.8	50.0	18.2
	115-200	113	6.7	46.7	46.7
	0-50	176	36.1	25.0	38.9
	50-90	194	20.6	3.2	76.2
4059	90-115	233	17.7	5.1	77.2
	115-175	169	13.9	41.7	44.4
	175-200	106	13.2	47.2	39.6
	0-40	378	3.9	62.3	33.8
	40-95	307	9.1	72.7	18.2
4454	95-152	284	15.4	74.4	10.3
	152-200	262	12.0	70.0	18.0

a. Expressed as percent of total active inorganic P.

Figure 2. Distribution of organic P within the soil profiles of some of the Vertisols.



Organic phosphorus

Organic P content in the surface soils ranged between 99 and 367 ppm (Table 4). In general, organic P content decreased with depth, as shown in Figure 2. Organic P values tended to vary according to the organic matter contents of the profiles, indicating a close relationship between the two variables. According to Tekalign and Haque (unpublished data 1), a highly significant correlation was observed between organic P and organic matter in 32 Ethiopian surface soils. Such a positive relationship between organic P and

organic matter has also been reported by other workers (Black and Goring, 1953; Uzu et al, 1975).

The organic C:organic P ratio (Table 3), an index of the mineralization capacity of organic P, was below 200 in the profile samples of all soils except the surface sample of Shola (soil 1615), indicating a possible rapid turnover rate for organic P. Similar low values were also observed by Piccolo and Gobena Huluka (1986) in some Ethiopian soils. Under tropical conditions, organic P is readily mineralised into inorganic P (Tisdale and Nelson, 1966) and can thus be an additional P source to plants. According to Tekalign and Haque (unpublished data 1), organic P in 32 Ethiopian surface soils was found to constitute about 41% of the total P content. According to Ahmad (1986), organic P content is estimated to be as high as 40-50% of the total P in the Vertisols of the Ethiopian highlands.

There was a common tendency of the C:P ratio to decrease with depth. Similar trends were reported in some tropical soils by Bornemisza (1966), but this was not confirmed by Piccolo and Gobena Huluka (1986) in their studies on some Ethiopian soils.

Active phosphorus fractions

The amount and distribution of the various active inorganic P fractions (the phosphates associated with Ca (Ca-P), Fe (Fe-P) and Al (Al-P)) are shown in Tables 4 and 5. The percentage distribution of the three active P forms varied among the eight soil profiles, reflecting the different conditions in which they were formed. Ca-P was more abundant at lower depths in soils 1614, 2301 and 3732 (Table 5). This can be explained on the basis of

the occurrence of less weathered parent material in the profiles. In addition, because Ca is the dominant cation in all the profiles (Kamara and Haque, 1987), added P might be transformed to Ca-P and moved further down due to the seasonal physical movement of the soil.

For the surface samples of the profiles, the distribution of the active P forms was in the order Fe-P > Ca-P > Al-P in 10 out of the 15 surface soils (Table 4). However, when the values within each profile for all the profiles were considered, the order was mixed (Table 5). Previous studies on different Ethiopian surface soils show that the active inorganic P fractions were found in the order Ca-P > Fe-P > Al-P (Desta Beyene, 1982; Tekalign and Haque, unpublished data 2). On the other hand, Piccolo and Gobena Huluka (1986), working on 7 Ethiopian soils (2 Pellic and 1 Chromic Vertisols, 2 Eutric Nitosols, 1 Dystic Cambisol and 1 Calcic Fluvisol) found that the relative abundance of the inorganic P forms in the profiles was in the order: Fe-P > Ca-P > reductant soluble P.

In the present study, the abundance of Fe-P in the poorly drained surface samples is supported by the general fact that under flooded conditions, Fe-P more than the other fractions is the source of available P (Uzu et al, 1975). The profile average of Fe-P is higher in soils from Shola (soil 1615) than in soils from Debre Birhan (soils 2299 and 2301). This is expected since Debre Birhan soils have among the highest contents of oxides of Fe and Al, as shown in Table 2. The contents of both Al-P and Fe-P at the lowest depth were almost invariably lower than the values at the surface, the exceptions being soils 4059 (for Fe-P) and 2299 (for Al-P).

Available phosphorus

Next to N, P is the most limiting nutrient in Vertisols (Finck and Venkateswarlu, 1982) and this holds true for Ethiopian soils. Available P contents, determined by the method of Olsen et al (1954), and the two methods of Bray and Kurtz (1945), are shown in Table 4. The profile distribution of Bray II available P is also shown in Table 3 for some of the profiles. Available P was low by the three methods in most of the surface soils. Using the Olsen method, which is often regarded as the most appropriate for Ethiopian soils (Tekalign and Haque, unpublished data 2), the maximum P content was observed in soil 3669 and the minimum in soil 1615. Interestingly, soil 1615 has also the lowest total P content after soil 3732.

Higher values of Bray II extractable P were observed at lower depths than at the surface for each of the profiles, as shown in Table 3. This may be due to the abundance at lower depths of Ca-P and the dissolution of Ca-P by the Bray II extractant. Similar trends were also observed by Piccolo and Gobena Huluka (1986) in their P studies of 7 Ethiopian soils.

The status of available P in soils is normally related to the different active inorganic P forms (Al-P, Fe-P, and Ca-P). In a previous study in which 32 Ethiopian surface soils (including 7 of the 15 Vertisols in this study) were considered, Tekalign and Haque (unpublished data 1) found that available P estimated by the Bray I, Bray II and Olsen methods was better correlated with Al-P and Ca-P. This was later supported by a further study (Tekalign and Haque, unpublished data 2) in which Al-P and Ca-P were

also the P forms that correlated best with plant P uptake. Based on these findings for the 15 Vertisols included in this study, the low Al-P and Ca-P contents reported in the surface soils are indicative of the limited capacity of the inorganic forms to act as a labile pool to supply available P to the plants.

In his survey of nutrient availability in 350 surface soil samples in the Shewa region of Ethiopia, Pulschen (1987) found that the mean Olsen-extractable P in 165 Vertisols or soils with vertic properties was 11.6 ppm--less than that in light soils (16.9 ppm) or reddish brown soils (13.9 ppm).

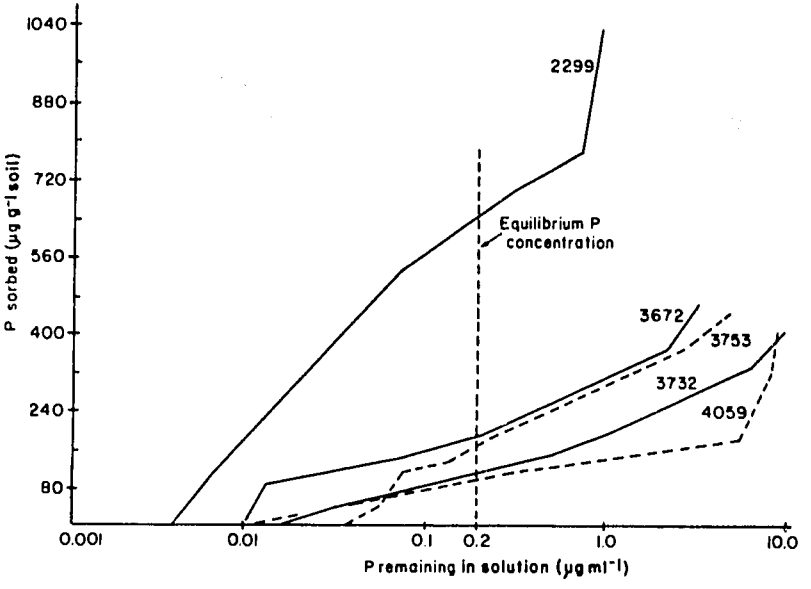
Phosphorus sorption

The data from the P sorption experiment are plotted in Figure 3 for low, medium, and high P sorbing soils. In all cases, the sorption and equilibrium P concentration in solution continued to increase with higher rates of P additions. There are three categories of P sorption isotherms based upon the quantity of P sorbed (Table 4): low P fixing soils, such as soil 4059; medium to high P fixing soils, such as soils 3753 and 3672; and very high P fixing soils, such as soil 2299.

Phosphorus sorption was positively correlated with contents of organic matter, ($r^2 = 0.364$ ($P<0.05$)), extractable Fe ($r^2 = 0.623$ ($P<0.01$)) and Al ($r^2 = 0.660$ ($P<0.001$)). The correlation of fixed P with clay content or pH was poor; in addition, there was no correlation between fixed P and pH.

Based upon the classification by Sanchez and Uehara (1980) of soils in terms of P sorption, it

Figure 3. P sorption characteristics of some of the Vertisols.



follows that about 70% of the Vertisols included in this study are high P fixing soils. This is in close agreement with previous reports (Tekalign and Haque, 1987) which showed that about 65% of 32 different Ethiopian surface soils were in the higher P sorption range.

SUMMARY AND CONCLUSIONS

Results show a wide range of differences in P status of the soil samples studied. The majority of the soils are low in available P; about 70% of

the soil samples are deficient in P. Phosphorus fraction results show low levels of the available forms. Phosphorus sorption studies indicate high sorption capacity of the soils. Phosphorus sorption is mainly controlled by content of Fe and Al oxides. More studies are needed to understand the P status of other Ethiopian Vertisols and related soils.

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VERTIC ARABLE SOILS OF CENTRAL ETHIOPIA: THEIR FERTILITY STATUS AND WEED COMMUNITY

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ABSTRACT

A survey of the agrestal weeds in 179 vertic soils was conducted during the 1983/1984 and 1985/1986 cropping seasons within Shewa Province, Ethiopia, to relate species and cover to topographic, edaphic and agronomic factors. Topographic and agronomic data were gathered at randomly selected sites. Weed cover was estimated using the Braun-Blanquet method.

Surface soil samples were collected at 165 sites. The mean soil reaction was slightly acidic (pH 6.7) and became more acidic with increasing elevation. Clay contents varied considerably (25-80%) and 75% of all samples were classified as clay soils. High mean CEC (44 meq/100 g soil) was tentatively attributed to the prevalence of montmorillonite clay minerals. The majority of the samples tested had ample K based on critical levels of K-saturation and were not deficient in Mn, Fe and Cu, whereas 22% were deficient in Zn.

The diversity of the weed flora (332 species), including broadleaved (253) and leguminous (55) species and a high number of perennials (32% of all species with a frequency of occurrence of >20%) was attributed to the topographic and edaphic complex and the low-input farming system.

Weed cover decreased with a decline in elevation. It was found that weeds could be classified according to their distribution within three elevation zones. The most common species throughout the surveyed area were *Digitaria scalarum* (Schweinf.) Chiov, *Cynodon dactylon* (L.) Pers., *Cyperus rotundus* L., *Guizotia scabra* Meisn. and *Galinsoga parviflora* Cav.

SOIL FERTILITY ASSESSMENT OF ETHIOPIAN VERTISOLS ON THE BASIS OF EXTENSION TRIAL SERIES OF THE MINISTRY OF AGRICULTURE

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ABSTRACT

Since 1986 responses of food crop yields to N and P fertilizers have been investigated in the National Trials Programme of the Ministry of Agriculture in Ethiopia. Some early findings of the 1986 trials on Vertisols are reported for Bichena, Goro and Degolo sites, using wheat and teff as test crops.

The soil fertility requirements of Vertisols are crop specific and vary with location. In this paper the results of investigations on the N and P requirements of wheat in the presence and absence of farmyard manure (10 t ha^{-1}) are presented. The response of teff to combinations of slow-release phosphate and triple superphosphate is also discussed.

RESPONSE OF *SESBANIA SESBAN* TO NITROGEN AND PHOSPHORUS FERTILIZATION ON TWO ETHIOPIAN VERTISOLS

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ABSTRACT

Findings from a glasshouse study to assess the response of *Sesbania sesban* to N and P fertilization on two Ethiopian Vertisols are presented. *S. sesban* is an important multipurpose tree, tolerant to physical environmental stresses, with great potential in tropical highlands. Two rates of N application, 0 and 100 kg ha^{-1}, were used. The rates of P application were 0, 40, 80, 120, 160 and 200 kg ha^{-1}. Soils used were from ILCA experimental fields at Shola (Addis Ababa) and Debre Zeit.

Nitrogen fertilization enhanced dry weights of leaves, stems and roots (thus total biomass). Response to P fertilization was dependent upon soil type and the presence of N. On the Debre Zeit soil, without N there was virtually no response; on the Shola soil, there was a linear increase in dry weight with increasing P. When N was supplied, maximum dry weight yields on both

soils were achieved at 120 kg P ha^{-1}, but declined at higher P rates. Improved plant weights as a result of N and P fertilization were generally greater on the Debre Zeit soil than on the Shola soil.

Soil analysis after cropping showed that soil available P increased with P application rates. Addition of N enhanced the uptake of P from the soils, especially the Shola soil. Soil available P decreased with length of growing period.

SOIL PROPERTIES AND DRY MATTER YIELD OF WHEAT AS AFFECTED BY THE QUALITY AND QUANTITY OF IRRIGATION WATER IN A SODIC VERTISOL OF NORTHEAST NIGERIA

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ABSTRACT

A greenhouse study was conducted to investigate the effects of irrigation water quality and quantity on soil properties and on the straw yield of wheat in a sodic Vertisol of northeast Nigeria. Five kilogrammes of the sodic soil were weighed into each of 36 small plastic buckets (pots). Wheat seeds were uniformly sown in these pots after wetting the soil to a predetermined "field capacity". Four rates of irrigation water corresponding to a total growing season application of 100, 200, 400 and 600 mm, and three water qualities having electrical conductivities (ECiw) of 0.5, 4.5 and 9.0 dS m-1, were applied in a completely randomised design with three replications. The irrigation water had an SAR value of 3.5. The plants were grown for 8 weeks.

The different grades of saline, non-sodic irrigation waters significantly reduced the exchangeable sodium percentage (ESP) of the soil, but increased the electro-conductivity of the

saturation extract (ECe). The greatest reclamation effect was achieved with water having an electro-conductivity (ECiw) of 0.5 dS m-1, which not only reduced the ESP of the soil by 34-48%, but also kept the ECe within tolerable limits.

Significant differences in wheat straw yield were observed with different quantities of irrigation water applied, the greatest yield occurring with a total application of 400 mm over the growing season. However, application of the different grades of the saline, non-sodic irrigation waters did not result in any significant difference in straw yield. No interactive effect of water quality and quantity on straw yield was observed.

RAINWATER MANAGEMENT ON VERTISOLS FOR CROP PRODUCTION IN SEMI-ARID REGIONS

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ABSTRACT

Trials were conducted on Vertisols in the semi-arid region of Zimbabwe to investigate the influence of landform and plant population density on the yield of sorghum.

When rainwater was conserved and concentrated in 1- 1.5- and 2.5-m wide furrows, sorghum grain yields increased by 25% in a dry year compared to the flat treatments. The highest yield was recorded from the 1.5-m wide furrows, which outyielded the widely practised 1-m row spacing on the flat by 34%. The 1.5-m row spacing on the flat outyielded the 1- and 2-m row spacings on the flat in the dry year. Yield of stover in the dry year showed no difference between furrow and flat, but the 1-m row spacing significantly outyielded the 1.5- and 2-m row spacing.

Population densities of 22 000, 44 000 and 88 000 plants ha^{-1} tested in a wet year did not show any significant difference in yield. However, the trend was that in a wet year the yield decreased with increasing population, while in a dry year the trend was the reverse.

RESOURCE MANAGEMENT

SOIL AND WATER

ECONOMIC EVALUATION OF IMPROVED VERTISOL DRAINAGE FOR FOOD CROP PRODUCTION IN THE ETHIOPIAN HIGHLANDS

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ABSTRACT

The Ethiopian highland Vertisols above 1500 m altitude cover about 7.6 million ha, of which only 1.93 million ha are currently cropped. Because of waterlogging during the growing season, food crop productivity of these soils is low. Surface drainage techniques are traditionally used only in limited areas despite evidence for their having a large impact on crop yield levels and stability.

Land cultivation in the Ethiopian highlands traditionally relies an animal power. However, there is no indigenous animal-drawn surface-drainage implement available. Such an implement (a broadbed maker, BBM) has been developed at ILCA and tested on-station and on-farm. The BBM, a low-cost device based on the Ethiopian ard, establishes 120 cm wide broadbeds-and-furrows (BBF) for effective surface drainage.

This paper reports on an economic evaluation of on-farm trials with the BBM in four highland locations. This evaluation, carried out in 1986, involved 66 individual farmers and four producers' cooperatives on an area of 81 ha. The economic performance of the technology was evaluated using partial budgeting methods.

On the Inewari plateau (2600 m altitude), where farmers traditionally make BBF by hand, the BBM considerably reduced human labour input in BBF construction. As a consequence, return to labour for faba bean and wheat increased by 43% and 140%, respectively.

On the Wereilu plateau (2600 m altitude), where no effective surface drainage is traditionally practised, faba bean and wheat yielded 330% and 131% more grain, respectively, when grown on BBF, than when grown on the traditional flat seedbed. Similar increments in crop residues, a very important animal feed in these areas, were recorded.

At Debre Zeit (1850 m altitude), wheat grain yields were 25% higher on BBF than on flat seedbeds despite 30% less than average (1977-85) rainfall in July and August 1986. This resulted in 40% higher return to labour per hectare.

Similar trends were recorded in the Fogera plains (1850 m altitude), although because of extreme meteorological conditions, with very late onset of heavy rains, differences were not significant.

INTRODUCTION

Vertisols (deep black clay soils) cover about 13 million ha in Ethiopia. The highland Vertisols above 1500 m altitude cover 7.6 million ha, of which 1.93 million ha are currently cropped (about 23% of all Ethiopian crop land). Average crop yields are very low on these soils (Berhanu Debele, 1985), mainly due to waterlogging in the

growing period, caused by high rainfall and by the high content of swelling clays in these soils.

Traditional methods of surface drainage, such as ridges and furrows or drainage furrows at various spacings, are in general use, but they cannot effectively overcome the waterlogging problem. Very effective surface drainage is, however, practised on the high elevation Inewari plateau at 2600 m altitude in central Ethiopia. There, raised beds about 80 cm wide, with 40 cm-wide furrows in between, are established each year on about 35 000 ha. This work is done by hand, without the help of any tool, which results in considerable human drudgery and low economic returns to labour.

Despite the long tradition of animal traction in the Ethiopian highlands, and despite the general awareness among farmers of the waterlogging constraint, there is no traditional animal-powered surface-drainage implement available. In many highland Vertisol areas farmers follow a strategy of avoiding much of the waterlogging effect by planting crops late in the season, towards the end of the rains. The crops thus rely on residual soil moisture. This practice implies incomplete utilisation of the growing period, low crop yields and considerable soil losses at the start of the rains due to soil erosion. Large areas of highland Vertisols are presently not cropped because of the waterlogging problem.

Research at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) (Kanwar et al, 1982) showed that the key to improved Vertisol utilisation for human food production is effective surface drainage. This was

also demonstrated in Ethiopia by ILCA (Jutzi et al, 1987) and the Ethiopian Institute of Agricultural Research (IAR, unpublished data). The potential for large increases in food output from these soils using improved management techniques led to the establishment of a collaborative Vertisol Management Project involving ILCA, ICRISAT and the government of Ethiopia.

An effective, low-cost, animal-drawn surface-drainage implement, based on the Ethiopian ard, was developed within the project in 1985, and has been tested on-station and on-farm. The implement is called the broadbed maker (BBM).

This paper provides an economic evaluation of the improved surface-drainage technology using the BBM on-farm in four Ethiopian highland Vertisol areas. Partial budgeting methods have been used in the absence of whole-farm data.

IMPROVED DRAINAGE TECHNOLOGY AND EVALUATION TECNNIQUE

The surface drainage implement

A detailed description of the BBM and some on-station performance results have been reported by Jutzi et al (1986). This implement establishes raised beds about 80 cm wide between two furrows of about 40 cm width and 15 cm depth. The BBM is cheap and can be made locally without much external input. Its cost structure is given in Table 1. The BBM weighs about 30 kg, compared with 20 kg for the conventional Ethiopian plough. Power requirements of the BBM on an adequately ploughed plot are about 50% higher than for the

conventional plough, but are still below the potential continuous power deployment of a pair of highland Zebu oxen.

Table 1. Cost structure of the broadbed-maker (BBM), 1986.

Part	Cost (EB)[a]
2 tines	20
6 bolts (12 x 200 mm)	21
3 bolts (10 x 90 mm)	3
2 metal hooks and 2 metal pins	7
4 wooden wings	8
Other wooden parts	7
Nylon rope	4
Metal chain	10
Total	80

a. US$1 = 2.07 EB.

On-farm implement evaluation

The promising on-station results prompted the joint Vertisol Management Project to test the BBM in an extensive on-farm verification programme during 1986. While the main focus of this programme was the effect of improved Vertisol drainage on yields and economic returns, fertilizer treatments were overlaid on land preparation treatments to establish differentials in response to plant nutrient supply. In one location improved crop cultivars were used. In all other locations seeds of landraces were used.

The verification programme was carried out on two high elevation Vertisol plateaux at Inewari, northern Shewa, and Wereilu, southern Wello, both at 2600 m altitude, and on two lower lying locations at Debre Zeit, central Shewa, and Fogera plain, southern Gonder, both at 1850 m altitude. Inewari and Wereilu receive about 1000 mm annual rainfall, while Debre Zeit and Fogera plain receive 800 and 1200 mm, respectively. The programme involved 66 farmers and four producers' cooperatives on 81 ha (Table 2). The crops monitored were faba bean, wheat, teff (*Eragrostis tef*), finger millet, noug (*Guizotia abyssinica*) and sorghum.

The participating farmers were selected on the basis of their willingness to cooperate in the programme. Female-headed farms were also included in line with their numeric importance in the locality.

All farmers and producers' cooperatives participating in the programme were asked to split their fields into two equal parts, and to prepare one part with traditional land preparation and seeding methods and the other with broadbeds-and-furrows made with the BBM. All other inputs and the planting time were the same for the two treatments. On all plots primary land preparation was done using the conventional Ethiopian plough.

All inputs in all experimental plots were monitored continuously by enumerators residing in the respective research locations. The inputs measured were human and animal labour by origin and operation, seed and fertilizer. Yields of grain and crop residue were estimated by sampling. about 1% of the total area under treatment.

Table 2. Crops, number of plots and area covered for the on-farm drainage technology assessment.

Location	Crop	Number of plots[a]	Total area (ha)
Inewari	Faba bean	4	8.3
	Wheat	2	4.0
Wereilu	Faba bean	40	11.6
	Wheat	34	13.5
Debre Zeit	Teff	62	14.0
	Wheat	68	17.0
Fogera plain	Finger millet	18	4.5
	Noug	26	6.6
	Sorghum	6	1.5
	Total	260	81.0

a. A plot is the part of a field which receives uniform treatment (traditional or improved drainage).

Economic evaluation method

In the absence of whole-farm monitoring, partial budgeting was used. Revenue, return to labour and return to land were computed. The estimation of these economic parameters used market prices at harvest for the value of grain and straw; local wage rate for labour value; prevailing hiring prices of oxen for oxen labour value; and official 1986 price for fertilizer. It was assumed that one BBM is shared by two small farmers, that it can cover 4 ha year^{-1} and that the life of the metal parts is 10 years. The total cost of the implement is Ethiopian Birr (EB) 80 (Table 1). It was further assumed that the conventional plough

is used to cultivate 2 ha year^{-1}, that the life of the wooden parts is 5 years, that the life of the tines and the metal hooks is 10 years and that the cost of a complete conventional plough is EB 32.

RESULTS

Labour use

The number of primary cultivation passes for seedbed preparation depends on the type of crop to be sown. In general, the larger the seed, the fewer the cultivation passes required. Labour investment in primary cultivation varies considerably between locations: at Wereilu for example, 34 hours (CV 19%) were spent by an oxen pair per ha and cultivation pass, while at Debre Zeit only 26 hours (CV 17%) were used.

Table 3 shows the oxen and human labour inputs in traditional seed covering and BBF construction by the BBM. Differences between locations were considerable. Oxen time input for BBF construction with the BBM was higher than for traditional seed covering at Inewari and Wereilu, but lower at Debre Zeit, where the traditional seed covering pass with the conventional plough is carefully done, and at Forage plain. The BBM was operated in the field verification by two handlers, so that the human labour inputs shown in Table 3 are inflated. If only one handler is used, which is technically feasible, introduction of the BBM will provide a very remarkable labour saving in the Inewari area where BBF are traditionally made by hand. Oxen are used at Inewari in the seed covering exercise in order to make furrows about 120 cm apart: women and

Table 3. Human and oxen labour input in traditional seed covering and BBF construction with the BBM, 1986

Location	Seed covering	Human labour hr ha^{-1}	Oxen pair labour hr ha^{-1}	Oxen pair labour CV %
Inewari	BBF/BBM	30[a]	15[b]	25
	Traditional	60	9	21
Wereilu	BBF/BBM	36[a]	18[a]	25
	Traditional	14	14	19
Debre Zeit	BBF/BBM	35[a]	17.6[a]	25
	Traditional	24	24	29
Fogera plain	BBF/BBM	30[b]	15[b]	24
	Traditional	35	35	87

a. Difference between BBF/BBM and traditional methods significant at $P<0.001$ level.
b. Difference between BBF/BBM and traditional methods significant at $P<0.05$ level.

children then scoop up soil from these to establish the BBF.

Regional on-farm verification results

Inewari

The two crops monitored on the Inewari plateau, wheat and faba bean, yielded 54% and 14%, respectively, more grain on the BBF made with the animal-drawn implement than on the traditionally

made BBF. This is most certainly due to a greater uniformity of the drainage structure established.

Table 4 shows a summary of the physical and economic evaluation of the BBM on the Inewari plateau. Higher total costs were incurred on plots with hand-made BBF, essentially due to higher labour input. This, in conjunction with the yield impact of the BBM, resulted in considerably higher return to labour per time unit spent on the plots managed with the BBM. Local wage rate is 0.40 EB/hour. Labour investment in crop production on the plots treated with the BBM is therefore comparatively a very attractive option.

The use of fertilizer (di-ammonium-phosphate (DAP) at 100 kg ha^{-1}) on the two crops did not result in a significant change in gross revenue in either system (Appendix). This unsatisfactory input efficiency is explained by the fact that unresponsive landraces were used.

Wereilu

Wereilu recorded very heavy rainfall in 1986 with 30 rainy days in August. This resulted in extreme waterlogging on plots under the traditional ridge-and-furrow land management system. The ridges, established with the conventional plough when covering the seed, are about 30-50 cm in width. Early heavy rains tend to level out the fields, so that the initial drainage effect of the system is quickly lost.

On the other hand, the BBF established with the BBM provided sufficient surface drainage and seedbed stability to withstand the impact of the rain. Grain yield of faba bean and wheat on BBF made with BBM were of 330% and 131% higher,

Table 4. Economic evaluation of improved, animal-powered surface drainage at Inewari, 1986.

Land preparation and crop	Average grain yield (kg ha^{-1})	Gross revenue[a,b] (EB ha^{-1})	Total cost[a,c] (EB ha^{-1})	Return to labour[a,d] (EB hr^{-1})	Increase in return to labour over traditional land preparation (%)
Faba bean					
BBF/BBM	810	475	224	1.0	+ 43
Traditional[e]	709	436	264	0.7	
Wheat					
BBF/BBM	618	535	234	1.2	+ 140
Traditional[e]	402	339	278	0.5	

a. US$1 = 2.07 EB.

b. Includes value of grain and straw.

c. Operational and fixed costs.

d. After deducting all cost except for labour.

e. The traditional land preparation system is hand-made BBF.

respectively, than yields with the traditional planting system (Table 5). Similar yield increases were recorded for straw, which is the main animal feed for much of the year.

Due to waterlogging damage to crops on traditionally managed plots, labour inputs for harvesting and threshing were lower than for BBF plots. This increased total operational cost of BBF plots (Table 5). Gross revenue from faba bean and wheat on the BBF plots was 347% and 131% higher, respectively, than on the traditionally managed plots. A lower coefficient of variation in the yield figures from the BBF plots is an indication of more stable yields.

As shown in Table 5, returns to labour from the BBF technology were much higher than from the traditional system. Results from the traditional system were very poor: return to labour was negative in the case of faba bean and just equal to the local wage rate in the case of wheat.

It is important to note that grain yields from the traditional system are not sufficient to meet the grain subsistence requirements of the farm families. The average cropland holding in the project area is 1.4 ha and the average family size is five: the family subsistence requirements could only be met in 1986 at the productivity levels achieved under improved drainage.

Fertilizer inputs (DAP at 100 kg ha^{-1}) only marginally improved crop performance on both BBF and ridge-and-furrow plots, which is attributed to the unsatisfactory response to improved soil fertility of the landraces used (Appendix).

Table 5. Economic evaluation of improved, animal-powered surface drainage at Wereilu, 1986.

Land preparation and crop	Average grain yield (kg/ha^{-1})	CV%	Gross revenue[a,b] (EB ha^{-1})	Total cost[a,c] (EB ha^{-1})	Return to labour[a,d] (EB hr^{-1})	Net return[a] (EB ha^{-1})
Faba bean						
BBF/BBM	736[e]	59	398[e]	206	0.62[e]	192[e]
Traditional[f]	171	72	89	162	-0.07	-73
Wheat						
BBF/BBM	689[e]	46	432[e]	214	0.61[e]	218[e]
Traditional[f]	298	71	187	177	0.22	9

a. US$1 = 2.07 EB.

b. Includes value of grain and straw.

c. Operational and fixed costs.

d. After deducting all cost except for labour.

e. Difference between BBF and ridge-furrow significant at P<0.001 level.

f. The traditional land preparation system is ridges and furrows made with the conventional plough.

Debre Zeit

Rainfall during the main rainy season in 1986 in Debre Zeit was evenly distributed but 30% less than average (1977-85) in July and August. Very little run-off was therefore recorded. Despite these rather dry conditions yields and economic returns from wheat on BBF were 25% higher than on the traditional flat seedbeds (Table 6). Return to labour was 40% higher and the net return per ha was 55% higher. The cost of growing wheat did not significantly differ between the two land preparation methods.

Teff, a traditional Vertisol crop with some waterlogging tolerance, showed quite remarkably high grain and straw yields and even higher economic returns than wheat due to higher producer prices. However, grain and straw yields did not differ significantly between the two systems.

Fogera Plain

In 1986 the Fogera plain experienced extreme meteorological conditions with a very late onset of extremely heavy rains. This resulted in a serious delay and in low quality of land preparation, and in very poor condition of the working animals due to shortage of feed from natural range. As a consequence of poor seedbed preparation, resulting in heavy weed infestation, and of very heavy late rains and extreme waterlogging, the crop yields were low from both land management systems (Table 7). Sorghum completely failed on traditionally managed plots while the performance of the other crops was slightly, but not significantly, better on BBF than on traditionally managed plots.

Table 6. Economic evaluation of improved, animal-powered surface drainage at Debre Zeit, 1986.

Land preparation and crop	Average grain yield (kg ha^{-1})	CV%	Average straw yield (kg ha^{-1})	Gross revenue[a,b] (EB ha^{-1})	Total cost[a,c] (EB ha^{-1})	Return to labour[a,d] (EB ha^{-1})	Net return[a] (EB ha^{-1})
Wheat							
BBF/BBM	1541[e]	76	5407[e]	1357[e]	378	2.1[e]	979[e]
Traditional[f]	1228	41	4261	1078	437	1.5	641
Teff							
BBF/BBM	1654	32	4918	1913	537	2.1	1376
Traditional[f]	1558	27	4538	1791	400	2.4	1391

a. US$1 = 2.07 EB.

b. Includes value of grain and straw.

c. Operational and fixed costs.

d. After deducting all cost except for labour.

e. Difference between BBF and flat seedbed significant at $P<0.01$ level

f. The traditional land preparation system is flat seedbeds.

Table 7. Economic evaluation of improved, animal-powered surface drainage at Fogera plain, 1986.

Land preparation and crop	Average grain yield yield (kg ha^{-1})	Average straw yield (kg ha^{-1})	Gross revenue[a,b] (EB ha^{-1})	Total cost[a,c] (EB ha^{-1})	Net return[a] (EB ha^{-1})
Sorghum					
BBF/BBM	336	1124	202	188	14
Traditional[d]	0	0	0	102	-102
Noug					
BBF/BBM	195	1733	156	104	52
Traditional[d]	139	1384	111	79	32
Finger millet					
BBF/BBM	522	1242	346	251	95
Traditional[d]	372	1051	257	223	34

a. US$1 = 2.07 EB.

b. Includes value of grain and straw.

c. Operational and fixed costs.

d. The traditional land preparation system is flat seedbeds.

Applying fertilizer (DAP, 100 kg ha^{-1}) slightly, but not significantly, increased the grain and residue yields of noug and finger millet on both BBF and traditionally managed plots (Appendix). This lack of response was due to the use of unresponsive local crop cultivars.

DISCUSSION AND CONCLUSIONS

The performance of the animal-powered drainage implement (BBM) in terms of effects on crop yields

and economic returns for the farm differ between locations, basically in line with the prevailing meteorological conditions.

At Inewari, where all main season crops except teff are grown on hand-made BBF, the considerable effects of the BBM on economic returns to labour are further upgraded by the fact that using this implement reduces human drudgery. The BBM is therefore likely to be quickly adopted in this area. General use of the BBM will also increase the value of the available draught cattle in the system.

At Wereilu the use of the BBM dramatically improved returns to labour. The 1986 season was considered, by farmers interviewed in a base-line survey, as a bad agricultural season with exceptionally heavy waterlogging. The BBM allowed participating farmers to overcome this constraint and achieve yield levels that were regarded by the same farmers as equal to those that would be expected in a good year. The crop yields achieved in the traditional system are below subsistence, while the ones achieved on BBF plots are considerably above this threshold. The BBM therefore contributed to providing food security to the participating farmers. This is the primary objective of introducing the technology in this area.

At Debre Zeit high yields were achieved on both land management systems in a meteorologically favourable year. However, there were indications that waterlogging decreased yields even under these low-rainfall conditions, which suggests that waterlogging constrains crop growth in most Ethiopian highland Vertisol areas in any one year. In Debre Zeit the BBM also

contributed to higher returns to labour due to time saving in seed covering.

The low yields and economic returns in the Fogera plain are explained by the extreme meteorological conditions, which resulted in poor land preparation, high weed infestation and poor quality of the BBF made.

Fertilizer effects on crops were consistently disappointing in both land preparation systems. It is assumed that this is primarily due to the fact that the landraces which were monitored tend to be not very responsive to improved soil fertility.

The on-farm evaluation of the animal-drawn surface-drainage implement is being continued for another season in order to strengthen the encouraging first year information base, which will serve as a justification for a larger scale extension scheme for the technology to be undertaken by the Extension Services of the Ministry of Agriculture. Other components of the improved Vertisol management technology, such as improved cultivars with higher response potential to improved soil fertility, improved cropping systems, and water harvesting for re-use in irrigation, are being integrated into the programme in order to further strengthen the impact of improved Vertisol surface drainage.

Appendix. Fertilizer effects on crop yields and economic return on plots with traditional management and with improved drainage at Inewari, Wereilu and Fogera plain, 1986.

Location, land preparation and crop	DAP[a] (kg ha^{-1})	Grain yield (kg ha^{-1})	CV[b] (%)	Straw yield (kg ha^{-1})	Gross revenue[c] (EB)	Marginal rate of return[c,d] (EB)
Inewari						
BBF/BBM						
faba bean	0	810		1110	475	
faba bean	100	907		1246	533	0.7
wheat	0	618		1953	535	
wheat	100	708		2234	613	1.0
BBF traditional						
faba bean	0	709		1171	436	
faba bean	100	732		1534	482	0.6
wheat	0	402		1175	339	
wheat	100	569		1797	493	1.9
Wereilu						
BBF/BBM						
faba bean	0	736	59	591	398	
faba bean	100	858	64	731	468	0.86
wheat	0	689	46	877	432	
wheat	100	848	35	1297	554	1.51
Ridge-furrow						
faba bean	0	171	72	187	89	
faba bean	100	257	125	243	143	0.67
wheat	0	298	72	379	187	
wheat	100	469	67	616	296	1.35
Fogera plain						
BBF/BBM						
sorghum	0	336	93	1124	202	
sorghum	100	258	141	685	144	- 0.7
noug	0	195	32	1733	156	
noug	100	251	16	2849	201	0.6
finger millet	0	522	66	1242	346	
finger millet	100	921	36	2245	614	2.3
Ridge-furrow						
sorghum	0	0	-	0	0	
sorghum	100	0	-	0	0	-
noug	0	139	51	1384	111	
noug	100	166	35	2080	133	0.3
finger millet	0	372	89	1051	257	
finger millet	100	692	29	2125	488	2.9

a. DAP = di-ammonium-phosphate: 18% N, 46% P_2O_5.

b. A meaningful CV for grain yield in Inewari was not computed because only two plots were used for each treatment for wheat, and four for faba bean.

c. US$1 = 2.07 EB.

d. Value of the grain yield effect of each additional EB of DAP.

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ECONOMIC ASSESSMENT OF VERTISOL TECHNOLOGIES IN INDIA: IMPLICATIONS FOR ON-FARM VERIFICATION IN SUB-SAHARAN AFRICA

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ABSTRACT

This paper contains the results of an ex-ante economic assessment of an improved Vertisol technology in a verification site of high production potential in Madhya Pradesh, central India. Implications from the Indian experience are drawn for on-farm verification of prospective technologies in sub-Saharan Africa.

The assessment is made by using the whole-farm modeling approach which allows technology verification with a farming system perspective. The results suggest considerable potential for the adoption of the improved Vertisol technology. Adoption varies between 71 and 97% across different farm-size classes. The marginal rate of return on additional production expenditure ranges from 101 to 142%.

Credit was identified as the constraint to potential adoption of the improved technology. Compared with the existing credit availability, the model's estimates are consistent with credit

gaps ranging from 50 to 75%. Therefore, in technology transfer in central India, the main emphasis must be on providing sufficient credit.

ICRISAT's experience of applying whole-farm modeling for economic assessment indicates that because of the comprehensiveness of the approach, the comparability of Vertisol management options, and the characteristics of the farming environment in sub-Saharan Africa, such an approach can effectively be used for making economic assessments of prospective technologies in sub-Saharan Africa.

OCCURRENCE, PROPERTIES AND MANAGEMENT OF VERTISOLS IN THE CARIBBEAN

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ABSTRACT

Vertisols and other clay soils with vertic properties are among the most important soils in the Caribbean region. They are developed on many parent materials, including Recent marine clays, lacustrine sediments, marls, corals, calcareous shales and volcanic ash. Many of the soils occur in humid climates which are presently too wet for synthesis of montmorillonite, but this clay material has been inherited from the parent materials. The soils range from highly acidic for those developed on lacustrine and leached marine sediments to alkaline for those on calcareous materials. Phosphorus and K contents vary. P contents are high in the soils derived from calcareous materials and low in those formed on other materials, while the situation is the reverse for K. The clay mineralogy shows varying amounts of montmorillonite and kaolinite for those soils on calcareous and volcanic materials, while those on sediments also have illite.

With appropriate management, a wide range of crops is grown on these soils. Since large areas are flat, rice cultivation is important. Sugarcane is an important crop also, but elaborate land layout is needed to aid external drainage. The crop is usually cultivated on highly cambered beds with ridges, and the required field drainage

can occupy up to 20% of the land space. All other cropping is done on some form of cambered beds and/or ridges or banks designed to improve external drainage.

Soil fertility management requirements vary according to the particular soil type. Nitrogen losses are great from the calcareous-derived Vertisols and losses due to surface wash may be important. Phosphorus response is indicated by chemical analysis for some of the soils, but field response is not always obtained. Potassium content varies widely, but crop response to fertilizers is only obtained on some Vertisols developed on coral. Those on clay sediments are well supplied.

EFFECTS OF SURFACE DRAINAGE ON SOIL EROSION AND WHEAT GROWTH ON A GENTLY SLOPING VERTISOL AT DEBRE ZEIT, ETHIOPIA

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ABSTRACT

Vertisols are potentially fertile soils occurring mainly on gentle slopes (less than 8%). If appropriate surface drainage is implemented in high rainfall areas, grain and straw yields can be increased over those obtained by traditional cultivation. The broadbed-and-furrow (BBF) system can be constructed using a low-cost animal-drawn implement developed from the traditional Ethiopian ard (*maresha*). The impact of surface drainage on soil and nutrient losses needs to be investigated to assess and recommend the optimum slope and furrow length for the technology.

A 1986 study found that the surface soil on broadbeds was significantly drier, and the daytime soil temperature higher, compared to the traditional system. No significant difference was observed in 1986 between the mean grain and straw yields obtained on BBFs and on the traditional system. The mean on BBFs, however, was higher and more consistent within the replications than on

the traditional system. Low rainfall during the main growing period contributed to higher grain and straw yields on the traditional system than in previous years due to limited waterlogging. Soil and nutrient losses were minimal for the same reason and no significant differences were found between the two systems.

SOIL CONSERVATION WORKS ON VERTISOLS OF CENTRAL ETHIOPIA

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ABSTRACT

Despite the location of Vertisols and soils with vertic properties in Ethiopia on gently sloping to almost flat terrain, serious water erosion problems are encountered.

Since 1981, the Community Forestry and Soil Conservation Development Department of the Ministry of Agriculture has been working on soil conservation. Some of the activities are undertaken on Vertisols.

Much attention has been given to physical conservation measures, but the results are not very significant and these measures require a lot of manpower. Emphasis in conservation of Vertisols will have to be given to soil- and agronomic-management practices, such as increasing the organic matter content in order to improve the structure and to stabilise the soil aggregates (ploughed-in straw, application of compost and green manure) and improving the land-use systems (intercropping, alley cropping, grass strips, etc).

FOOD AND FEED

CHARACTERISTICS AND MANAGEMENT PROBLEMS OF VERTISOLS IN THE NIGERIAN SAVANNAH

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ABSTRACT

The Vertisols in Nigeria occur mainly in the Savannah region. Extensive occurrences are restricted mainly to the northeastern part of the country bounded by latitudes 8°30′ and 12°30′N and longitudes 10° and 14°E.

The soils are developed mainly on calcareous materials which include lagoonal clays, olivine basalt, ancient alluvium and shales, all of Quaternary or Cretaceous origin. The Ngala Vertisols are usually underlain by a sandbed within 100-200 cm depth. All the soils, except the Ngala series, exhibit gilgai microrelief features. Calcium carbonate and Fe-Mn nodules or concretions are also common features in all the soils.

Clay contents range from 42 to 75%, and soil pH from 6.3 to 8.0. The soils are non-saline, but are mildly to strongly sodic, especially the subsoils. They are high in basic cationic nutrients, but are very low in organic matter, N, P and Cu.

Management problems discussed include cultivation problems due to extreme stickiness of the soils when wet and their intractability when dry, and the lack of appropriate tillage

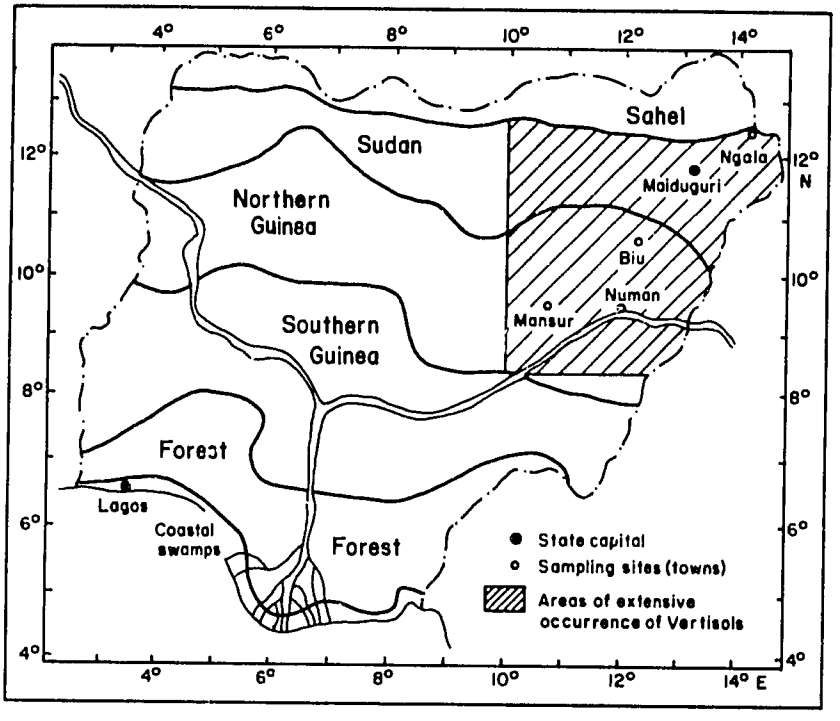
implements. Other problems are those related to seasonal flooding, nutrient deficiencies, sodicity in irrigated fields and soil erosion. The potential productivity of the soils is probably quite high, but a number of management problems must be solved before this potential can be fully exploited. Some integration of livestock and crops would seem workable.

INTRODUCTION

The Vertisols in Nigeria occur over an area of about 4 million ha, between latitudes 8°30' and 12°30'N and longitudes 10° and 14° E within the savannah ecological zone of the country (Klinkenberg and Higgins, 1968). The bulk of Nigerian Vertisols occur in the Sudan and Northern Guinea Savannah zones in the northeast of the country (Figure 1) in subhumid and semi-arid environments. The mean annual rainfall in the area ranges from 500 to 1000 mm, most of it falling between May and September. The mean annual potential evapotranspiration ranges from 1600 to 2000 mm, while mean annual air temperatures vary from 24 to 28°C (Kowal and Knabe, 1972).

Unfortunately, except for a few very restricted studies of the soils (Tomlinson, 1965; Klinkenberg and Higgins, 1968; Siewierski et al, 1982; Esu, 1983), little is known about their properties and peculiar problems of their management. Large Vertisol areas are still uncultivated, although some are fairly intensively grazed.

Figure 1. Major vegetation zones of Nigeria.



This paper examines the properties of Nigerian savannah Vertisols, and highlights some associated management problems of these soils.

MATERIALS AND METHODS

Study area

Representative pedons were sampled from Ngala, Biu, Numan and Mansur (Figure 1). The Ngala

Vertisols are derived from Quaternary lagoonal clay deposits of the Chad Basin formation and are found on the nearly level "Firki" clay plains (Tuley, 1972). The Firki clay plains are often interspersed by a number of sand islands, while the vertic clay deposits are often underlain by a sandbed at variable depths of 100-200 cm. The Biu Vertisols are found on the flat to gently sloping Biu plains, and are derived from Tertiary to recent calcareous olivine basalt (Esu, 1983). They have also been described as lithomorphic Vertisols by Klinkenberg and Higgins (1968). The Numan Vertisols are derived from Quaternary alluvium underlain by Bima sandstone and are found on nearly level plains. The Mansur Vertisols are located on gently sloping terrain (2-4%) and are derived from Tertiary clays and shales of the Kerri-Kerri formation (Bowden, 1972).

Field studies

Vertisols in northeastern Nigeria which were previously mapped by remote sensing were surveyed. At Ngala, Biu, Mansur and Numan, where extensive occurrences were delineated, a number of auger borings and one or two representative pedons were studied to give a broad overview of the main soil characteristics. Bulk soil samples were collected from seven representative pedons for laboratory analysis.

As part of the field study, a number of large-scale farm projects located on Vertisols were visited, including the wheat fields of the South Chad Irrigation Project in the Ngala area, the sugarcane plantations of the Savannah Sugar Company in Numan and a number of private cotton, sorghum, and maize farms. During the visits extension staff and farmers discussed current

management problems and how such problems were being solved.

Laboratory studies

Soil samples were air-dried, ground and passed through a 2-mm sieve. Physico-chemical properties were determined according to standard laboratory procedures.

RESULTS AND DISCUSSION

Morphological properties

The most striking feature of the soils is the occurrence of numerous wide, oblique and vertical cracks which divide the surface into "microslabs" when the surface is dry. When water is poured on them, the "slabs" expand visibly and the small cracks seal. In addition to the cracks, gilgai microrelief features are in the form of either microknolls and basins or low mounds and shallow depressions. These features are strongly expressed in the Biu, Numan and Mansur Vertisols.

In general, the surface soil structure is very unstable. Structural units slake instantaneously when moistened, so that the granulated surface layer easily turns into mud, and the soil becomes very sticky. This phenomenon is most common in the Mansur and Numan Vertisols but also occurs in the Biu and Ngala Vertisols. The substrata of the Biu, Numan and Mansur Vertisols are often massive due to high amounts of moisture retained in the soil even during the peak of the dry season. However, the Ngala Vertisols, perhaps because of the underlying sand layer which helps to drain the substratum, often maintain

continuous strong, coarse and prismatic structural units.

In general, the soils are calcareous, the $CaCO_3$ being present in the form of nodules or concretions. Manganiferrous concretions and Mn nodules are common in the Ngala, Biu and Numan Vertisols, but are abundant in the Mansur Vertisols.

The colour of the A-horizon is dominantly hue 10YR for the Ngala and Numan Vertisols, and 5Y and 2.5Y for the Biu and Mansur Vertisols, with moist values ranging between 3 and 5. Chromas rarely exceed 1.5 except in the Mansur Vertisols, which are on slopes. According to the criteria of *Soil Taxonomy* (Soil Survey Staff, 1975), the Ngala, Biu and Numan Vertisols may be classified as Pellusterts, while the Mansur Vertisols are classified as Chromusterts. These are equivalent to Pellic and Chromic Vertisols, respectively, in the FAO/Unesco system (FAO/Unesco, 1974).

Particle size distribution

The dominent textural class of these Vertisols is clay (Table 1). In general, the Ngala and Numan Vertisols, which appear to be better drained than the other Vertisols, contain the highest amounts of clay, while the Biu and Mansur Vertisols have lower clay contents.

Sand content in the Ngala Vertisols increases with depth to the underlying sand layer, while the silt content decreases rapidly from the surface to the substrat. The Biu Vertisols, perhaps because of their basaltic origin, have a rather low sand content (14-16%), while the silt content is almost as high as the clay content.

Table 1. Particle size distribution and selected chemical properties of representative pedons.

Depth (cm)	Particle size distr. Sand (%)	Silt (%)	Clay (%)	pH 1:2.5 water	EC ($dS\ m^{-1}$)	Organic C (%)	Total N (%)	Available-P (Bray I) (ppm)
Ngala Vertisols on lagoonal clays								
Pedon 1	Typic Pellustert (USDA) / Pellic Vertisol (FAO)							
0- 50	18	31	51	6.8	0.42	0.42	0.20	trace
50- 85	15	27	58	7.9	0.74	0.32	0.06	trace
85-105	20	14	66	7.9	1.52	0.20	0.06	trace
105-160	20	12	68	7.9	0.88	-	-	-
160-180	97	3	nil	8.6	0.66	-	-	-
Pedon 2	Typic Pellustert (USDA) / Pellic Vertisol (FAO)							
0- 60	7	21	72	6.3	0.38	0.28	0.14	trace
60-113	17	11	72	7.3	1.12	0.30	0.14	trace
113-178	22	6	72	7.4	0.96	0.20	0.08	trace
178-218	25	8	67	7.4	2.20	-	-	-
218-225	92	4	4	8.0	0.52	-	-	-
Biu Vertisols on olivine basalt								
Pedon 3	Entic Pellustert (USDA) / Pellic Vertisol (FAO)							
0- 60	14	42	44	6.3	1.20	0.40	0.17	0.7
60-115	14	42	44	7.8	1.60	0.40	0.08	1.4
115-160	14	38	48	8.0	3.20	0.40	0.14	1.4
Pedon 4	Entic Pellustert (USDA) / Pellic Vertisol (FAO)							
0- 20	14	42	44	7.0	1.10	0.93	-	0.7
20- 87	15	41	44	7.8	2.80	0.70	-	trace
87-120	16	36	48	7.8	1.90	0.71	-	trace
Numan Vertisols on ancient alluvium								
Pedon 5	Typic Pellustert (USDA) / Pellic Vertisol (FAO)							
0- 25	8	22	70	7.4	0.16	0.72	0.18	trace
25-135	7	18	75	7.8	0.11	0.48	0.13	trace
135-180	11	16	73	7.8	0.34	0.42	0.13	0.35
Mansur Vertisols on clay and shales								
Pedon 6	Entic Chromustert (USDA) / Chromic Vertisol (FAO)							
0- 25	28	20	52	6.9	0.06	0.89	0.05	11.10
25- 43	26	22	52	7.2	0.05	0.87	0.11	8.34
43-100	32	22	46	7.6	0.07	1.59	0.05	8.34
Pedon 7	Entic Chromustert (USDA) / Chromic Vertisol (FAO)							
0- 31	34	24	42	6.6	0.08	1.41	0.06	0.34
31- 69	34	16	50	6.9	0.06	0.73	0.04	1.38
69-117	36	18	46	7.2	0.52	0.73	0.03	1.81

The Mansur Vertisols contains the highest sand fraction, while the Numan Vertisols have the lowest sand and silt contents.

Chemical properties

Soil reaction

Soil pH in all the soils ranged between 6.3 and 7.4 for the surface soils and 6.9 to 8.0 for the subsoils (Table 1). In general, the pH increases with depth, perhaps corresponding to increased $CaCO_3$ and exchangeable Na contents (Table 2).

The soils are not saline. The electrical conductivity of the saturation extract averages less than 1.0 dS m^{-1} in the surface soils and less than 3.0 dS m^{-1} for the subsoils (Table 1). Sodicity is also not yet a major problem since the ESP is within the favourable limits of less than 15%, except for the Ngala Vertisols where ESP values range from 7.3 to 52.2% from the surface to the subsoil (Table 2). However, given the slow permeability of the soils and the high rate of evapotranspiration during the dry periods of the year, the soils are likely to become sodic under irrigation, especially because the ESP values generally increase with soil depth.

Organic carbon, total N and available P

Despite the generally dark colour of the soils, the organic carbon hardly exceeds 1.0%. The distribution of organic matter is uniform throughout the profile, although subsoil organic C contents in some of the Mansur Vertisols are higher than surface soil values (Table 1). This is probably because of considerable pedoturbation within the profile as the soils expand, contract,

Table 2. Selected chemical characteristics of representative pedons.

Depth (cm)	Exchangeable cations (meq/100 g soil) Ca	Mg	K	Na	CEC (pH 8.2)	ESP (%)	Extractable Fe (ppm)	Zn (ppm)	Cu (ppm)
Ngala Vertisols on lagoonal clays									
Pedon 1	Typic Pellustert (USDA) / Pellic Vertisol (FAO)								
0- 50	21.2	7.1	1.2	3.8	28.3	13.4	9.0	2.32	trace
50- 85	20.1	6.9	1.6	6.7	37.9	17.7	0.8	1.04	trace
85-105	21.5	8.7	1.8	8.5	39.6	21.5	6.0	1.06	trace
105-160	16.8	8.1	1.7	10.0	38.5	26.0	-	-	-
160-180	2.2	0.7	0.2	1.2	2.3	52.2	-	-	-
Pedon 2	Typic Pellustert (USDA) / Pellic Vertisol (FAO)								
0- 60	27.0	8.9	0.7	3.5	48.2	7.3	5.0	4.48	trace
60-113	26.7	8.4	0.4	4.4	43.0	10.2	4.0	2.32	trace
113-178	22.8	7.5	0.3	4.2	38.6	10.9	3.4	2.64	trace
178-218	21.3	6.9	0.2	4.1	38.8	10.6	-	-	-
218-225	3.0	0.8	0.1	1.1	4.0	27.5	-	-	-
Biu Vertisols on olivine basalt									
Pedon 3	Entic Pellustert (USDA) / Pellic Vertisol (FAO)								
0- 60	12.5	7.20	0.54	0.43	23.6	1.8	2.2	2.24	trace
60-115	13.28	7.71	3.08	0.98	25.6	3.8	8.0	1.60	trace
115-160	15.63	9.56	3.85	2.28	31.4	7.3	1.6	1.12	trace
Pedon 4	Entic Pellustert (USDA) / Pellic Vertisol (FAO)								
0- 20	15.22	4.69	0.60	0.78	27.1	3.7	-	-	-
20- 87	18.46	5.10	0.60	2.83	32.4	10.5	-	-	-
87-120	13.97	5.51	0.80	5.22	29.1	20.5	-	-	-
Numan Vertisols on ancient alluvium									
Pedon 5	Typic Pellustert (USDA) / Pellic Vertisol (FAO)								
0- 25	21.75	9.87	1.54	0.78	34.94	2.2	0.6	0.60	trace
25-135	22.00	10.20	1.28	1.57	36.05	4.4	0.6	0.72	trace
135-180	19.50	11.84	2.84	4.34	39.52	11.0	0.6	0.88	trace
Mansur Vertisols on clay and shales									
Pedon 6	Entic Chromustert (USDA) / Chromic Vertisol (FAO)								
0- 25	17.50	8.08	0.36	1.35	36.6	3.7	-	1.36	trace
25- 43	11.67	8.88	0.25	0.85	42.0	2.0	-	2.64	trace
43-100	16.67	8.88	0.83	0.29	42.0	1.3	-	1.52	trace
Pedon 7	Entic Chromustert (USDA) / Chromic Vertisol (FAO)								
0- 31	10.75	7.50	0.49	0.28	32.0	0.9	-	1.12	trace
31- 69	10.75	8.33	0.27	0.86	28.8	3.0	-	1.12	trace
69-117	12.13	7.50	0.31	2.17	30.8	7.0	-	0.80	trace

crack and self-mulch. Zein et al (1969) have calculated that in a Sudan Vertisol, 0.33% of the surface soil was mixed into the subsoil over a 2-year period.

Contents of N and P, like the organic matter content, are very low and probably limit the production of most crops. Total N ranges from 0.06 to 0.20% in all the soils, while available P was either present only in trace amounts or in most cases completely absent in the entire profile. Only Pedon 6 of the Mansur Vertisols contained appreciable amounts of available P (Table 1).

Exchangeable bases and cation exchange capacity (CEC)

Data related to exchangeable bases (Table 2) show that the soils have very high base status with Ca, followed by Mg, dominating the exchange complex. Levels of exchangeable K are in general adequate to support the production requirements of crops such as wheat, maize, rice, sorghum, and millet.

The CEC (pH 8.2) is high for all the soils and ranges from 23.6 to 48.2 meq/100 g of soil. As with the values for organic C, there appears to be no consistent change in sorptive capacity of the soils with depth. Since the organic matter content of the soils is low, it is probable that clay minerals are the major contributors to cation exchange capacity.

Micronutrients

There has been little investigation of micronutrient availability in the Vertisols of the Nigerian savannah. Iron, Zn and Cu status were

investigated in this study (Table 2). Of these three, Zn is the most important micronutrient in the area for arable crop production; average Zn content varied from 0.60 to 4.48 ppm, which is slightly higher than the critical level of 1.0 ppm suggested for most crops. Copper is the most important from the livestock point of view, because of the very low amounts in these soils. Indeed, Cu appears to be the most deficient micronutrient in all the soils. Only marginal to low levels of Fe are present in the soils.

PROBLEMS OF SOIL MANAGEMENT

The Vertisols in Nigeria offer a considerable potential for agricultural development, particularly under irrigation, provided their management problems can be overcome Large areas remain uncultivated because of the serious problems associated with the soil management. Major efforts to use these Vertisols have involved government-sponsored projects, such as the production of wheat and rice on 2000 ha in the South Chad Irrigation Project on the Ngala Vertisols, and the production of sugarcane on the Numan Vertisols by the Savannah Sugar Company. Other major users are local farmers and a few large-scale enterpreneurs who cultivate cotton, sorghum, maize, cowpea and millet. The vast areas which are presently not cultivated are used mainly as dry-season grazing with no control of stock density and pasture species.

Tillage is a major management problem. The high clay content makes these soils very hard and almost intractable when dry, and consequently they cannot easily be cultivated with a hoe or an ox-drawn plough. Cultivation with specially designed

tractor-drawn rotovators is the common practice in the South Chad Irrigation Project and the Savanna Sugar Company plantations, but this gives some compaction problems in the root zone.

Since the Vertisols are generally in flat terrain with poor drainage, they are seasonlly waterlogged, especially in years with high rainfall. Consequently, only crops that tolerate waterlogged conditions are grown on the soils. The use of ridges to grow crops that are sensitive to waterlogged conditions could be a useful management strategy. The construction of open ditches/drains to the depth of the underlying sandy layer would considerably ameliorate the problems of waterlogging. These Vertisols of the Nigerian savannah, especially the Mansur Vertisols on gentle slopes, are susceptible to soil erosion. This can be largely attributed to the low infiltration rates, slow permeability and the dominant 2:1 layered silicate expanding clays. Research on the control of soil erosion should be another area of management interest.

The Vertisols in Nigeria are generally well supplied with the basic cationic nutrients (Ca, Mg and K), but are clearly deficient in N, P and some micronutrients, notably Cu. Soil S was not determined in the present study, but widespread S deficiency in northern Nigerian Savannah soils has been reported by Bromfield (1972).

Copper deficiency is likely to pose the most serious micronutrient problem, especially for livestock production. About 45% of Nigerian livestock are found in the area covered by the Vertisols, and for many years this area has been used by nomadic cattle herders. So far, seasonal movement of herds in search of 'green pastures',

has protected the vegetation of the savannah Vertisols from overgrazing.

The use of such fertilizers as sulphate of ammonia might be preferred on these soils. Phosphate and some micronutrient fertilization will also obviously be inevitable. Few fertilizer experiments have been done to determine the nutrient requirements of crops on these soils. There is also a need to study the feasibility of integrating forage legumes into food crop systems under smallholder conditions.

ACKNOWLEDGEMENT

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LAND-USE SYSTEMS FOR VERTISOLS IN THE BAY REGION OF SOMALIA

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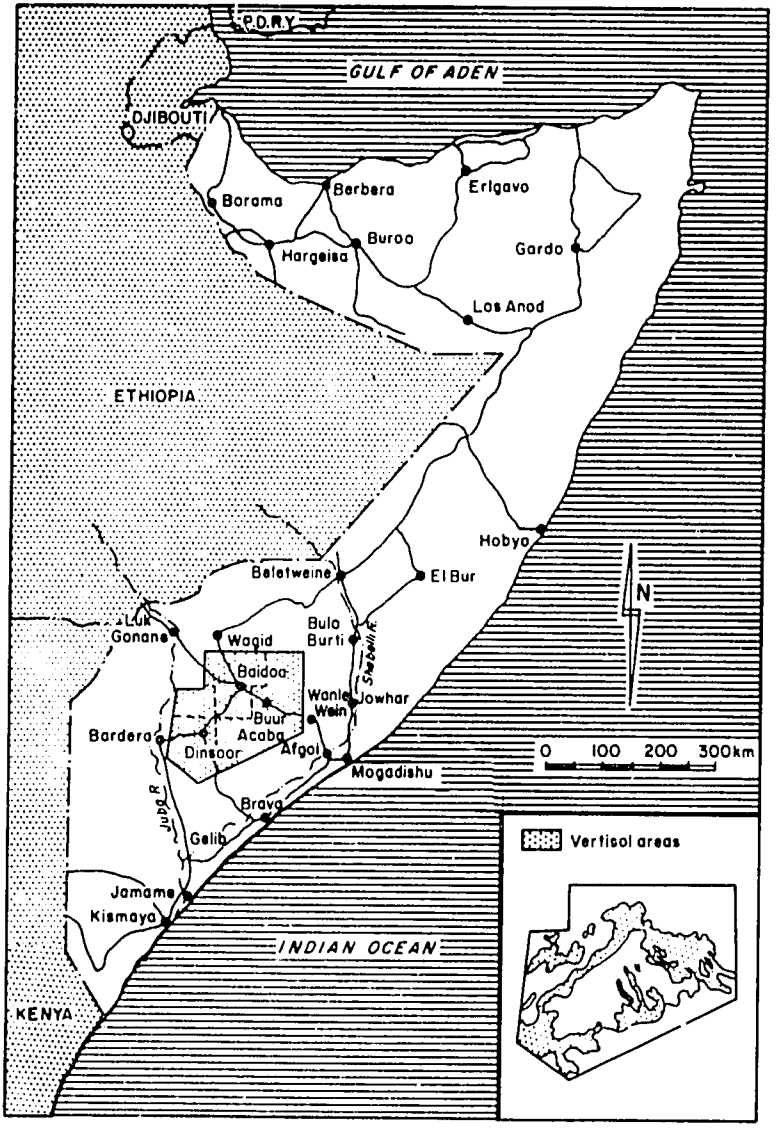
ABSTRACT

Vertisols occupy less than 20% of the Bay Region of Somalia, yet virtually all the crop production in the region occurs on these soils. The other soils of the region are suitable for rangeland. The combination of soil types supports an established, stable and well-adapted agropastoral system that integrates livestock and crop activities. Constraints to the system include unreliable rainfall, household labour shortages, and low soil fertility.

INTRODUCTION

The Bay Region is located between the Juba and Shebelle rivers in south-central Somalia (Figure 1). Due to the relatively good climate and soils, it is considered to have the greatest potential in Somalia to intensify and expand dryland agriculture (USAID, 1980). The area has more livestock than any other region in Somalia (HTS, 1982). Rainfed farming has coexisted with pastoralism in an agropastoral economic system that has evolved over the centuries. The majority of the rural population are agropastoralists (Putman, 1985). Crop production and livestock rearing are integrated within nearly every household to secure subsistence (HTS, 1983).

Figure 1. Map of Bay Region in Somalia, and Vertisol area in Bay Region (inset).



Source: HTS (1983).

With an area of 4 million ha and a population in 1982 of approximately 440 000, the Bay Region had a population density of 11 km^{-2}. The total livestock population was roughly 2.5 times the human population (HTS, 1982). Livestock numbers are greatly reduced in times of drought.

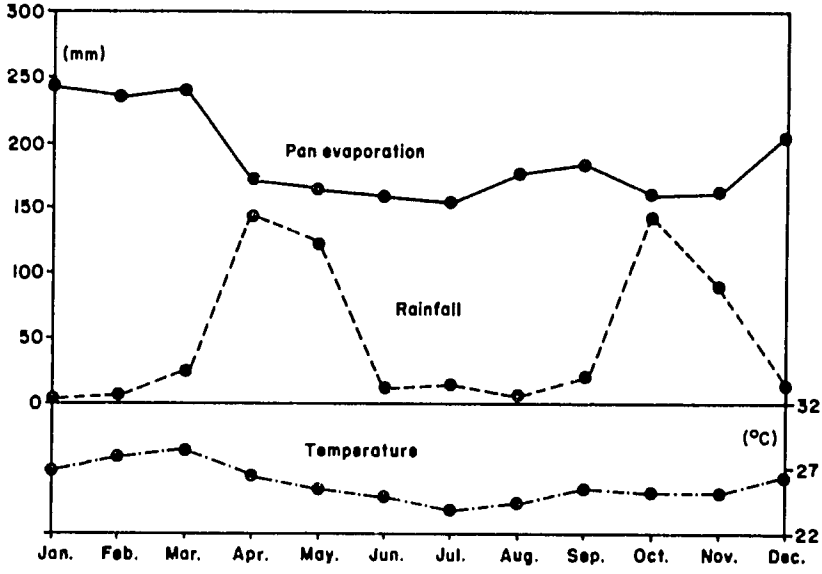
The climate of the Bay Region follows a bimodal rainfall pattern. The light rainy season (*Dayr*) usually begin by mid-October, and the heavy rainy season (*Gu*) usually begins by mid-April (Figure 2). Both rainy seasons last only 3-6 weeks and are extremely variable and unpredictable. Crops can be expected to fail 3 out of 10 years in the heavy rainy season and even more frequently during the light one (Schmidt, 1981).

The region has no natural perennial surface water. Lack of reliable water supplies is a major constraint to increasing livestock and crop production (HTS, 1983).

Based on soils, vegetation and geology, the Bay Region has been subdivided into five major geomorphological-ecological units: basement complex peneplain, limestone plateau, basement complex-limestone interface, coastal plain deposits, and clay plains (HTS, 1982). The topography of much of the region, which is at 100-500 m altitude, is flat to gently rolling.

About 18% of the Bay Region is occupied by the clay plains. These are Vertisols (Figure 1) on which the majority of crops are grown. Aerial surveys in 1982 determined that 11% of the Bay Region was cropped land and associated fallow. The remaining area was suitable only as rangeland (HTS, 1982).

Figure 2. Climatic conditions at Bonka Research Station in the Bay Region of Somalia.



Mean annual rainfall = 590 ± 210 mm
Mean annual evaporation = 2250 mm
Mean annual temperature = 26.2°C
Mean annual maximum temperature = 32.1°C
Mean annual minimum temperature = 19.8°C

Sources: HTS (1982); HTS (1983).

The major soils surrounding, and also spotted throughout, the cultivated Vertisols area are Regosols. Because these soils are better drained and less sticky when wet than the Vertisols, villages are frequently located on the Regosols, adjacent to the Vertisols. This allows the agropastoralists to have immediate access to land for both cultivation and livestock.

The Vertisols have characteristics (Table 1) similar to other Vertisols found in East Africa (Berhanu Debele, 1985; Muchena and Gachene, 1985.

Table 1. Physical and chemical characteristics of the major Vertisols in the Bay Region of Somalia.

	Soil type designation				
	Amin	Baidoa	Bur Acaba	Uiamo	Mode Mode
Total area (ha)	100 000	133 000	192 000	273 000	43 000
Cropped area(%)	30	72	52	42	52
Surface horizon characteristics					
Colour	red-brown 5YR 4/3	dark brown 10YR 4/3	brown 7.5YR 4/2	grey 10YR 5/2	grey 10YR 5/2
Texture	clay	clay	clay	clay	clay
pH	8.0	8.1	8.0	8.4	8.1
Organic matter (%)	1.7	1.2	1.4	1.8	1.3
CEC (meq/100 g)	50	70	40	50	55
Available P	low	low	low	low	low
Available K	high	high	high	high	high

Sources: HTS (1982); FAO (1968); Newton, (1968).

The clay minerals are the montmorillonitic type. Deep, wide cracks are common during the dry seasons. In some areas a gilgai microrelief is present, but not well expressed. Slickensides are present in subsurface horizons of most profiles.

The soils are calcareous, especially in the subsurface horizon where calcium carbonate is irregularly distributed as soft powdery lime or calcium carbonate concretions or nodules.

The cation exchange capacity of these soils ranges from 40 to 70 meq/100 g of soil. The predominant exchangeable cation, which accounts for up to 80% of the exchange complex, is Ca followed by Mg. Na and K contribute nearly equal proportions in the surface horizon of most profiles. The contribution of other cations in the exchange complex is negligible. Salinity and Na hazards are low to nil in the surface horizon, and low to moderate in the subsurface horizon (HTS, 1982). The organic matter content is less than 2% in the surface horizon, decreasing to about 1% at 1 m. These soils are high in available K and very low in available P (Newton, 1968; Strong, 1986). Experiments conducted at the Bonka Research Station on the Baidoa soils have shown a doubling of both sorghum and mungbean grain yields with the proper application of triple superphosphate. Goat and cattle manures gave similar results (Buker, 1986).

CROP PRODUCTION

Sorghum is by far the major crop grown in the Bay Region. It is grown in both cropping seasons on over 90% of the cultivated land (HTS, 1983). Although there have been attempts to introduce new sorghum lines, the local variety remains dominant throughout the region. Sorghum, along with animal products, such as meat, milk and ghee, comprises the staple diet of the region. Occasionally cowpea and mungbean are interplanted with the sorghum. Other crops of minor importance include maize, sesame and peanuts.

Most farmers produce subsistence crops by traditional methods on small cultivated areas, with low inputs and low yields. The most common

agricultural implement is the *yambo*, a hoe with either a short or long handle. It is used to plant and cultivate. The average area of cultivated land per household unit has been estimated at 1-8 ha. Grain yield per hectare is variable, depending primarily on the amount and distribution of rainfall: estimates generally range from 300 to 1000 kg ha^{-1} in seasons of adequate rainfall (University of Wyoming, 1984; Putman, 1985; Watson and Nimmo, 1985).

Seldom is all of the farmland owned by a single household farmed each season. In addition to the major constraint of labour shortages, and the calculation of an inadquate return, land left idle provides grazing for livestock, which is recognised as a way to control weeds as well as to increase soil productivity (University of Wyoming, 1984).

Most of the sorghum is consumed by the household unit which produces it. Only small amounts are marketed as needs arise. Some people with large farms may market relatively large amounts of sorghum when conditions are favourable, but this is the exception rather than the rule (University of Wyoming, 1984; Watson and Nimmo, 1985).

There have been numerous attempts over the past 30 years to introduce animal traction into the Bay Rgion, yet today very few farmers incorporate animal traction in their farming system. According to Martin (1986) the major constraint to the use of animal traction is drought and its effect on the availability of forage and water: the second most important constraint is inadequate and broken implements.

LIVESTOCK PRODUCTION

In February 1982 there were approximately 320 000 camels, 370 000 cattle, 360 000 goats, and 40 000 sheep in the Bay Region (HTS, 1982). The camels are single-humped dromedaries and the cattle are mainly of the East African short-horn Zebu type. Two types of goats are found in the region--the short-earned East African type, White and Southern Somali (the more common type) and the *Arbed*, "Arab Goat". The sheep are essentially all the Somali Blackhead type.

Between 1975 and 1982 the numbers of camels and sheep appeared to decline, while the numbers of cattle and goats increased in the region. This may indicate an increasing trend towards a more sedentary way of life in the Bay Region (HTS, 1982).

Livestock are kept for subsistence food production and to generate cash to purchase other foods, clothes and consumer goods. Livestock provide the means for capital accumulation during favourable periods and security for stock owners to survive droughts by the consumption and sale of animals. In addition to food, security and investment, livestock (especially camels) also offer prestige. Putman (1985) states that most agropastoralists would rank livestock higher as an investment item than agricultural implements.

A number of livestock management systems are employed depending on family labour availability, location, herd sizes and livestock types. Watson and Nimmo (1985) describe 10 livestock production strategies, varying from settled agropastoralism to nomadic pastoralism, used by the inhabitants of the region. Keeping mixed species herds is

common. It is favoured because a range of environments can be exploited, a range of products can be produced, species have different survival and recovery rates after droughts, and family labour availability can be best exploited (Hendy, 1985).

DISCUSSION

The major influences on the distribution of livestock within the region are water and forage. Livestock concentrate at the more reliable or permanent water sources as the dry season progresses. Vertisols, due to their good water retention properties, support the majority of these water sources. These soils also have a greater forage potential and a longer growing period than the other soils of the region (HTS, 1982; Watson and Nimmo, 1985).

The availability of forage is dependent on rainfall and soil type, and is influenced by the species of livestock and the supply of crop residues. In normal years livestock move onto cropland during and following harvest, where they feed on sorghum stover, on limited rangeland between sorghum fields, and on weeds on fallowed land. If a growing season is poor, livestock are brought back to the cropland earlier to graze on the growing sorghum (Watson and Nimmo, 1985).

The availability of sorghum stover is a major factor in maintaining livestock numbers and in influencing management systems. Sorghum crop residues may supply as much as 25-33% of the mean annual total of the forage produced in the region (HTS, 1982). Watson and Nimmo (1985) state that the value of these residues during the dry seasons

cannot be overestimated and they suggest that sorghum should be regarded as a fodder crop which occasionally produces grain.

Typically the stover is grazed in the field once the heads have been harvested. Less often the stover is removed from the field and either fed directly to penned livestock near the homes or stored for later use. Although rangeland is regarded as communal and cropland as private, sorghum stover left after the initial grazing is generally considered common property.

Sorghum stover is a good source of roughage, but is low in digestible crude protein. The mineral status of the natural diet of the livestock in the region is unknown. Typical P deficiency symptoms of pica and excessive hoof growth have been observed (HTS, 1982).

According to Watson and Nimmo (1985), between 1973 and 1983 the area of cropped Vertisols in the Bay Region expanded at about 3% per year, a rate similar to the rate of expansion of the human population. They suggest that the expansion of cropped land is actually a reduction of the period that land is fallowed, and that this may lead to a long-term reduction in fertility and change soil characteristics of the Vertisols which are under intensive and continuous sorghum cropping.

Efforts to improve livestock and crop production in the Bay Region must reflect the interdependence of the two. In order to improve the well-being of the inhabitants of the region, development projects should take a holistic approach to problem solving. In this manner, unforeseen imbalances between livestock and crop production will be minimised.

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CROP AGRONOMY RESEARCH ON VERTISOLS IN THE CENTRAL HIGHLANDS OF ETHIOPIA: IAR'S EXPERIENCE

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ABSTRACT

Some results obtained from a series of experiments carried out on Ethiopian Vertisols at Sheno and Ginchi, two research stations of the Institute of Agricultural Research (IAR), are reported.

Barley is the major food crop around Sheno. Its production is associated with soil burning, or "guie", and long periods of fallowing. Fairly high yields are obtained in the first crop season after "guie", but yields decline quickly after the second crop season. The major crops around Ginchi are Teff (*Eragrostis tef*) and wheat. They are planted late in the main rainy season and yields are low.

Crop agronomy research has been conducted by IAR at Sheno and Ginchi since 1968 and 1974, respectively. The major objective was to replace the traditional practices of crop production with improved drainage, fertilizer and crop management techniques.

At Sheno, barley and wheat yields increased substantially when grown on 4-6 m wide cambered beds with the application of 60/26 (N/P) kg ha^{-1}. Fertilizer was more efficient with wheat than with barley. Grain yields from continuous barley

production under improved management fluctuated over the years.

At Ginchi wheat yields more than doubled with improved drainage and application of 60/20 (N/P) kg ha^{-1}. Improved cultivars responded well to fertilizer application.

INTRODUCTION

Currently about 2 million ha of Vertisols are cropped annually in Ethiopia and some 6 million ha are left under native pasture because of severe drainage problems in the main rainy season (Jutzi et al, 1987). With the present trend of population growth in Ethiopia, estimated at 2.9%, there is a strong need for increased agricultural production which may be achieved by increasing productivity per unit area and/or opening new lands. Both options may be applied on Vertisols in the highlands.

Some of the major limitations for crop production on Vertisols are poor drainage, difficulty of seedbed preparation, and low soil fertility. In the high altitude areas the impact of low temperature complicates the soil problems. Traditionally farmers cope with these problems by late sowing of crops to mature on residual moisture, fallowing the land in the main rainy season, and soil burning, or "guie" (Berhanu Debele, 1985). Land that is ploughed early for late planting of crops is exposed to soil erosion due to high and intense rainfall, hence diminishing soil fertility.

The Institute of Agricultural Research (IAR) has been conducting agronomy research at Sheno,

about 70 km north-east of Addis Ababa, since 1968 and at Ginchi, 85 km west of Addis Ababa, since 1974. Crop production patterns and the research experiences at these locations are reviewed in this report. It is possible to increase crop productivity on Vertisols through improved drainage, fertilizer and crop management (Hiruy Belayneh, 1986; Jamal Mohammed, 1985; Jutzi et al, 1987; Mesfin Abebe, 1979 and 1982; Taye Bekele, 1986).

CROPS AND PRODUCTION PATTERNS

Sheno

Sheno is situated at an altitude of 2800 m, surrounded by a large highland plain. The soil has about 60% clay, a slightly acid pH, 0.2-0.3% total N and 7 ppm of available P (Mesfin Abebe, 1982). Annual rainfall is about 900 mm, with excess rain in July and August. "Guie" is extensively practised in the region. "Guie" plots are cropped to barley for 2-3 seasons and then left fallow for 10-20 years.

The predominant crop is barley with some faba beans, wheat, fieldpeas and oats, and lentils and linseed on a few hectares. Average yields of crops around Debre Birhan are 846 kg ha^{-1} for barley, 1295 kg ha^{-1} for faba bean, 964 kg ha^{-1} for wheat, and 846 kg ha^{-1} for fieldpeas (Gryseels and Anderson, 1983). Crop intensity is high on the hillsides and low on the bottomlands which are flooded during the main rainy season. Faba beans and wheat are mainly produced on the hillsides which have better drainage and less frost hazard; barley is produced on the flatter lands (Gryseels

and Anderson, 1983). "Belg", or off-season barley, is mainly produced on bottomlands.

Tillage operations may start in September or October for "belg" season production and "guie" fields with repeated ploughings in the short rainy season. "Guie" fields are planted in June. Early sowing is practised for all crops except wheat, although barley may be sown in late June to escape aphid infestation.

Ginchi

The research site at Ginchi is at an altitude of 2200 m. Average annual rainfall is about 1080 mm of which about 65% falls between June and September. The soil is a heavy clay with 0.91-1.32% organic matter, 0.09-0.14% N and 4.2-9.9 ppm available P (Morton, 1977); the pH is about 6.4 (Hailu Kenno and Lulseged Gebre Hiwet, 1983).

The major food crops are teff (*Eragrostis tef*), wheat, niger seed and chickpeas. Sorghum, roughpea and barley also are grown to some extent. Estimates of yields of major crops are 500 kg ha^{-1} for teff and chickpeas, 600 kg ha^{-1} for wheat, and 300 kg ha^{-1} for niger seed (Agricultural Economics and Farming Systems Research Division, Survey date 1986).

The frequency of ploughing varies for crops: 3-4 times before planting for teff, 3 times for wheat and 1-2 times for pulses, niger seed and sorghum. Ploughing starts in March for cereals and niger seed; the first ploughing for pulses may be done in May. The small grains and pulses are sown late in the main rainy season and mature on residual moisture. Sorghum is sown in March or April and niger seed towards the end of May.

Pulse/cereal rotation is a common practice. Teff follows chickpeas in most cases, or roughpea and niger seed. Niger seed may follow sorghum for weed suppression.

REVIEW OF RESEARCH RESULTS

Sheno site

The major objective for agronomy research was to replace the inefficient traditional practice of "guie" crop culture with improved drainage, fertilizer and crop management techniques for continuous crop production.

Barley grain yields of about 1.5 t ha^{-1} are obtained on "guie" fields in the first crop season (Taye Bekele, 1986). The high yield is due to improved soil structure and increased availability of ammonium-N and P; on the other hand, there is a high loss of organic matter and total N, with a detrimental consequence on the cation exchange capacity and microbial activity (Berhanu Debele, 1985; Mesfin Abebe, 1979 and 1982; Taye Bekele, 1986). "Guie" plots respond to fertilizer application and the efficiency is better than on regularly ploughed plots (Taye Bekele, 1986). Yields on "guie" plots decline dramatically after the second season of barley production (Taye Bekele, 1986; Mesfin Abebe, 1979).

In the early years, research on soil and fertilizer management was directed towards comparing the crop yields obtained from plots prepared by tractor-drawn ploughs (such as disc, mouldboard, and chisel) with those from narrow and wide cambered beds (prepared with mechanised operation), using different rates of application

of N and P fertilizers. Narrow cambered beds gave higher yields at all N and P fertilizer application rates than the plots prepared by other methods. In 1970 about 2.5 t ha^{-1} of barley grain yield was obtained on a 6 m-wide cambered bed with application of 60/13 (N/P) kg ha^{-1} (Mesfin Abebe, 1979). Grain yields of barley, wheat and oats were also better on narrow cambered beds than on "guie" plots (Mesfin Abebe, 1979). Fertilizer efficiency was high on narrow cambered beds for barley and wheat.

The higher yield advantages of narrow cambered beds over local ploughed and mouldboard ploughed plots were further confirmed in later years on barley and wheat. The best yields of barely were obtained on cambered beds due to improved drainage (Table 1). However, efficiency of fertilizer with local barley was nearly similar on local ploughed and cambered beds (Mesfin Abebe, 1982; Taye Bekele, 1986). Fertilizer efficiency with wheat was much higher with improved drainage; wheat also responded better to additional P application than barley at a standard level of 60 kg N ha^{-1} (Table 2). Grain yields from continuous barley production fluctuated over the years; it was difficult to maintain stable yields even with improved drainage and optimum fertilizer application (Table 3). Rotation with pulses may be essential to sustain grain yields.

Ginchi site

In 1971 a testing site was established at Wollencomi, 74 km west of Addis Ababa, for research on drainage and fertilizer management and on the selection of high yielding crops and cultivars for early sowing on Vertisols. The

Table 1. Effects of seedbed preparation methods and N/P fertilizer application rates on mean grain yields of barley, Sheno, 1979-84.

Fertilizer rate (kg ha^{-1}) N/P	Grain yield (kg ha^{-1})[a] LP	MP	CB
0/0	200	400	780
30/13	630	690	1200
60/26	870	1230	1670
90/40	1090	1410	1990

a. LP: Local plough; MP: Mouldboard plough; CB: 6-m wide cambered beds.

Source: Taye Bekele (1986).

Table 2. Effects of seedbed preparation methods and N/P fertilizer application rates on grain yields of wheat and local barley, Sheno, 1976.

Fertilizer rate (kg ha^{-1}) N/P	Grain yield (kg ha^{-1})[a] Wheat cv Enkoy LP	MP	CB	Barley cv Local Sheno LP	MP	CB
0/0	119	387	559	82	316	565
60/13	395	1267	1561	909	1277	1385
60/26	385	1318	1877	1055	1246	1598
60/40	657	1452	1995	1079	1194	1692

a. LP: Local plough; MP: Mouldboard plough; CB: 4-m wide cambered beds.

Source: Mesfin Aebe (1982).

Table 3. Effects of seedbed preparation methods on grain yields of barley at optimum level of fertilizer application (60/26 (N/P) kg ha $^{-1}$), Sheno, 1979-84.

Year		Grain yield (kg ha^{-1})[a]		
		LP	MP	CB
1979		1510	1990	2490
1980		870	1940	2270
1981		470	410	700
1982		690	1470	2050
1983		300	520	850
1984		1350	1020	1650
	mean	865	1225	1668

a. LP: Local plough; MP: Mouldboard plough; CB: 6-m wide cambered beds.

Source: Taye Bekele (1986).

Ginchi site, 11 km further west, was selected in 1974 as being a better representation of the surrounding area.

From 1975-1977 different drainage system methods--cambered beds, open trenches, and sub-surface trenches filled with wooden poles and branches at 4, 6 and 8 m intervals--were compared using improved and local varieties of wheat, teff and chickpeas at zero and optimum fertilizer levels.

Improved drainage had a significant effect on grain yields of crops, especially of wheat, whose yields increased by more than 100% compared to the yields from undrained plots;

however, no significant differences in grain yields were observed between the various drainage methods (Table 4).

Fertilizer efficiency was highest with wheat with improved drainage; chickpeas responded poorly (Table 5). Among the wheat varieties, Enkoy gave the best response to fertilizers and improved drainage, yielding 1.8 t ha^{-1}, while Bahir Seded yielded 0.65 t ha^{-1}; there was no difference among the varities of teff or chickpeas (Hiruy Belayneh, 1986).

Results of sowing date studies on three cultivars of wheat (Enkoy, Cocorit 71 and Bahir Seded), covering the period from the end of June to the third week of August (Jamal Mohammed, 1985), showed no significant differences on 8-m wide cambered beds. Average grain yields were 2.1 t ha^{-1} on cambered beds and 1.3 t ha^{-1} on flat beds; improved drainage gave about a 70% yield increase over undrained plots. The yield of Enkoy, at 2.4 t ha^{-1} was significantly better than that of Cocorit 71 or Bahir Seded (2.1 and 1.9 t ha^{-1}, respectively) on cambered beds.

Undersowing wheat with barrel medic, snail medic and lolium was found promising with wheat grain yields of 2-3 t ha^{-1} (which are comparable to sole cropping yields), and dry matter forage yields of over 2 t ha^{-1} from the forage crops (Lulseged Gebre Hiwet et al, 1987).

The major direction in cereal breeding is to select high yielding, late maturing cultivars for sole cropping to utilise the whole growing season. Long season wheat cultivars giving about 3.2 t ha^{-1} are identified for Ginchi (Hailu Gebre Mariam and Bekele Geleta, 1985).

Table 4. Influence of drainage methods on grain yields of wheat, teff and chickpeas, Ginchi, 1975-77.

Drainage methods	Grain yield (kg ha^{-1})		
	Wheat	Teff	Chickpeas
Cambered bed	1150	1280	1250
Open trench	1150	1180	1200
Subsurface drain	1100	1000	1480
Control	520	940	870

Source: Hiruy Belayneh (1986).

Table 5. Influence of drainage and fertilizers on grain yields of wheat, teff and chickpeas, Ginchi, 1975-77.

Crops	Grain yields (kg ha^{-1})			
	Undrained[a]		Drained[a]	
	F0	F1	F0	F1
Wheat	360	670	720	1530
Teff	740	1140	840	1470
Chickpeas	850	900	1220	1400

a. F0: no fertilizer;
F1: 60/20 (N/P) kg ha^{-1} for wheat and teff,
27/30 (N/P) kg ha^{-1} for chickpeas.

Source: Hiruy Belayneh (1986).

FUTURE RESEARCH

Current research on Vertisols is being strengthened by collaborative work involving ILCA, ICRISAT (International Crops Research Institute for the Semi-Arid Tropics), IAR, the Agricultural University of Alemaya and the Ministry of Agriculture. The sharing of experience among the institutions helps to streamline research efforts. Applied agronomic research based on animal-drawn implements would have more relevance to the highly subsistence-oriented nature of crop production on highland Vertisols. For high altitude areas it may be worthwhile considering appropriate tillage methods, proper seeding and fertilizer application, and alternative cropping systems for small grain-based production.

Tillage

Timeliness of tillage with respect to soil moisture content is important to work the soil properly for effective control of weeds. The local plough is not effective for weed control, and better implements are needed. Reduced tillage with shallow cultivation and the use of glyphosphate for weed control may be important (Willcocks and Browning, 1986).

Proper seeding and fertilizer application

The wastage rate of fertilizers is high on Vertisols due to the broadcast method of sowing and denitrification due to waterlogging. Proper methods of seeding and method and time of application of fertilizers are important for efficient fertilzer use.

Cropping Systems

Crop productivity on Vertisols can be increased through early planting and improved surface drainage. Appropriate cropping systems are required for efficient use of the whole growing season. Some forage legumes are known to benefit food crop production by enhancing soil fertility when planted in association, or in rotation, with a major food crop. Most of the available information is relevant to maize and sorghum production in mid-altitude areas, such as Debre Zeit. In the higher areas, small grains are major food crops, so cropping systems based on such crops would be more appropriate. Some *Vicia*, *Trifolium* and *Medicago* species have high potential for sequential cropping with cereals. Some useful cropping systems may include forage legume-cereal sequences in the off-season and main rainy season, and cereal-pulse sequences in the main season.

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RAINFED AGRICULTURE AND CROPPING SYSTEMS ON VERTISOLS IN SUDAN

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ABSTRACT

Of Sudan's total cropped land area of about 7.4 million ha, some 4.1 million ha (more than 55%) are Vertisols. Only about 825 000 ha of Vertisols are under irrigation; rainfed agriculture on Vertisols thus occupies some 45% (3.3 million ha) of the country's total cropped area. This rainfed area is farmed by traditional methods (about 900 000 ha) or mechanised systems (about 2.4 million ha). In both sectors, sorghum and sesame are virtually the only crops, occupying about 2.8 million and 400 000 ha, respectively.

The predominance of sorghum cropping by mechanised cultivation methods is presenting severe problems. Virtual monocropping with sorghum causes rapid decline in soil fertility and serious infestation with sorghum-associated weeds, especially striga. The use of the disc harrow as the only tillage implement working the soil to the same shallow depth year after year is producing a hard soil layer. And delaying sowing until late July/early August (a consequence of relying on the secondary tillage operation to destroy germinated weeds, and hence save on the cost of weeding) on Vertisols is wasteful of available moisture, forces farmers to use low crop densities, and results in machinery being used under unfavourable conditions.

Ways to cope with these problems are suggested, such as adopting a crop rotation system in which sorghum occupies not more than half the land, and the area devoted to sesame is increased; making use of herbicides to permit early sowing; deep ploughing the land every 2-3 years, preferably with a chisel plough; and replacing the tall sorghum cultivars with dwarf types, which can be grown at higher densities and hence provide higher yields.

STATE OF KNOWLEDGE AND CRITICAL ANALYSIS OF THE USE AND MANAGEMENT OF VERTISOLS IN BURKINA FASO

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ABSTRACT

Vertisols in Burkina Faso are of the lithomorphic and topomorphic types. They are found throughout the country, mainly located in plains with a high hydro-agricultural potential. Their mineral and clay contents are high but they are deficient in N, P and K; their physical properties make tillage with traditional implements difficult.

The use of these soils in Burkina Faso has, for a long time, been limited to sorghum, maize, cotton and rice production on Vertisols with a granular structure in the upper horizon, and to dry-season grazing on hydromorphic Vertisols. As a result of the activities of the Autorite de l'menagement des Vallees des Volta, use of these Vertisols has been intensified.

IRAT and CERCI trials have shown that strategic use of fertilizer and manure, and adequate selection and rotation of appropriate crops, can lead to yields two to five times greater than those obtained on farmers' fields. Irrigation increases productivity of forage crops grown on Vertisols. On Vertisols in Sourou, *Vigna unguiculata*, *Desmodium distortum* and *Stylosanthes gracilis* performed well under irrigated farming, and *S. hamata and Cendrus ciliaris* under dry farming.

NIGERIAN DARK CLAY AND ASSOCIATED SOILS

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ABSTRACT

Dark clays and associated soils cover extensive areas (estimates vary between 1 and 10 million ha) of northeast Nigeria. They are also found in the southwest part of the country (about 7000 ha)

This paper reports the results of studies on 12 soil profiles, 7 from the north and 5 from the south of Nigeria. The northern soils are Vertisols: they show the typical cracking pattern, gilgai and other morphological features of these soils, and their clay content is high (above 40%) throughout the profiles. The southern soils have variable clay contents--generally low in the topsoils and 31-57% in the subsoils: one soil has a low clay content throughout the profile. Despite their low clay contents, these soils show vertic properties: the clay mineralogy is mainly 2:1 lattice-type highly expanding clay; they are slightly acidic to alkaline, with Ca and Mg as the dominant cations in the exchange complex; and they have low permeability.

In the north these soils are used for growing wheat and sorghum, and for grazing. In the south they are used for grazing, and for growing a wide range of food crops, such as maize, yams and vegetables. The main management problems are flood control, maintaining a stable soil structure, correcting salinity problems (in the northern soils) and establishing cropping sequences and irrigation and drainage systems.

VERTISOLS IN BURUNDI: THEIR IMPORTANCE, USE AND POTENTIAL

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ABSTRACT

Burundi is a country of hills and mountains. Its soils are generally very acidic and sloping. Vertisols occur only over a very small proportion of the country's land area, mainly on the few flat plains north of Lake Tanganyika.

The majority of the Vertsiol areas of Burundi are agriculturally underexploited; only small areas are used for dry farming of cotton and for animal husbandry. However, because the agricultural potential of these soils is very high, especially under gravity irrigation; because Burundi has a growing need for soil resources to meet its food demands; and because the close proximity of the Vertisols areas to the capital city, Bujumbura, offers good marketing possibilities for produce grown on Vertisols, rational and intensive use of these soils is both possible and desirable.

Research on new management practices for Vertisols is urgently required, and the national agency that will be responsible for this programme should also participate in international networks on Vertisol-related problems.

THE EXTENT AND UTILISATION OF VERTISOLS IN SWAZILAND

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ABSTRACT

Swaziland is located in the southeast of Africa, and has 875 000 inhabitants. On the basis of physiography and rainfall distribution, it is divided into three regions: highveld, middleveld and lowveld. The Vertisols are found in the entire lowveld region, at an altitude of 213 m.

Sugarcane and cotton are the major commercial crops in Swaziland; sugar is the largest exported commodity. The three big sugar companies, together with neighbouring estates, grow sugarcane and cotton on the Vertisols under irrigation.

Government-managed cattle ranching stations--sisa ranches, cattle breeding stations and fattening ranches--are also situated in the lowveld region

There is great potential for developing livestock management and sugarcane and cotton production on the Vertisols of Swaziland.

PROPERTIES, USES AND MANAGEMENT OF VERTISOLS IN MALAWI

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ABSTRACT

Although the Vertisol area in Malawi is limited, these soils are important because the country's economy is largely based on agriculture, and so any useable soil is valuable regardless of its extent. Vertisols have unique properties, and thus need special management if they are to be agriculturally exploited. Improved management practices can therefore lead to increased agricultural production.

VERTISOLS OF ZAMBIA: THEIR MANAGEMENT, PRODUCTIVITY AND ECONOMIC ASSESSMENT

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ABSTRACT

Research during the past 20 years in Zambia has shown that, with adequate management, Vertisols can be made as productive as other soils. With early planting, irrigation, ridging and fertilization, the crop yields obtained were comparable with, and sometimes even higher than, those from experimental plots on upland soils.

The dominant use of Vertisols in tsetse-free areas is for livestock production, primarily for cattle rearing. Adequate disease control, controlled grazing and early burning to produce fresh grass growth are necessary technical measures to keep the grassland productive.

It appears that high-input agriculture has more scope to achieve economically satisfactory returns from Zambian Vertisols. Because of the emphasis put by the government on the development of the small-scale farming sector, the current utilisation of the Zambian Vertisols is likely to persist. This assumption is also supported by the fact that a relatively low human population pressure does not force traditional farming on these soils.

LIVESTOCK

THE ROLE OF LIVESTOCK IN THE GENERATION OF SMALLHOLDER FARM INCOME IN TWO VERTISOL AREAS OF THE CENTRAL ETHIOPIAN HIGHLANDS

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ABSTRACT

The paper examines the contribution of livestock to farm income in two Vertisol areas of the Ethiopian highlands: around Debre Zeit (1850 m altitude) and around Debre Birhan (2800 m altitude). The data used in the analysis were obtained in a farm management survey of randomly selected smallholder farms in each area. Trade in livestock and livestock products contributes a significant proportion of farm cash income, ranging from 85% in the high-altitude zone to 35% in the medium-altitude zone. Livestock also provide approximately 50% of the farm gross margin, which increases to 60% if the value of draught power is also taken into account.

In the subsistence farming system of the Ethiopian highlands, principal functions of livestock are security and investment: animals are purchased as a store of wealth and are sold according to cash flow needs. Despite the low productivity of livestock in this traditional farming system, this investment is sound: the annual rate of return on investment is estimated at 25% for sheep and 31% for cattle.

The principal contribution of cattle to the farming system is the provision of draught power for crop production. Although the two study areas contrast in terms of ecology and the availability of draught animals, there appears to be a direct correlation between ox ownership and farm cereal production, reflected in area cultivated, cropping pattern and, at least for the Debre Birhan area, yield per unit area.

INTRODUCTION

Almost all farmers in the central Ethiopian highlands own livestock. A typical herd contains cattle, sheep, equines, and poultry. In terms of monetary value or contribution to agricultural production, Zebu cattle are the most important species: their prime role is to supply draught power for crop cultivation, and manure, most of which is dried and used as household fuel. Small ruminants are often numerically the most important species: sheep and goats are kept mainly as an investment and a source of cash in times of need, but they also supply the dominant type of meat consumed in rural areas, as well as manure for fuel. Donkeys are mostly used as pack animals while horses are used for human transport. Poultry are scavengers and kept for egg production and human consumption.

Human diets in the Ethiopian highlands consist mainly of cereals and pulses, and the consumption of meat is largely confined to feast-days. Yet, livestock are of crucial importance to the farm economy.

This paper investigates the role of livestock in the generation of farm income in two Vertisol

areas of the central Ethiopian highlands, and shows that livestock provide an important, even predominant, part of farm income.

MATERIALS AND METHODS

The data used in this analysis were collected in farm management surveys undertaken by ILCA in the two main study areas of its Highlands Programme (Gryseels and Anderson, 1983a): around Debre Zeit, 50 km south of Addis Ababa at an altitude of 1850 m, and around Debre Birhan, 120 km northeast of Addis Ababa at an altitude of 2800 m.

The Debre Zeit data were collected between 1979 and 1980 for a total of 80 farmer-years from farmers who were members of three different Peasants' Association (PA). The survey covered approximately 40 farmers each year, or about 10% of the local farmer population. The Debre Birhan data were collected between 1979 and 1983 for a total of 200 farmer-years from farmers who belonged to four PAs. The survey also covered approximately 40 farmers each year, in this case about 5% of the farmer population of each PA concerned.

The farmers surveyed were randomly selected from PA population lists supplied by the local district office of the Ministry of Agriculture. The data were collected by experienced enumerators, all high school graduates, through direct measurement, observation and weekly formal interviews. The data were analysed using SPSS routines.

A general description of the study areas is given in Gryseels and Anderson (1983b). The soils

in both areas are predominantly Vertisols. Although both areas have a similar farming system, they form a marked contrast. The area around Debre Zeit is representative of Ethiopia's large middle-altitude cropping zone. It is more productive and intensively cultivated than the area around Debre Birhan, with virtually no arable land kept fallow. The average farm size is around 2 ha. Teff is the principal cereal grown, the other important crops being wheat, maize, sorghum, faba beans, chickpea and field peas. The average livestock holding consists of 4.24 cattle, 2.55 small ruminants and 1.03 equines, or the equivalent 4.27 TLU (Tropical Livestock Unit, defined as an animal of 250 kg liveweight) (Table 1). Only 21% of farmers own fewer than two oxen.

Debre Birhan is representative of the higher-altitude zone of the country. Frost, hail, a short growing season and low soil fertility, severly limit agricultural production. Average farm size is around 3.3 ha, of which 2.3 ha are cultivated and 1 ha is kept fallow. The main crops are barley, wheat, oats, faba beans, field peas, lentils and linseed. Mean livestock holdings are larger than elsewhere in the Ethiopian highlands, averaging 6.18 cattle, 11.16 small ruminants and 2.83 equines, or the equivalent of 7.66 TLU (Table 1). About 50% of farmers have only one ox or none at all.

CONTRIBUTION OF LIVESTOCK TO FARM INCOME

Cash income

Farmers in the central Ethiopian highlands are subsistence oriented and only a small proportion

Table 1. Mean livestock holdings per farm at Debre Zeit and Debre Birhan.

Livestock type	Debre Zeit	Debre Birhan
Oxen	1.86	1.23
Cows	0.93	1.50
Heifers	0.33	1.74
Bulls	0.48	0.60
Calves	0.64	1.11
Total cattle	4.24	6.18
Sheep	1.55	10.99
Goats	1.00	0.17
Total small ruminants	2.55	11.16
Donkeys	0.98	1.70
Horses/mules	0.05	1.13
Total equines	1.03	2.83
Total TLU[a]	4.27	7.66
Monetary value (Ethiopian Birr/farm)[b]	1185	1614

a. TLU: Tropical Livestock Unit is defined as an animal of 250 kg liveweight.
b. US$1 = 2.07 Ethiopian Birr.

of farm grain production is sold. In the study areas, the mean proportion marketed was 20% at Debre Zeit and 4% at Debre Birhan. The proportion of livestock products sold, rather than consumed at home, is relatively higher, averaging between 30 and 50%, in value terms, in both areas.

Total annual cash income per farm averaged 379 Birr at Debre Zeit and 415 Birr at Debre Birhan (Table 2). Significant proportions of farm

Table 2. Mean cash income from farm sales at Debre Zeit and Debre Birhan (Ethiopian Birr/farm)[a].

Source	Debre Zeit (average 1979-80)	Debre Birhan (average 1979-83)
Crop and crop by-products	247	53
Livestock and livestock products[b]	129	362
Total	379	415
% of cash income from livestock	34	87

a. US$1 = 2.07 Ethiopian Birr.
b. Net sales of livestock calculated as the difference between animals sold and purchased.

cash incomes orginate from trade in animals and the sale of livestock products--an average of 34% at Debre Zeit and 87% at Debre Birhan. At Debre Birhan, the trade in livestock was particularly important, accounting for 56% of farm cash income against 31% from the sale of livestock products. In this high-altitude area 46% of cash income from animal trade orginated from the sale of cattle, 40% from sheep, 13% from equines and 1% from poultry. Animals are purchased and sold according to cash flow needs. Farm cash incomes should therefore not necessarily be considered as a proxy for wealth accumulation. As crop yields fail, farmers are forced to sell animals to purchase food grain. Cash incomes may therefore increase from one year to the next, even though there is a

decline in overall farm earnings. In view of the importance of livestock as a source of security and investment, there is some evidence that farmers with larger livestock holdings derive a relatively smaller proportion of their cash income from livestock production.

At Debre Birhan, manure alone accounted for 25% of the sale of livestock products, and dairy products just over 50%.

Farm gross margin

The overall gross margin per farm per year averaged 948 Birr at Debre Zeit and 1403 Birr at Debre Birhan. Approximately half of this gross margin (45% at Debre Zeit and 53% at Debre Birhan) could be attributed to the value of livestock production (Table 3). When the value of intermediate products was included (return from draught power and opportunity cost of farm produced straw and hay), the fraction of the gross margin provided by livestock production increased to 59% at Debre Zeit and 60% at Debre Birhan.

The gross value of production (GVP) per farm per year averaged 1773 Birr at Debre Zeit and 2570 Birr at Debre Birhan, of which 43% and 46%, respectively, were contributed by livestock production.

The subsistence nature of these traditional farming systems is highlighted by relating the annual farm cash income to the gross value of production. At Debre Zeit, cash income accounted for 21% of GVP; at Debre Birhan the figure was 16%.

Table 3. Mean gross margins and gross value of production per farm at Debre Zeit and Debre Birhan (Birr/farm)[a].

	Debre Zeit (average 1979-80)	Debre Birhan (average 1979-83)
Gross margin[b]		
from crops	322	659
from livestock production	426	744
Total	948	1403
% from livestock	45	53
Gross margin including intermediate products[c]		
from crops	522	659
from livestock production	747	983
Total	1269	1642
% from livestock	59	60
Gross value of production[d]		
from crops	1005	1385
from livestock production	768	1185
Total	1773	2570
% from livestock	43	46

a. US$1 = 2.07 Ethiopian Birr.

b. Gross margin of crops is calculated as: (crop yield x output price) - (seed use x seed price) - (fertilizer use x fertilizer price) - (cost of hired labour + cost of hired traction) + (yield of cereal straw x price).

Gross margin of livestock is calculated as the difference between returns (including value of progeny, milk, meat, manure, hide/skin and wool) and costs (veterinary expenses, hired labour, purchased feed) per unit of livestock.

c. Intermediate products refers to the value of draught power (returns) and the market value of farm produced straw and hay (costs). Draught power value per ox is estimated at the equivalent of 0.6 ha of crops or 180 Birr per annum. Young bulls are valued at 50% of this value. Donkey transport is estimated at 60 t km^{-1} $year^{-1}$ and valued at 0.50 Birr each. Straw and hay are valued at market prices.

d. Gross value of production is calculated as the total market value of crop and livestock products produced on the farm. It does not take into account the value of intermediate products.

Draught power and grain production

Gryseels et al (1986) have investigated the impact of draught power availability on crop production in both the Debre Zeit and Debre Birhan areas. It was found that on smallholder farms in both study sites, the number of oxen owned had a significant effect on area cultivated, and there was a positive relationship between ox-holding and farm grain production. At Debre Zeit, farmers with two or more oxen cultivated 59% more land than those with fewer oxen, but there was no effect on yield per ha. At Debre Birhan, farmers owning two or more oxen cultivated 32% more land than those owning none, while their net cereal yields per ha were 48% higher.

When the effects of draught power on yield per ha and on area cultivated were combined, Debre Zeit farmers owning two or more oxen produced 82% more cereals than farmers with one or no oxen. The effect of draught power on grain production at Debre Birhan was also substantial, farmers with two oxen producing on average 63% more grain than farmers with no oxen, and 19% more than farmers with one ox (Table 4). Overall, farmers with one ox had an estimated total net farm cereal production 267 kg higher than farmers with no oxen, while the margin due to second ox was a further 186 kg.

There also appeared to be an effect of ox holding on farm cropping patterns. Cereals require higher draught power inputs for land preparation than pulses. Farmers with no oxen sowed a greater proportion of their arable land to pulses, which have lower gross margins than cereals. These differences in cropping patterns

Table 4. Impact of ox holding on net farm cereal production (kg/farm)[a].

No of oxen owned	Debre Zeit (average 1979-80)	Debre Birhan (average 1979-83)
None	722	877[b]
One	989	
Two or more	1175	1597

a. Statistical estimates from least square analysis.

b. Data limitations meant farms with one or no ox had to be treated as a single group in the analysis.

Source: Gryseels et al (1986).

may therefore have led to income differences across ox-ownership classes.

Livestock for security and investment

A principal function of livestock is its use for security and investment. It is the second most important function of cattle, but the major objective for farmers with sheep enterprises. Farmers consider livestock to be a more reliable store of wealth than other alternatives, such as bank deposits, as well as an investment which is easy to convert into cash. Despite the low productivity of livestock in this traditional system, this investment is a sound one. The annual rate of return on investment in livestock of local breeds can be estimated at 25% for sheep and 31% for cattle. This figure was calculated

using a methodology first developed by Upton (1985).

The method is simplified as it takes only the major livestock products (meat from sheep, and milk and meat from cattle) into account. The model could, however, easily be expanded to take into account other livestock commodities. The sheep model (Table 5) follows the Upton method. The cattle model (Table 6) was modified to enable the incorporation of milk into the model. The assumptions made for the calculation of the annual rate of return are based on the technical parameters collected in livestock productivity surveys in both study areas. As there was no evidence of a significant difference in the productivity of livestock enterprises of local breeds between the study areas, the results are valid for both Debre Zeit and Debre Birhan.

The rate of return on investment in livestock can be considered as being attractive, and farmers will therefore invest their surplus cash in the purchase of animals. This occurs particularly after good harvests when a substantial part of the crop can be marketed. Oxen are purchased when they are required for farm production, just before and during the ploughing season.

Animals are sold according to cash flow needs, and the opportunity of making profits. Farmers will raise the cash needed for major household or farm expenditure (the purchase of food grain after poor harvests, of household items or of farm inputs such as seeds, or to pay for social obligations such as wedding parties) by selling, sheep or young cattle. The sale of livestock is a selective process. Smallstock (lambs, sheep and goats) are sold first, then

Table 5. Annual rate of return from sheep enterprise[a].

A. Average litter size	1.00
B. Parturition interval	300 days
C. Annual reproductive rate (1.00 x 365/B)	1.22
D. Survival rate to three months	0.72
E. Survival rate from three to twelve months	0.90
F. Survival rate zero to twelve months (D x E)	0.65
G. Effective lambing rate (C x F)	0.79
H. Liveweight at twelve months	15 kg
I. Liveweight production per ewe (G x H)	11.85 kg
J. Number of ewes per ram	16
K. Mortality of breeding stock	0.18
L. Mean price per kg liveweight	1.2 Birr
M. Price per adult ewe	30 Birr
N. Price per adult ram	40 Birr
P. Gross output per ewe (I x L)	14.11 Birr
Q. Ewe depreciation (K x M)	5.40 Birr
R. Ram depreciation (K x N)	7.20 Birr
S. Breeding stock depreciation (Q + R/J)	5.85 Birr
T. Net output per ewe per year (P - S)	8.26 Birr
U. Capital investment per ewe (M + N/J)	32.30 Birr
V. Annual rate of return (T/U x 100)	25.41%

a. US$1 = 2.07 Ethiopian Birr.

young cattle and equines, then cows, and in a final and desperate stage, oxen. This need for cash is Most sales take place from April to June.

CONCLUSIONS

Livestock make a substantial contribution to the economy of smallholder farmers in the central Ethiopian highlands.

Trade in livestock and the sale of livestock products contribute 34% of total farm cash in the medium-altitude zone and 87% in the high-altitude zone. Livestock also provide approximately 50% of the farm gross margin (60% when the value of intermediate products such as draught power is taken into account). Farmers receive attractive

Table 6. Annual rate of return from cattle enterprise[a].

A. Calving interval	690 days
B. Annual reproductive rate (365/A)	0.53
C. Survival rate to twelve months	0.78
D. Effective calving rate (B x C)	0.41
E. Liveweight at twelve months	75 kg
F. Liveweight production per cow (D x E)	31 kg
G. Number of cows per bull	3
H. Mortality of breeding stock	0.10
I. Mean price per kg liveweight	1.50 Birr
J. Price per cow	180 Birr
K. Price per bull	250 Birr
L. Gross meat output per cow (F x I)	47 Birr
M. Gross milk production per cow	292 litre
N. Annual milk production (M x D)	120 litre
O. Milk price per litre	0.50 Birr
P. Cross value milk output (N x O)	60 Birr
Q. Total gross output per cow (P + L)	107 Birr
R. Cow depreciation (H x J)	18 Birr
S. Bull depreciation (H x K)	25 Birr
T. Breeding stock depreciation (R x S/G)	26 Birr
U. Net output per cow per year (Q - T)	81 Birr
V. Capital investment per cow (J + K/G)	263 Birr
W. Annual rate of return (U/V x 100)	31%

a. US$1 = 2.07 Ethiopian Birr.

rates of return from investment in livestock, and livestock are important as a cash reserve in ensuring survival during bad agricultural years.

A positive correlation exists on smallholder farms between the ownership of draught animals and grain production.

The modest cash component within the farming system highlights the very limited opportunity for internal financing of improvements. Agricultural inputs compete for this cash with household needs. It is important that this limitation is given consideration in the design of new technology.

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VERTISOLS OF GHANA: USES AND POTENTIAL FOR IMPROVED MANAGEMENT USING CATTLE

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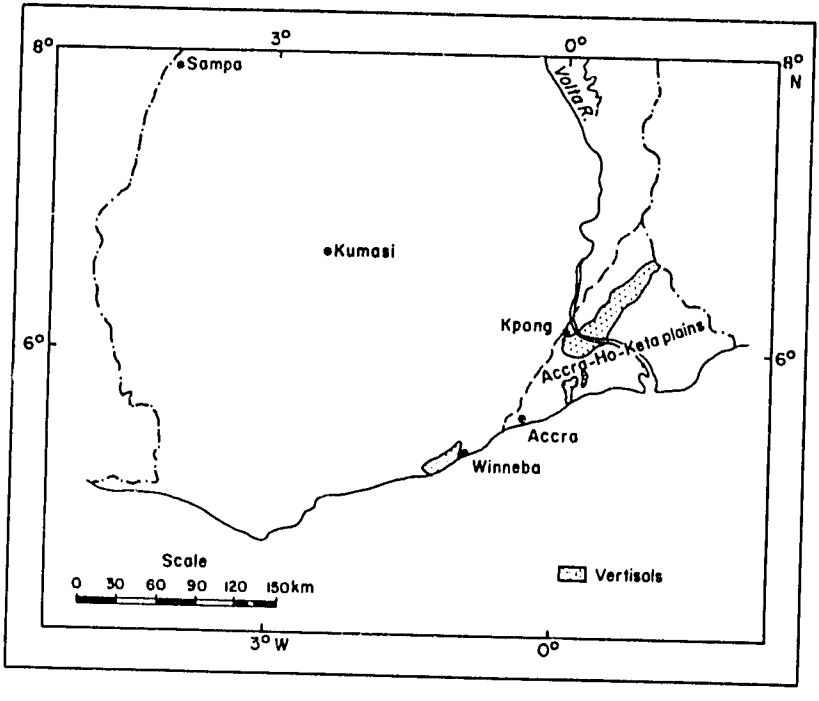
ABSTRACT

Vertisols, because of their high montmorillonite clay content, are difficult to till using hoes. Because many of the peasant farmers in Ghana till the land with simple hand implements, such as hoes and cutlasses, large areas of Vertisols remain uncultivated and unproductive. There is a need to develop simple, low-cost technologies to bring these soils into production. Soil characteristics, uses, management and productivity of Vertisols in Ghana are described, and the potential for improved management using draught oxen is discussed. The recommendation is made that the broadbed-and-furrow technology be adapted to improve productivity. Crop residues supplemented with leucaena and gliricidia fodder could be used for oxen feed.

INTRODUCTION

In Ghana, Vertisols are found the Accra, Ho-Keta, and Winneba plains (Figure 1). Although Ghana has only small areas of Vertisols (about 168 000 ha) compared to the total area in sub-Saharan Africa, interest in their development dates back to the mid-1940s. Early visits to the country by experts who made recommendations on their use (Hutchinson and Pearson, 1947; Clark and Hutchinson, 1949)

Figure 1. Vertisol locations in southern Ghana.



were followed by detailed soil surveys (Vine, 1950; Brammer, 1955) which emphasised the suitability of the soils for rice, sugarcane and irrigated cotton.

To generate information for agricultural development, the Ministry of Agriculture, with assistance from FAO, established the Agricultural Research Station at Kpong (ARS-Kpong) in 1954. The administration of the station was transferred to the University of Ghana in 1958.

Although ARS-Kpong worked out a scheme for tilling Vertisols using heavy machinery and mouldboard ploughs, peasant farmers still shun

these soils, apparently because they are difficult to cultivate with hand implements (hoes and cutlasses), and mechanised methods are too expensive for farmers who have little or no access to credit. As a result, the productive potential of Vertisols in Ghana has still not been realised.

ENVIRONMENTAL AND SOILS CHARACTERISTICS

Climate

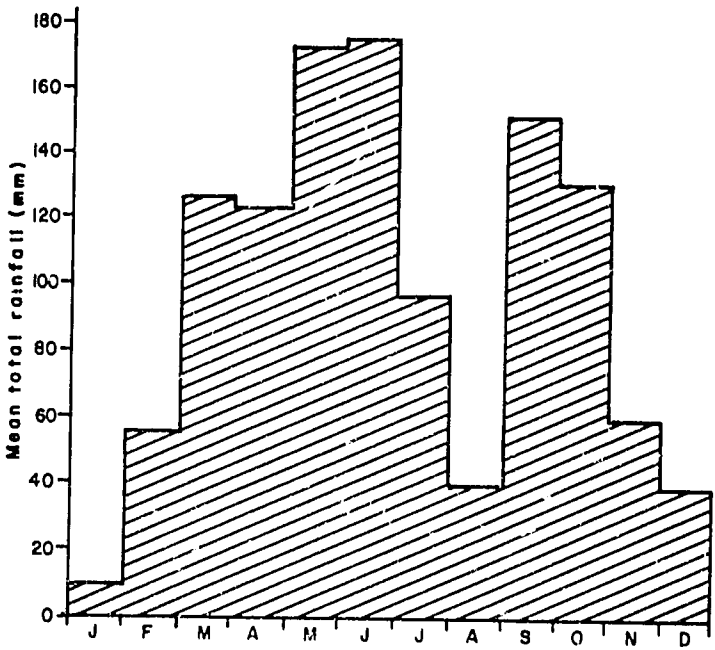
In Ghana, Vertisols occur in the subhumid climatic zone. Mean annual temperature is stable around 31°C. Mean annual rainfall is about 1100 mm, with monthly rainfalls ranging from 10 mm in January to 170 mm in June (Figure 2). The rainfall is bimodal with the long rainy season peak in May/June and the short season peak in September/October.

The total annual evaporative losses from a free water surface can be as high as 1800 mm (Brammer, 1967). The ratio of precipitation to evaporation ranges from a low of 0.1 in January to about 1.5 in June (Figure 3). Precipitation exceeds evaporation for only about 3 months a year.

Vegetation

The Vertisols of Ghana are covered with open (tussocky) medium grassland and scattered fire-resistant trees or coppiced shoots, particularly on the very deep soil types. *Vetiveria fulvibarbis*, in frequent association with *Brachiaria falcifera* and occasional species of *Schizachyriam semiberne* and *Euclasta sandylotricha* are dominant. Numerous other grass species

Figure 2. Mean monthly rainfall at the University of Ghana, Agricultural Research Station, Kpong, 1955-1981.



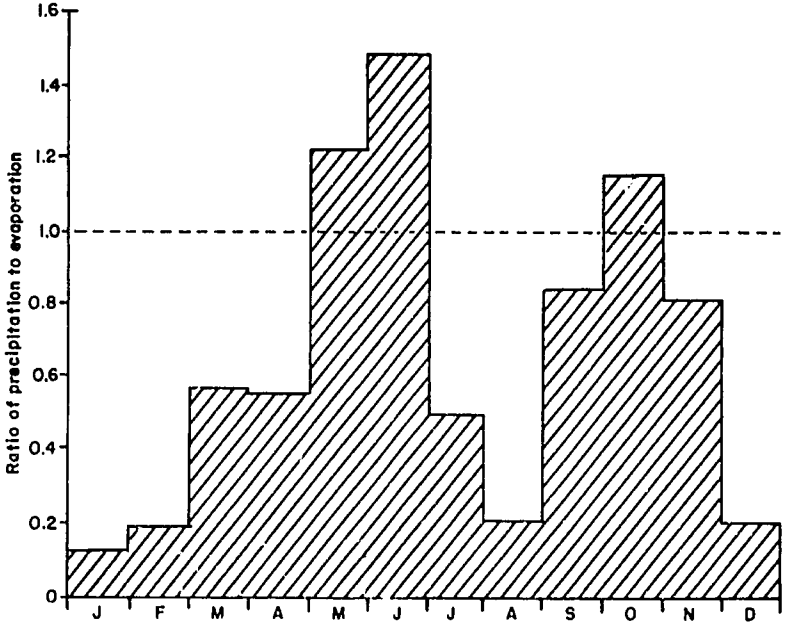
including *Andropogon* and *Ctenium* spp. occur. Two legumes commonly found are *Tephrosia elegans* and *Casia mimosoides*. The most common trees are *Combretum ghasalense*, *Millettia thonningii*, and *Boahinnia thonningii* (Kowal, 1963).

Soil characteristics

Brammer (1959) classified the Vertisols of Ghana into four groups according to location of the soil in the toposequence:

- Normal black clays: deep soils developed in situ over basic rock associated with

Figure 3. Mean monthly ratios of precipitation to evaporation at the University of Ghana, Agricultural Research Station, Kpong.



flatland or with middle to lower slopes of gently undulating topography.

- **Immature black clays**: shallow soils extensively developed in basic gneiss and associated with steep slopes and upper parts of the topography.

- **Black Vleisols**: deep soils developed in material associated with depressed sites subject to seasonally poor drainage.

- **Black Vleisols with brown subsoils**: deep soils in which the normal black clay surface layer passes into yellow or olive-brown

clays which continue to the base of the profile. They are associated with flat topography and high rainfall.

The Vertisols occupy an entire topographic range from summits to valley bottoms without being developed into catenary associations. Soil depth may range from a few to 180 cm or more. The soils generally lack distinct horizons in the profile with only the "A" and "C" horizons being discernible.

The profiles may contain spherical, hard, dark-coloured ironstone concretions. There may also be small, black, brittle manganese oxide and white to medium-grey irregular calcium carbonate concretions. Occasionally quartz gravel or pebbles occur as a stone line.

The clay content of the soils is high (Table 1). The clay mineral is composed of 40 to 60% montmorillonite and less than 20% kaolinite (Bampoe-Addo et al, 1968). The high montmorillonite content influences the moisture characteristics of the soils. The coefficient of expansion and contraction on wetting and drying is high with resultant cracking. Dramatic volume changes (about 30%) occur on wetting or drying (Kowal, 1963). The soil consistency is plastic to sticky when moist to wet, and very hard when dry. Internal drainage and aeration are very poor due to massive structure and compactness. Estimated available moisture is 10-20% (Kowal, 1963) and is a direct effect of the high water adsorption capacity of the clay minerals. Permeability is also very slow, about 0.1 cm h^{-1} with a 25 cm head of water (FAO-UN, 1963).

Table 1. Physical and chemical properties of a mature tropical black clay.

Depth (cm)	Particle size analysis (%)					Free $CaCO_3$ (%)	Organic carbon (%)	Total N (%)	pH (H_2O)	Exchangeable cations (meq/100 g soil)							Truog avail P (ppm)
	V.coarse sand	Coarse sand	Fine sand	Silt	Clay					CEC	Total bases	Ca	Mg	Mn	K	Na	
0-12	2.6	18.0	38.9	7.3	32.2	0.1	1.7	0.10	6.4	39.8	35.1	21.5	12.7	0.13	0.2	0.6	3.2
12-38	6.6	14.4	29.5	7.0	36.8	0.1	0.8	0.06	7.0	39.2	33.4	20.8	11.4	ND	0.2	1.0	ND
38-60	2.4	9.4	32.5	6.9	42.0	2.2	0.6	0.04	8.2	41.7	41.7	26.2	13.1	ND	0.2	2.2	ND
60-75	2.3	6.4	28.4	9.0	46.1	5.0	0.5	0.03	8.3	42.9	46.3	26.1	16.9	ND	0.2	3.1	ND
75-105	4.3	5.5	18.8	7.6	39.7	18.0	0.2	0.01	8.4	40.5	38.6	22.8	12.6	ND	0.1	3.1	ND
105-120	4.7	7.1	23.5	10.6	40.9	12.1	0.1	ND	8.4	41.9	40.5	22.1	15.0	ND	0.2	3.2	ND
120-142	3.8	17.5	36.7	11.0	27.2	2.0	ND	ND	8.4	34.0	36.6	19.6	14.0	ND	0.2	2.8	ND
142-180	3.4	21.8	47.8	10.4	13.8	0.7	ND	ND	8.6	22.2	24.0	11.9	10.3	ND	0.2	1.7	ND

Source: Brammer (1955).

The chemical characteristics of a mature Vertisol in Ghana are presented in Table 1. The pH of the soils ranges from near neutral in the surface horizons to alkaline in the subsoil. Cation exchange capacities (CEC) are high about (20 to 40 meq/100 g soil) reflecting the high montmorillonite content. The exchangeable Ca and Mg contents are also high. This may be due to a relatively low loss of soluble cations through leaching. The exchangeable Na content is low in surface horizons (about 0.5%) but increases substantially with depth. Exchangeable Mn is virtually absent in all horizons. Free $CaCO_3$ ranges from traces in surface horizons to 18% in deeper layers. Available P content (Truog) is very low in surface layers and decreases with depth. This may be due to adsorption onto free $CaCO_3$ particles which are abundant in deeper horizons. The organic C content of surface soils is low, reflecting the fact that organic matter is added mainly through the roots of the sparse grass vegetation. The low organic C content is, in turn, responsible for the low total N content.

The characteristic properties of the Vertisols of Ghana qualify them to be classified as Pellusterts, Pelluderts, and Chromusterts (Soil Survey Staff, 1975) or as Pellic and Chromic Vertisols (FAO/Unesco, 1974)

USE, MANAGEMENT AND PRODUCTIVITY

Although the Vertisols are characterised by a high nutrient status and can withstand intensive and prolonged cultivation, their physical characteristics and poor drainage have inhibited their use by peasant farmers. The Vertisols in Ghana are therefore mainly used as grazing lands

by Fulani cattle herdsmen. The peasant farmers restrict cropping to lands around homesteads. Crops grown include pepper (*Capsicum* sp.), tomatoes, okra (*Hibiscus esculentum*), maize and cassava (*Manihot esculenta* Crantz). In addition to these crops, ARS-Kpong has conducted studies into the productivity of cowpea, soya bean, cotton, rubber (*Hevea brasiliensis*), cocoa, citrus (*Citrus sinensis* [L] Osb.), pawpaw (*Carica papaya* L.), oilpalm (*Elaeis guineensis*), pineapple and sorghum (*Sorghum bicolor*) on Vertisols (ARS-Kpong, 1986). Cropping and livestock rearing enterprises on these lands are highly segregated.

Crop production

Because of the poor physical properties of Vertisols a properly prepared seedbed that enhances drainage is necessary for high productivity. Under the traditional farming system, tillage is done with simple implements such as hoes and cutlasses which cannot be used to till to any great depth on heavy soils such as Vertisols. The improved system of land tillage developed by ARS-Kpong is not suitable for peasant farmers, because it involves the use of heavy machinery and hence is capital intensive. As a result peasant farmers crop only flat land. However, cropping on a modified form of cambered bed, known as a broadland (Hill, 1961), increased yields of maize and groundnut (*Arachis hypogaea*) by about 100% (Table 2).

Livestock production

After a dramatic drop in 1977, cattle populations in Ghana steadily increased over the period 1978 to 1985, from about 750 000 to well over 1 million (Euwsi, 1986). Seventy-five percent of the cattle

Table 2. Comparison of land productivity under broadland and traditional system of land management on Vertisols in Ghana.

Crops	Yield (kg ha^{-1})	
	Broadland	Flatland
Maize[a]		
(1st season)	2100	1000
(2nd season)	1400	700
Groundnut[b]	700	400

a. 125 kg ha^{-1} triple superphosphate was applied at planting with supplementary irrigation.
b. 250 kg ha^{-1} triple superphosphate was applied at planting.

Source: Kowal (1963).

are concentrated in northern Ghana (Table 3). Of the 25% in the southern areas, 80% are found in the four regions where Vertisols are located. Although the actual figures for cattle raised strictly on natural grassland supported by Vertisols may be lower, the proportions indicate the relative value of Vertisols in cattle production in Ghana.

Although the cattle population has increased substantially over the the past several years, the productivity of individual animals remains low. This may be attributed in part to climatic effects and lack of genetic improvement of the stock.

Table 3. Cattle population in the various regions of Ghana.

Region	Population (x1000)	Percentage of total
Ashanti	13.0	1.2
Brong Ahafo	34.3	3.2
Central[a]	4.1	0.4
Eastern[a]	30.5	2.9
Greater Accra[a]	72.7	6.8
Northern	355.9	33.4
Upper	453.6	42.6
Volta[a]	96.5	9.1
Western	4.2	0.4
Total	1064.8	

a. Administrative regions within which Vertisols are located.

Source: Ministry of Agriculture, Ghana (1985).

Generally, in the savannah areas the total biomass and the nutritive value of the natural grassland declines sharply during the dry season (January to March), which reduces animal growth rates. In a study conducted at the University of Ghana Agricultural Research Station at Nungua (Accra plains), where some Vertisols are present, liveweight gain during the dry season from January to March was about 20% of that during the second rainy season, from September to November (Larsen and Amaning-Kwarteng, 1976). Supplementary feeding with dried cassava peels mixed with urea and molasses during dry periods increased liveweight gain by 200% compared to animals which only grazed on Vertisols.

Crossbreeding to improve the genetic make-up of local animals also enhanced their capability to use natural grassland as well as supplements. In another study at University of Ghana ARS, Nungua (Cameron, 1970), Santa Gertrudis-West African Shorthorn crossbreds performed better than the local West African Shorthorn, even when grazing native pasture (Table 4). In general, crossbreeding increases birth weight, weaning weight, and pre-, and post-weaning liveweight gains (Kahoun, 1972; Ngere and Cameron, 1972; Arthur, 1985). Recent crossbreeding work at ARS-Kpong (Arthur, 1985) indicates that introducing exotic blood into N'Dama cattle significantly improves their performance compared with pure local breeds (Table 5).

POTENTIAL FOR IMPROVED MANAGEMENT OF VERTISOLS USING CATTLE

Although cattle herding is a major occupation on Vertisols on the Accra, Ho-Keta and Winneba plains, mixed farming is uncommon. The low crop yields on peasant farms and the generally low growth rate of livestock during the dry season could both be improved by integrating the two farming systems. Draught oxen could be used to prepare raised seedbeds, which could improve drainage and hence increase crop yields at reduced cost. The crop residues could in turn be fed to the animals to raise their productivity. The following section discusses the potential for adapting a low-cost technology developed by ILCA in Ethiopia to till and improve crop yield on Vertisols in Ghana.

Table 4. Response of local and crossbred cattle to three feeding regimes over an 18-week period on Vertisols in Ghana.

Breed	Type of feed	Total liveweight gain (kg)
N'Dama	Pasture alone	15.7
	1.4 kg suppl/day	10.7
	Suppl. ad lib.	11.8
West African Shorthorn	Pasture alone	17.5
	1.4 kg suppl/day	20.7
	Suppl. ad lib.	21.3
Santa Gertrudis x West African Shorthorn	Pasture alone	25.0
	1.4 kg suppl/day	25.9
	Suppl.ad lib.	62.7

Source: Cameron (1970)

The broadbed-and-furrow technology

ILCA has developed an ox-drawn broadbed-maker (BBM), based on the Ethiopian plough, which can construct raised beds and furrows, called broadbeds-and-furrows (BBFs). On a Vertisol, the BBFs permit drainage of excessive surface water. The BBM can construct raised beds (20 cm high and 120 cm wide) at a rate of 0.4-1.2 ha day^{-1}. In a series of on-farm tests in Ethiopia BBFs increased the grain yield of bread wheat by about 78% over the traditionally managed plots (Jutzi et al, 1987). This technology could be used on Vertisols in Ghana.

Table 5. Pre-weaning growth of three breeds of calves reared on Vertisols in Ghana.

Trait	Breed[a,b]		
	N	SGxN	RPxN
Birth weight (kg)	18.8a	21.2b	22.2b
Weaning weight (kg) (adjusted to 205 days)	78.6a	107.4b	100.6b
Pre-weaning average daily gain (kg/day)	0.29a	0.42b	0.38b

a. N = N'Dama bull x N'Dama cow
SGxN = Santa Gertrudis x N'Dama crossbreed.
RPxN = Red Poll x N'Dama crossbreed.

b. Values in the same row followed by the same letter are not significantly different at 5% probability level.

Source: Arthur (1985).

Draught animals and feed requirements

The ox is particularly suitable as a draught animal on fairly heavy soils. However, draught performance depends on the breed of the ox and the quantity and quality of feed available. Heavier animals perform better than lighter ones. The amount of feed required by a draught animal is a function of its weight and the amount of work it performs (Smith, 1981).

Work conducted at ILCA in Ethiopia indicates that farmers should ensure that their draught oxen are in good condition before the start of the

cropping season (Soller et al, 1986). However, the major cropping season in Ghana is preceded by a long dry season during which animals may lose weight if not provided with supplementary feed. Assuming an average liveweight of 250 kg for cattle about 2-3 years old (Ngere and Cameron, 1972; Otchere et al, 1985) and a daily feed intake of 2 kg dry matter per 100 kg liveweight (Soller et al, 1986), then for a 3-month period (from January to March) two draught oxen would consume 900 kg of feed. Based on crop harvestable yields reported by ARS-Kpong and ratio of straw to grain provided by Chadhokar (1983), even rainfed rice, can provide 1.5 to 2.5 t of residue per hectare (Table 6), more than enough to feed two draught oxen.

However, cattle fed only rice straw grow slowly (Jackson, 1977). Thus the diet will have to be supplemented using materials such as legume fodder. The leguminous brows trees, *Gliricidium sepium* and *Leucaena leucocephala* can provide low-cost dry-season feed supplementation for draught oxen. *Leucaena* grows on black earth (Vertisols) in Queensland, Australia (Skerman, 1977). At ARS-Kpong, *Gliricidia* stems previously used as fencing poles have grown into big trees. Therefore production of high-protein browse fodder should be feasible.

CONCLUSIONS

The Vertisols of Ghana are in the subhumid zone. Because of their high water-holding capacity and low permeability, drainage must be improved in order to increase crop yields. Crop and livestock productivity on peasant farms is low due to lack of adequate implements to till the land, but it

Table 6. Crop residues for on-farm feeding of ruminants on Vertisols in Ghana.

Crop	Yield of grain (t ha^{-1})[a]	Residue	Grain: straw ratio[b]	Yield of residue (t ha^{-1})
Rice (irrigated)	3.0-6.0	straw	1:1	3.0-6.0
Rice (rainfed)	1.5-2.5	straw	1:1	1.5-2.5
Sorghum	4.0	stover	1:2	8.0
Cowpeas	1.5-2.0	straw	1:1	1.5-2.0
Soybeans	2.0-3.5	straw	1:2	4.0-7.0
Sugarcane	170-200 (cane)	tops (20% DM)	3:1	56-66

a. Yield data for crops obtained from ARS-Kpong (1986).

b. Ratio of grain (cane) to straw obtained from Chadhokar (1983).

should be possible, by transferring BBF technology, for peasant farmers to increase crop yields. As crop yields increase following improved management of the soils, large quantities of crop residues would become available during the dry season to feed cattle. The crop residues ration for feeding during the dry season could be supplemented with leucaena and gliricidia prunings.

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ASSESSMENT OF THE PRODUCTIVITY OF NATIVE AND IMPROVED FORAGES ON VERTISOLS IN THE CENTRAL HIGHLANDS OF ETHIOPIA

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ABSTRACT

Work by the Institute of Agricultural Research to assess and improve primary production on Vertisols is summarised. Results of research on the adaptability and productivity of improved annual and perennial forage species on Vertisols are also reported.

Native pastures on Vertisols, if properly managed, could supply a good quantity of quality roughage. In small plot experiments, annual dry matter yields of 5-6 t ha^{-1}, with crude protein content of 6%, were recorded. Large-scale pasture fields yielded 3.5-4.5 t ha^{-1}. It is estimated that these pastures could support two bulls ha^{-1} for about 6 months or 10 sheep ha^{-1} for a year, with weight gains of 86.4 and 154.7 kg ha^{-1}, respectively. A number of improved perennial grasses and two local annual *Trifolium* species were also found to be productive on undrained Vertisols. Most of them yielded over 5 t ha^{-1} dry matter. The fodder crops, oats and vetch, yielded about 6 t ha^{-1} dry matter.

Smallholders do not benefit from this research, because of limited resources. Hence, it is suggested that forage research should focus more on the integration of crops with livestock.

EFFECT OF TILLAGE FREQUENCY OF CLAY SOILS ON THE DRAUGHT OF THE ETHIOPIAN ARD (*MARESHA*)

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ABSTRACT

Crop-land soils in the vicinity of Debre Birhan in the Ethiopian highlands have a clay content of more than 50%. Land preparation using the traditional ard (*maresha*) in this area requires several ploughings in order to prepare an adequate seedbed. Three to four ploughings are usually needed for short-term fallow plots, those which have been cropped at least once within a 2-year period. Long-term (*guie*) fallow plots, those cropped only once within an 8-15-year period, may require up to seven or eight ploughings.

The force output of paired indigenous Zebu oxen was measured using a loadcell attached between the yoke and the maresha beam by a nylon rope and connected to a hand-held digital liquid crystal display indicator. Data collected from 24 smallholder farms showed that a team, with each animal having an average bodyweight of 280 kg, is capable of developing a mean force output of 0.963 kN over a 5-6-hour working day when ploughing short-term fallow plots. No significant differences ($P<0.05$) were observed in force output or tillage depth across the first three ploughing operations. Force output for the fourth or fifth ploughing, which is used as a covering operation, was significantly lower than for the three previous ploughings. Mean force output for initial ploughings of guie plots was high--1.69 kN

for the first and 1.26 kN for the second. Significant differences in force output ($P<0.05$) were observed across the first four ploughings.

These findings demonstrate that the draught of the Ethiopian ard can be highly variable depending on the tillage frequency and the length of the previous fallow period.

UTILISATION OF FEED RESOURCES BY DRAUGHT ANIMALS ON SMALLHOLDER FARMS IN THE ETHIOPIAN HIGHLANDS

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ABSTRACT

The major livestock feed resources on smallholder farms in the central highlands of Ethiopia are hay, crop residue straws and natural pasture grazing. At the beginning of the major growing season, freshly cut weeds from plots are available. The use of feed concentrates or salt/mineral blocks is minimal because costs are high and supplies erratic. Fodder crops, such as oats (*Avena sativa*) are grown to a limited extent by some farmers.

In addition to grazing, oxen in the Debre Birhan area are usually fed twice on non-working days and three times on working days, provided stored feed supplies last. Hay is fed on working days beginning at the end of April or early May, and straw on non-working days, although this regime varies between farms, depending on the amount of hay available. As the major ploughing season progresses, and hay supplies decrease, a mixture of hay and straw is fed, usually straw in the morning and evening and hay at midday. Depending on feed supplies remaining by mid-July, farmers may be forced to feed only straw on working days, with oxen having access only to grazing on non-working days. Once straw supplies are exhausted, oxen are maintained on grazing.

Laboratory analysis of feed samples showed apparent digestible dry matter (ADDM) and metabolisable energy (ME) of both hay and crop residue straws to average 55% and 8 MJ kg^{-1} dry matter (DM), respectively. Crude protein (CP) averaged 6 - 8% for hay and 5% for crop residue straws. Forage sampled from grazing areas at the height of the dry season had 55% ADDM, 6.3% CP and ME of 8.6 MJ kg^{-1} DM, with quality increasing to 62% ADDM, 12% CP and ME of 9.7 MJ kg^{-1} DM following the minor rains. Based on nutritional quality of feedstuffs and the estimated daily intakes of oxen, energy needs for maintenance were adequately met throughout the year. Energy requirements for work were also met, except towards the latter part of the major ploughing season.

DIAGNOSIS OF TRADITIONAL FARMING SYSTEMS IN SOME ETHIOPIAN HIGHLAND VERTISOL AREAS

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ABSTRACT

Results of farm surveys carried out in three important Vertisol areas in the Ethiopian highlands are reported. The main objective of the surveys was to establish a reference data base for on-farm verification of improved Vertisol management technologies. The surveys covered a total of 353 smallholder farms.

Landholdings in the surveyed areas are small. Almost all land is cultivated with food crops for subsistence production. On the Inewari plateau, 75% of the average 2.5 ha landholding is cultivated with food crops, while in Wereilu and in the Fogera plain the ploughed areas amount to 82 and 86% of 1.7 and 2.1 ha average landholdings, respectively.

The average household size ranges from 4.7 to 6.0. Grazing pressure is very high with a TLU (tropical livestock unit) density of 14. Due to the limited extent of grazing land, most of the animal feed in Inewari and Wereilu is in the form of crop residues. The average draught-animal holding in the Fogera plain is considerably higher than in the other two survey reas. The animal condition, however, is far better in these latter two areas.

Waterlogging is the most important production problem in the surveyed Vertisol areas. A conventional implement to improve surface drainage does not exist in the traditional production system. Farmers' traditional strategies to overcome deficient surface soil drainage have generally not been effective; the exception is the handmade broadbeds-and-furrows, which are almost confined to the Inewari plateau, where about 20 000 ha crop land are treated by this method.

INSTITUTIONAL SUPPORT AND NETWORKING

INTER-INSTITUTIONAL MODES OF OPERATION IN RESEARCH AND DEVELOPMENT OF IMPROVED VERTISOL TECHNOLOGIES FOR THE ETHIOPIAN HIGHLANDS

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ABSTRACT

Research and development activities on improved Vertisol management technologies in Ethiopia have been considerably strengthened in recent years. National as well as international agencies are directing sizeable efforts into the better agricultural utilisation of this vast crop-land resource which, in the Ethiopian highlands, covers 7.6 million ha. For a number of technical, ecological and sociopolitical reasons there is scope for very substantial returns from these research and development efforts in terms of grain and crop residue production.

Formal and informal links have been established between the agencies involved in these activities in order to develop coordinated programmes. The objectives of these institutional links go well beyond mutual information exchange and avoidance of effort duplication into areas of

activity programming and execution across institutional borders. A critical mass of information can therefore be assembled in several areas where individual institutional efforts might fail to achieve the aims set.

Areas of activity include agroecological and socioeconomic resource assessment of Vertisol areas, soil and water management, new cropping systems for drained Vertisols, investigation of the available power sources (particularly traction animals) for the improved land management, on-farm technology verification and validation, and technology extension, staff training and institution building.

These inter-institutional arrangements are being made in order to generate maximum returns from scarce available resources. Given the large acreage of Vertisols in high rainfall, high potential Ethiopian highland areas, and given the large gap between actual and potential production from these soils, these returns may have a significant bearing on the national thrust towards food self-sufficiency.

INTRODUCTION

Almost 2 million ha of Vertisols are presently cropped in the Ethiopian highlands. They represent more than one quarter of all highland Vertisols and about the same proportion of total Ethiopian crop land. Severe waterlogging of most highland Vertisols, a common feature of these heavy clay soils in high rainfall areas, drastically constrains their productivity: average grain yields of the common Vertisol crops range from 290 to 860 kg ha^{-1} (Berhanu Debele, 1985). However,

this problem can be almost entirely overcome with the help of adequate surface drainage structures, and hence the potential productivity of these soils, given the ecological circumstances in which they occur, is considerably higher. Improved surface drainage technologies, once validated on-farm, should therefore be brought into the extension phase as soon as possible. This will involve the extension services of the Ministry of Agriculture, as well as institutes mandated with research.

Convincing evidence for the strong impact of Vertisol surface drainage on crop production has motivated a number of international and national agencies to direct increased attention to the agricultural utilisation of these soils. A formal agreement on the coordination of these efforts has been adopted and quite detailed procedures for the implementation of inter-institutional research and development initiatives have emerged from this agreement.

This paper reports on the formation, rationale and operational features of these arrangements, and also on potential future developments.

RATIONALE FOR INTER-INSTITUTIONAL ACTIVITIES IN VERTISOL RESEARCH AND DEVELOPMENT

Improved Vertisol management technologies are the result of multi-disciplinary efforts. These efforts deal with agroecological and socioeconomic resource assessment of Vertisol areas, improved soil and water management, new cropping systems for drained Vertisols, improved land management techniques, on-farm technology verification,

extension and manpower training. Such a diversity of activities requires a large degree of intra- and inter-institutional coordination. The work of individual institutes can be substantially upgraded if directly or indirectly assisted by collaborators of partner institutes working along similar lines. The assembling of a critical mass of information is thus more likely to be achieved in more areas of work and in less time.

Funding for development, and especially for research activities, tends to be chronically deficient. The coordination of efforts is therefore crucial for the judicious use of scarce available resources in order to maximize the returns from the respective investments.

Agricultural research centres such as those within the CGIAR (Consultative Group on International Agricultural Research) system have an important innovative potential given the considerable human and material resources allocated to them. However, these centres can only fully exploit this potential for the benefit of their mandate areas if they are all properly linked with national research and extension systems.

PRESENT FEATURES OF INTER-INSTITUTIONAL RESEARCH AND DEVELOPMENT AGREEMENTS FOR THE ETHIOPIAN HIGHLANDS

In 1985 the International Livestock Centre for Africa (ILCA) and the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) decided to set up an African Vertisol Management Project. The project was to deal with research, training and outreach topics in a collaborative

mode involving these two CGIAR centres and the Ethiopian national agricultural research and extension system in a first five-year phase. It was proposed that an Advisory Committee, composed of the executives of the participating agencies, would be responsible for ensuring the inter-institutional implementation of the project, and that the project should be based at ILCA, Addis Ababa, to implement the first phase in Ethiopia.

The Advisory Committee was constituted in March 1986 after the project found adequate funding. Its members are the Ethiopian Vice-Minister for Animal and Fishery Resources, who is currently chairing the committee: the General Manager of the Ethiopian Institute of Agricultural Research (IAR); the President of Alemaya University of Agriculture (AUA); the Director of Research of Addis Ababa University (AAU), and the Directors General of ILCA and ICRISAT.

The Advisory Committee has agreed on its terms of reference as follows:

(1) to consider key policy issues associated with the project,

(2) to maintain a watching brief on the project's progress,

(3) to ensure adequate coordination of all agencies involved,

(4) to assign relative responsibilities for key actions,

(5) to supervise the work of the technical committee appointed to implement the project, and

(6) to develop and assess overall guidelines for resource acquisition and allocation.

The technical project-implementing committee was appointed by the Advisory Committee at its inaugural meeting on 28 March 1986. It is composed of specialist personnel from the participating agencies, and is currently chaired by the Dean of the Faculty of Agriculture in the Alemaya University of Agriculture. The Technical Committee was given the following functions:

(1) to implement the project as a joint activity thereby ensuring inter-institutional flow of information with the aim or avoiding duplication of efforts,

(2) to propose mechanisms for strengthening relevant activities in national institutions by suggesting activities in areas of inadequate, or of no, coverage, and to make efforts to acquire funds for these activities where necessary,

(3) to advise on the nature, location and extent of outreach activities in the context of the project,

(4) to organise information exchange and briefing sessions for staff from participating agencies, in order to increase general awareness and commitment,

(5) to keep a comprehensive inventory of research protocols and development-oriented activities of participating agencies, and

(6) to report annually to the Advisory Committee on project progress and any other functions assigned by the Advisory Committee.

Both committees meet about three times per year. Given the constitution of the two committees, and the functions agreed upon, the degree of inter-institutional interaction is actually and potentially very significant. This interaction is taking place at all levels of institutional responsibility and at all stages of project planning and implementation.

It is generally understood that each participating agency will, in principle, independently fund its own Vertisol-related activities. The CGIAR centres involved are, however, determined to provide strategic inputs into national research and development institutions and to be instrumental in catalysing incremental funding for national partner institutes to implement agreed activities.

Strategic ILCA or ICRISAT inputs are basically in the form of the provision of research and transport equipment and the secondment of qualified scientific staff, as well as conventional research support. Within the framework of the project, a considerable number of research protocols have already been established in inter-institutional agreement between ILCA and IAR, ILCA and AUA, ILCA and MA (Ministry of Agriculture), IAR and MA, and AUA and MA. These protocols concentrate, in general, on crop germplasm, new cropping systems for drained Vertisols and soil fertility management. ILCA has provided extensive training opportunities in the manufacturing of the animal-drawn surface-drainage implement, and in handler and oxen

training, to all national partner organisations. ICRISAT has provided specific training in economics and agroecology to staff of IAR and ILCA. IAR has formed a Vertisol management team to direct and coordinate the research activities on Vertisols in the various research centres. A general agreement on the inputs of each institution into the collaborative activities has been adopted, as shown in Table 1. The commitment of the institutions is, in principle, made on the basis of their respective comparative advantages.

POTENTIAL AND ENVISAGED DEVELOPMENTS IN THE INTER-INSTITUTIONAL COORDINATION OF VERTISOL-RELATED ACTIVITIES

The constitutions of the Advisory and Technical Committees, and the general agreements on institutional coordination, can potentially be the basis for a very considerable degree of integration of work. The extent to which this can be implemented is a function of time, project success and individual institutional commitment.

It is planned to address this project development in three stages:

(1) Consolidation of Vertisol-related activity planning and implementation in participating agencies with necessary support organisation across institutional borders,

(2) Organisation of comprehensive programmes for research and development with the aim of implementing project-internal procedures for the formulation of priorities, strategies and work and reporting routines for

Table 1. Areas of institutional collaboration in the joint Vertisol Management Project in Ethiopia.

Area of interest	ICRISAT	ILCA	AUA	IAR	MA	AAU
1. Agrometeorology, soil and socioeconomic studies						
(a) Agrometeorology						
data analysis	x	x				
training	x	x				
crop modelling	x					
(b) Soils						
survey, characterisation classification,	x		x		x	
soil physics	x	x	x			
soil microbiology	x	x	x	x		x
soil chemistry	x	x	x	x	x	
(c) Socioeconomics						
baseline surey		x		x		
monitoring		x				
2. Soil and water management agronomy, animal husbandry						
(a) Soil and water management	x		x	x	x	
(b) Crop improvement/agronomy	x		x	x	x	
(c) Animal husbandry		x		x	x	
3. Farm power (animal) and implements						
(a) Animal power		x		x		
(b) Farm implements	x	x		x		
4. On-farm verification and extension						
(a) Verification		x	x	x	x	
(b) Outreach		x	x	x	x	

collaborative projects across institutional borders,

(3) Acquisition of funds and major strategic inputs, including qualified manpower for national institutes in order to remove operational constraints.

The joint Vertisol Management Project is in itself a national Ethiopian network in research, training and development of these issues. It is therefore to be considered as a natural national cell of the IBSRAM (International Board for Soil Research and Management) auspiced international network on improved utilisation of Vertisols.

ILCA and ICRISAT have supra-regional and regional mandates and will therefore make arrangements with the governments of their mandate areas to initiate such concerted programmes for research and development of this important land resource in other areas.

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NETWORKING ON VERTISOL MANAGEMENT CONCEPTS, PROBLEMS AND DEVELOPMENT

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ABSTRACT

The IBSRAM Vertisols network in Africa, Management of Vertisols under Semi-Arid Conditions (MOVUSAC), aims by collaborative research, to study Vertisols management in a range of semi-arid environments, and, by transferring experience between similar areas, to evolve locally adapted management techniques and cropping systems. Because of their difficult physical properties Vertisols are generally underutilised at present. Agreed priorities for Vertisol management research include soil water management and tillage problems. The aim is to develop techniques for using as much as possible of the water received while also providing surface drainage to avoid waterlogging. Man-made microrelief patterns to improve surface drainage include cambered beds, ridges, narrow beds and furrows, and broadbeds and furrows. In very dry areas, water harvesting techniques involve planting crops in the furrows rather than on the beds and ridges.

INTRODUCTION

Since its inception in September 1983 at the close of an international workshop on soils (ACIAR, 1984), the International Board for Soil Research

and Management (IBSRAM) has worked to establish soil management networks in the tropics. IBSRAM is establishing regional soil management networks around three major target areas: the management of Vertisols, the management of acid tropical soil, and tropical land development for sustainable agriculture. The African Vertisols network--Management of Vertisols under Semi-Arid Conditions (MOVUSAC)--was created at a regional seminar held in Nairobi in December 1986 (IBSRAM, 1987). Thirteen countries participated in the seminar and most of them have presented project proposals to form a collaborative research network.

This presentation explains the concepts on which soil management and networks are based, the major problems of Vertisol management under semi-arid conditions and the current development of the MOVUSAC network.

SOIL MANAGEMENT AND NETWORK CONCEPTS

Soil management is a broad concept which encompasses soils, crops and the farmers who use them. It must embrace such aspects as fertilizer and lime application, transfer of technologies on well classified soils, soil and water management and adapted cropping systems, in order to provide comprehensive technologies which can easily be applied by farmers. Soil management research thus requires a multidisciplinary approach.

A collaborative research network, as envisaged by IBSRAM, involves cooperators in a range of countries who work on similar problems. In the case of the African Vertisol network (MOVUSAC) the common problems relate to the management of these very distinctive cracking

clays under a range of semi-arid environments. The properties of these soils set them apart from non-cracking soils, and pose management problems which, up to now, have made these soils relatively underutilised.

The properties of Vertisols are very well defined, and as these soils are widespread throughout the tropics, there are obvious possibilities for transferring aspects of successful Vertisol management experience from one area to another. With appropriate management, their productivity can be greatly increased, often with little extra cost. ICRISAT's (International Crops Research Institute for the Semi-Arid Tropics) experience in semi-arid peninsular India has shown that in some cases appropriate management can increase yields several fold, at little cost, and has demonstrated to farmers that Vertisols have a much greater potential productivity under rainfed conditions than was thought.

As the IBSRAM African Vertisols Network takes shape and research proposals are discussed, it is becoming clear that if they can all be implemented, the result will be a Pan-African effort, with many countries conducting coordinated research on soils which are essentially similar, but which require somewhat different management according to rainfall amount and distribution differences. IBSRAM's role in this effort has many characteristics, reflecting its view of how a network should function. Initially IBSRAM, in collaboration with the Network Coordinating Committee, assists cooperators in presenting their proposals to potential donors and in helping to secure the necessary funding. Since a network requires a methodology which has been agreed upon

and is well understood by network cooperators, IBSRAM also organises training courses for "front-line" researchers. During experimental work, IBSRAM assists by providing information relevant to Vertisol management from its own data bank and from external sources.

In addition to its own staff, IBSRAM draws on the services of specialised consultants to help solve specific problems. Meetings of network cooperators will be held to discuss problems, results and future work, so that their experiences are shared. In this way, cooperators are not working on soil management in isolation, each in his own country, but should feel themselves part of a Pan-African team, supported by IBSRAM and by each other as well as by donor organisations. Thus the concept of a "network" moves from being a goal to a reality.

MAJOR VERTISOL MANAGEMENT PROBLEMS

To be efficient, a network must focus on a limited number of objectives. From the report of the inaugural workshop on management of Vertisols for improved agricultural production (IBSRAM, 1985) and from the report of the participants in the Nairobi seminar (IBSRAM, 1987) major constraints to production as seen by African cooperators can be ranked: soil water management, tillage, cropping systems, and nutrient management.

Management of soil water is both the most difficult and the most important aspect of Vertisol management in the semi-arid tropics. The crops, particularly at the seedling stage, can suffer from extremes of drought, or from excess water, leading to waterlogging. In the semi-arid

regions of the Vertisol Network, where rainfall averages between less than 500 mm and 1200 mm a year, the first priority is to make full use of as much as possible of the water received. In practice, farmers often make use of only part of the available water, usually by planting too late for various reasons. This is true for many soil types in semi-arid areas, but is particularly a problem with Vertisols because the moisture range at which tillage can take place is narrower than for most soils, and the difficulties of tillage outside this range are greater, due to the rather extreme consistency properties shown by Vertisols. When dry, they are extremely hard, and when wet, extremely sticky (Willcocks, 1987). Attempts to cultivate when too wet can lead to soil sticking to implements and the formation of large clods. Tillage has to take place at an intermediate moisture content, and waiting for this intermediate moisture content may cause delays.

Tillage of the dry soil before the rains, while feasible on light textured soils, is not normally practiced by African small farmers on Vertisols. ICRISAT's deep Vertisol management technology in India includes pre-monsoon tillage to prepare a seedbed. An initial ploughing after the harvest leaves clods which, helped by occasional showers, crumble during the dry season. A further passage with an ox-drawn cultivator in the few days before the predicted onset of the rains prepares a loose seedbed some 15 cm deep in which seeds and fertilisers are placed while the soil is still dry. The advantage is that seeds germinate with the first rain heavy enough (25 mm or more) to moisten the soil sufficiently to the seed depth.

Most traditional Indian farmers do not try to get on to Vertisols during the first few weeks of heavy rains; they do not start ploughing until the rains have subsided and the soil moisture has fallen to a level allowing tillage. Thus most of the extensive Vertisols of peninsular India are fallow during a good part of the rains, so that crops planted on them make use of only the late wet season showers and residual soil moisture. In many areas of Africa, farmers delay moving on to at least the poorer-drained Vertisols for similar reasons. The poor internal drainage of Vertisols and their extremely slow hydraulic conductivities, leading to waterlogging, thus delay planting, and a part of the wet season is lost, whereas other lighter soils in the same area may be planted promptly at the onset of the rains.

In the case of a Vertisol which has formed wide deep cracks in the dry season, initial entry of rainfall when it comes is easy, since water moves freely into the cracks. If the first rains of the wet season are heavy and large quantities of water enter the cracks before the soil swells and the cracks close up, the soil profile may be well charged to the depth of cracking (which, by definition, is at least 50 cm in a Vertisol). Much less favourable is an initial fall of light rain, which closes the cracks before much water has entered. Once the cracks are closed most Vertisols are notoriously impermeable. Infiltration rapidly falls to very low rates, and water may simply form puddles on the soil surface, much of it to be lost by evaporation. Important management differences are related to the degree to which a grumusolic self-mulching topsoil is present, and hence to differences in rainfall acceptance by the wet soil.

In addition to the need to get as much of the rain as possible into the soil for use by the crop, there is the need to provide adequate surface drainage to avoid plant injury or slow growth from waterlogging once the cracks have closed and infiltration rates are very slow. A traditional and relatively early method was the cambered bed, also useful on many clay soils other than Vertisols. A cambered bed can be formed by ploughing up and down so that the soil is turned inwards to the centre. Cambered beds have been used successfully in many areas of Africa, including the Accra plains of Ghana and the northwestern cotton growing areas of Tanzania. Other man-made microrelief patterns designed to improve surface drainage include various beds and mounds made with hoes and other implements, and a range of ridges, narrow beds and broadbeds, often made by animal-drawn implements, and all separated by a furrow whose essential role is to provide surface drainage in about the upper 10-15 cm of the ridge or bed and to lead away the drainage water gently, on a low gradient, and dispose of it safely.

In very dry areas, waterlogging is less likely to be a problem, and tillage is important to get every drop of water in the soil, and minimise runoff and evaporative losses. The roles of ridges and furrows are reversed: water is designed to run off the ridge, sometimes suitably broadened, which then becomes a water harvesting device designed to lead runoff into the furrow in which the crop is planted. To block the water movement in the furrow, the ridges may be 'tied' at intervals with a cross ridge, although in occasional unusually wet years the ridges may be untied. The fact that Vertisols, once wetted, have very slow infiltration rates so that water

runs off easily is in this case an advantage for water harvesting in the ridges.

Water movement into cracking clays illustrates a further fundamental difference between cracking and non-craking soil. When rain falls on a non-cracking soil, such as an Alfisol, Ultisol or Oxisol, the wetting front moves downwards from the surface fairly evenly, particularly if the surface is without marked microrelief and has good rainfall acceptance properties. Although infiltration rates may decrease as the soil surface horizons approach field capacity, there are no sudden changes affecting the pattern of water entry and movement.

In contrast, the initial entry of water into Vertisols through cracks may be rapid; the heavier the downpour the more precipitation will enter the subsoil. Water in the cracks then diffuses laterally and relatively slowly to areas between cracks, resulting in very uneven water distribution patterns. Similar patterns may form in relation to uneven entry related to gilgai microrelief.

The lower the rainfall, the more critical is detailed study of differential water movement in Vertisols, which should be used is an adapted cropping system. Detailed water studies of this type, if applied to the water-harvesting ridge and furrow system being tried in southeast Zimbabwe, can be expected to show to what extent water is channeled into the furrows and where it is stored in relation to the crop root system. These studies could indicate what proportion of rain is exploited by the crop, and whether there is enough moisture in the soil at harvest to have supplied a crop with a longer growing season, or an

additional short-season sequential crop. In this way studies of soil physics, soil management, and crop needs can be used to adopt cropping systems better adapted to soils and rainfall, and to raise yields, particularly in years of low rainfall.

Cropping systems are a major aspect of Vertisol management, and different strategies have to be adopted according to the amount and distribution of the rain (Willey, 1987). For example, intercropping and relay cropping may increase yields several-fold, as found by ICRISAT in India (Kanwar and Virmani, 1987). The success of these systems depends on a good understanding of the soil moisture regime and a better use of available water.

Fertility problems may also become a constraint, particularly in sustained, high-input systems. Under these conditions N, P and micronutrients (particularly Zn and Fe) may limit crop production (Le Mare, 1987; Katyal et al, 1987). In most African countries however, at the present stage of rainfed Vertisol use in semi-arid areas, nutrients are less important than soil water management, as indicated by the fact that yields are more often raised by improved surface drainage or increased available water than by the use of fertilisers. For these reasons, a strategy giving priority to soil water management has emerged as the main focus for the Vertisols Network. Related to this is the development of improved techniques and an examination of the advantages of post-harvest tillage over rainy season tillage.

The ICRISAT system of post-harvest ploughing followed later by seedbed preparation and dry seeding before the rains illustrates what can be

done when the onset of the rains is predictable. However, in many African areas of low and unreliable rainfall, both the amount of rain and the onset of the wet season vary widely from year to year. Forecasting is more difficult, even with the sophisticated techniques for climatic analysis now available.

An acceptable strategy under these conditions is to secure a higher minimum yield in dry years, and thus reduce the risk of crop failure, while recognising the need for surface drainage to minimise waterlogging effects in wet years. However, the farmer who plays safe on part of his land may also wish to devote additional space to a higher-risk crop or a longer growing season variety which, although it will fail in a bad year, will give higher or more valuable yields in a good year. This is the case where a relatively safe sorghum crop is combined with a riskier but more appreciated maize crop, or where a higher yielding long-season maize is planted in addition to safer but lower-yielding short-season maize.

DEVELOPMENT OF THE MOVUSAC NETWORK

These considerations suggest the main emphasis of the MOVUSAC Network. The properties of Vertisols which distinguish them from the more extensive non-cracking soils of the tropics are fundamentally similar wherever these soils occur. The variations which affect soil management are of two types: edaphic and climatic. Variations in the properties of the Vertisols, and variations in climate (amount, distribution, and reliability of rainfall), together ensure that management and cropping systems are site-specific. This means that we cannot plan to transfer a cropping system

from one locality to another without modification. What we can do is to look at basic principles and patterns of adaptation to local conditions in relation to changes in soil and climatic parameters relevant to management.

Vertisols on the African continent are found in a range of rainfall regimes, from relatively wet in Ethiopia, to semi-arid in Zimbabwe and the Sudan. Individual network cooperators working in a single country will study local soil management, and their results will be shared with other parts of Africa, so that the management research as a whole is not national but continental. It is hoped that this work will eventually produce a gradation of management practices adapted to rainfall, soils, and socioeconomic factors.

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RECOMMENDATIONS

PANEL RECOMMENDATIONS ON RESEARCH NEEDS FOR SUSTAINED AGRICULTURE ON AFRICAN VERTISOLS

INTRODUCTION

At a panel session on the final day of the conference, 14 participants formulated recommendations for future research on Vertisols in the areas of resource assessment, resource management and inter-institutional cooperation and networking.

The participants in this panel session were:

H. Eswaran	G. Lombin
M.F. Purnell	O. Osman
J. Sehgal	R.D. Ghodake
S.M. Virmani	P.L. Porter
Desta Beyene	Mesfin Abebe
G. Haider	G. Gryseels
N. Ahmed	M. Latham

RESOURCE ASSESSMENT

Research on Vertisols, directed at developing new technologies for their enhanced agricultural exploitation, must be based on comprehensive analytical knowledge of these soils, including their geographical distribution, their agroclimatic properties and their agricultural potentials. Sub-Saharan Africa, with about 83 million ha of Vertisols (more than 25% of the world total) occurring under a wide range of agroecological conditions, can be considered an ideal field laboratory for such research.

Several specific gaps in the present information base have been identified.

The current system for classifying Vertisols does not take sufficient account of practical aspects of soil management and its variability as a function of agroclimate. Many clay soils which behave in much the same way as Vertisols in terms of their agricultural management are not classified as true Vertisols. Partly as a result of these shortcomings in the classification system, there are large differences in the estimates of Vertisol areas in individual countries, as well as in the African continent as a whole.

Detailed soil maps of Vertisol areas, produced from data gathered by aerial and ground surveys, are useful for resource allocation and planning purposes. However, full assessment of the agricultural potentials of Vertisols, and of the technological interventions necessary to realise these potentials, requires, in addition, detailed agroecological zoning of these soils, on the bases of average lengths of growing periods, and local and special climatic features influencing crop growth, such as rainfall distribution and dependability, frost, etc.

Vertisol surface characteristics vary considerably with agroclimate. More understanding is needed of the nature of this relationship, which can decisively influence the suitability of these soils for arable cropping.

Vertisols are, in general, regarded as marginal agricultural soils. Because their physical properties hinder conventional arable cropping, extensive areas are left under native

range, supporting large numbers of domestic livestock and game. More data are needed on present land use systems.

Several specific research efforts are identified as being necessary to fill these gaps:

- A more flexible classification system for Vertisols needs to be devised, which also considers related clay soils and interactions between agroclimate and groups of clay soils in terms of their agricultural use.

- Expansion of the information base on the geographical distribution and management-related properties of Vertisols can be undertaken by FAO and Unesco. IBSRAM's African Vertisol Network may support these activities.

- The preparation of detailed agro-climatological maps of Vertisol areas, which can be superimposed on the already available soils maps, will lead to comprehensive resource inventories at national and sub-national levels.

- More attention should be given to characterising the surface properties of Vertisols and their dependence on climate and management practices.

- Of particular interest for the design of improved Vertisol use options is the listing of all major production constraints encountered in the traditional farming systems on these soils.

- Aerial surveys should be used to gather detailed information for use in making accurate land-use analysis. National land-use planning departments are mandated to carry out this work.

RESOURCE MANAGEMENT

In formulating proposals for Vertisol management research in sub-Saharan Africa, a systematic approach is needed which takes into account agroclimatology, socioeconomics, target farming systems and agrocultural policy considerations.

Soil water and nutrients

Soil moisture is the dynamic factor that largely determines the potential for arable farming on Vertisols. Very rapid changes from dry to wet and from wet to dry phases are likely to make Vertisols rather marginal arable soils in traditional farming, while slow changes may allow more extended cropping.

Improved Vertisol surface drainage in high rainfall areas affects not only soil moisture, but also soil surface temperature, nutrient mineralisation rates and therefore nutrient availability to crops. The acidity of Vertisols in these areas poses important fertility problems.

Rainfed agriculture on Vertisols in semi-arid and arid regions requires systematic interception of the scarce rainfall. The broadbed-and-furrow technology with tied furrows, constructed by using animal power, may represent a valuable alternative to conventional systems such as tied ridges.

Careful research on the complex interactions between soil water, plant nutrient availability and crop growth will lead to improved prediction of input efficiency on these soils.

- More detailed studies on Vertisol moisture dynamics are needed. The results are likely to have direct management implications (moisture conservation, crack reduction).

- For cropping Vertisols in humid zones, there is a need for more research on more effective means of draining excessive water from fields without contributing to increased soil losses through erosion.

- Much experience on the use of Vertisols under irrigation is available in sub-Saharan Africa. Major research needs relate to the avoidance of salinisation with effective surface drainage, and to the avoidance of seepage water losses caused by cracking in field irrigation channels. Tillage/ vegetative soil coverage practices affect soil water and irrigation water conservation, and need special attention.

- In the cropping of arid-zone Vertisols, under both rainfed and irrigated conditions, the most vital point to consider is the conservation of soil water through the use of appropriate tillage practices. Cropping systems must be devised in line with their most effective water use and in line with soil fertility maintenance requirements. Deep-rooted crops must be incorporated into the systems for maximum use of the moisture stored in the profile. Crops should also have adequate drought resistance to survive

extended dry spell. Much attention should be given to building up organic matter in these Vertisols, which will contribute to better workability and soil water conservation.

Livestock

The most important contribution livestock can make to improved management of sub-Saharan Vertisols is their use as traction animals. Crop-livestock interactions in the predominant mixed and agropastoral farming systems can thereby be utilised and strengthened for the benefit of both sub-systems. Another contribution of livestock to the cropping part of the farming system is manure, which ought to be used more effectively as a source of domestic plant nutrient.

The application of draught animal power in improved Vertisol management for increased crop output will concurrently also increase the availability of crop residues for use as animal feed. Crop residues can quite easily be upgraded to productive animal diets with the use of suitable nitrogen supplements which should preferably be grown on-farm (legumes, particularly tree legumes). Increased crop grain output per unit area will also ease the pressure on arable land for exclusive grain production. This may allow some production of high quality animal feed on a portion of the land.

- Apart from work on draught animal technologies, livestock research on Vertisols with mixed farming patterns should focus on interactions with arable crop production.

Socioeconomics, on-farm research and technology transfer

In the generation of Vertisol technology it is vital to have a clear understanding of the target farming community and its resource endowment, and to tailor research programmes according to specific requirements.

Improved Vertisol management technology is never a single commodity technology; it normally implies quite considerable changes in farm resource allocation, cropping systems, soil fertility practices and animal husbandry. Transfer of such a complex technology tends to be a slower than single commodity transfer.

- Vertisol technology research needs to carry an economic dimension right from the start, to ensure that the economic implications of this technology can be adequately assessed, with clear indications of cost-benefit ratios, of the means necessary to guide the transfer and adoption of this technology in the target farming community, and of the actual impact of the technology. This economic dimension must therefore cover aspects of detailed economic analysis of the technologies proposed, of comprehensive base-line information of the resource including socioeconomic parameters, of risk studies, and of detailed economic monitoring of the technolgy performance on-farm. Market studies will reflect opportunities and bottlenecks in the target farming systems.

- On-farm research on Vertisol technology needs a long-term perspective in view of the

generally high variability in technology performance from year to year.

- In structuring Vertisol technology transfer, special attention should be given to the selection of representative test locations within the target areas on carefully identified benchmark Vertisols.

- Decisive efforts are required to simplify the technological message for the extension system, so as to lay down a foundation on which more advanced technological elements can later be built. This requirement calls for interdisciplinary research work, both on-station and on-farm, with research and extension institutions formally interlinked.

INTER-INSTITUTIONAL COOPERATION AND NETWORKING

The transfer of Vertisol technology depends largely on the establishment of a formal inter-institutional agreement between research and extension agencies, with clear assignment of responsibilities in order to ensure effective feedback.

The considerable gaps in detailed knowledge, both of the Vertisols themselves and of the agroecology determining their most effective agricultural use in the sub-Saharan context, call for specific manpower training opportunities which range from formal training to in-service training of national staff working on such soils.

The African Vertisol Network coordinated by IBSRAM should be actively utilised by interested national research systems in sub-Saharan Africa:

- to increase the exchange of technical and management information,

- to enhance specific training opportunities for scientific and technical staff working in Vertisol utilisation,

- to facilitate necessary funding for the implementation of Vertisol management research in member countries,

- to facilitate necessary counselling to national research programmes, and

- to offer and facilitate attractive publication opportunities for achievements of national programmes.

CLOSING ADDRESS

Closing remarks by Comrade Gizaw Negussie, Vice Minister, Animal and Fishery Resources Development Main Department, Ministry of Agriculture

Distinguished delegates, invited guests, ladies and gentlemen, comrades.

Thirteen years have now passed since the first world conference on food, held in Rome in October 1974, signaled the deteriorating trend of the food situation in the developing countries, particularly in Africa, Asia, and Latin America. Total food production increased by 4% per year in Latin America and South-East Asia but remained far short of meeting requirements in Africa and South Asia. During the first half of the 1980s Africa's food and agriculture production declined by 2% a year, which is equivalent to a fall in daily per capita food supply, on calorie basis, of 1.2% a year.

A lot has been said about Africa's poor performance in food production. The causes are numerous and varied, and are of internal and external origin. Lack of technology appropriate to Africa's agricultural setting is one of several internal constraints limiting food production in the continent. Most agricultural research systems in African countries have been concentrating on internationally traded agricultural produce to the neglect of food crops. The very limited research work on food crops has been concentrated on high yielding varieties and application of fertilizer and very little attention has been given to land and water management and livestock as means of expanding food supply. Defective delivery mechanisms for the dissemination of innovations

and the supply of inputs equally constrain self-sufficiency in food in Africa.

This conference on Management of Vertisols in Sub-Saharan Africa has now reached its conclusion. The conference has, I believe, created a congenial atmosphere for scientists from national and international research and development organisations to exchange experiences. The 60 paper contributions presented during this week have conveyed, to an exceptionally wide audience, established and new knowledge on the nature, ecology and management-related problems of these soils. In total acreage terms, Vertisols may not be very important on the African continent, but they are a most vital resource for human food and animal feed production in certain regions. One of these regions is certainly Ethiopia, your host country, as has been documented in the course of this conference. This explains our interest in the most positive outcome of this conference. As has also been documented this week, adequate management interventions have considerable scope for drastically increasing off-take from these soils. Experiences gained in Africa, Asia, Australia and the Caribbean region on the use of these rather special soils have been discussed. These discussions can be of considerable use in our own efforts to bring these soils to a stage of higher and sustained production. For staff of Ethiopian institutions this conference has been an opportunity to increase general awareness in various aspects related to the use of these soils. I hope this increased awareness will be coupled with an increased commitment toward the development of practical measures for the tapping of the considerable productive potentials of this resource. In this connection you may all realise

that in a number of our countries national and international research institutions generate more technologies than development agencies can effectively disseminate.

In an attempt to make an assessment of this conference, I would remind you of a statement made by the Minister of Agriculture in his opening speech. He said "I sincerely hope that you will come up with detailed suggestions for research and develoment on the improved agricultural utilisation of Vertisols for human food production. These suggestions should take into account not only the ecology and pedology of the Vertisols, but also the socio-economic environments and resource constraints prevailing in our production systems. It is only then that we will be able to make reasonable use of these soils." This week you have deliberated extensively upon the potentials and inherent constraints of Vertisols, their agro-meteorology and livestock aspects, and on management technology and its applicability under varying physical and socio-economic conditions. The improved utilisation of Vertisols in the light of the incremental analytical knowledge is perhaps one aspect where one might expect more emphasis to be put in future research work.

Many African Vertisols support large numbers of livestock which play a diversity of roles. If Vertisols are cropped, livestock in the same production system normally have important functions in tillage or crop residue utilisation, or both together, as well as additional attributes such as financial security, supply of protein-rich food and raw materials. Livestock, especially in agropastoralist systems and in smallholder mixed farming, can therefore hardly be separated from

any interventions in soil utilisation. A truly systems-oriented approach in research and development of these interventions is therefore necessary, taking into account interactions between crop and livestock production, and the general socio-economic conditions of target areas. There have been some reports on such an approach during the conference. I would hope, however, that such effects can be strengthened in the future. The development of new management methods for Vertisols is clearly a matter of interdisciplinary endeavour which, in most cases, requires the productive interaction of institutions with complementary mandates. I am pleased to witness serious efforts and suggestions in this direction. These institutional interactions have both national and international dimensions. The fact that international bodies such as ICRISAT and IBSRAM have not only strongly contributed to the efforts made by ILCA for this conference, but are also committed to establishing formal links with national efforts, is most encouraging. We are, therefore, convinced that this conference has contributed to the strengthened commitment to work along the lines of interinstitutional task-sharing with accelerated technology generation and transfer.

On behalf of my Government, and on my own behalf as an offical of the Ministry of Agriculture and Chairman of the Advisory Committee for Vertisol Management Research in Ethiopia, I would like to express my appreciation to all individuals and organisations who have contributed to the success of this conference. First I thank ILCA for organising, and ICRISAT and IBSRAM for cosponsoring, such a large, important and impressive conference. My appreciation is also due to scientific paper contributors, participants and observers. The role of the

organising team at ILCA and the Technical Committee of the Vertisol Management Project in Ethiopia deserves special mention. I do not think I would be fair not to single out Dr Samuel Jutzi's outstanding contribution to the successful completion of this conference. I would like to express a special tribute to Dr Walsh, Director General of ILCA, for his wise initiative and guidance in organising this conference at a time when Africa's food situation is disturbing. Last, but not least, I thank interpretors, photographers and technicians for their most valuable assistance.

I hope your stay in Ethiopia has been a pleasant one and I wish you a safe journey home. I now officially declare this conference closed.

APPENDIX

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