TECHNICAL HANDBOOK No. 30

Soil fertility and land productivity

A guide for extension workers in the eastern Africa region

Charles K.K. Gachene
Gathiru Kimaru

RELMA

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Foreword

Much smallholder farming in the eastern Africa region today takes place on semi-arid lands that have infertile soils and where rainfall is both low and erratic. The very poor soil fertility status on these farms, and resulting low yields, are a cause of great concern, but it is possible to address the problem in a positive manner.

This handbook is intended as a basic guide for trainers and extension workers involved in work aimed at improving land productivity. The six chapters in it can be read separately by those looking for specific information on each of the topics covered, but it is the integration of all these that will give a full picture of the opportunities that are available for improving soil fertility and thus increasing agricultural production and farm incomes in the region.

By integrated soil fertility management we mean paying simultaneous attention to all the activities and factors that affect soil fertility. First, the fertility status of the soil on cultivated land is affected by the entire range of farm activities from land preparation to post harvest because these activities are interlinked and cannot be treated in isolation from each other. Secondly, the availability of nutrients and water is critical. These two factors are also linked together like Siamese twins: neither an abundance of nutrients with no water nor a paucity of nutrients with a plentiful supply of water can sustain crop production. Water management must be addressed in parallel with nutrient management. The third factor is the availability and use of fertilizers.

There are three categories of fertilizer: brown (manure, dung and urine – including human waste with the potential for use of ecological toilets), green (plant waste), and white (manufactured nutrients). All three types should be used in an appropriate integrated mix for best results. In some quarters, the view is that 'brown' and 'green' fertilizers are good, but that 'white' are not. 'White' fertilizers are often wrongly lumped together with plant-protection products (herbicides, fungicides and pesticides) as undesirable 'chemicals'. Of course they are all chemicals, but 'white' fertilizers are specifically tailored to the plant's nutrient requirements, and the ions taken up from them are built into the organic structure of the plant – therefore such fertilizers should not be classed together with plant-protection chemicals.

There may also be strong arguments against 'white' fertilizers in Europe and America, for example, because of their excessive use (some 25 times more per hectare compared

to eastern Africa) and the attendant risks of nutrient leakages into groundwater resources, and because of the great overproduction of food in those countries. However, we stress the urgent need to use sufficient fertilizer if improved yields are to be achieved on most of the soils in eastern Africa, and any attempts to limit the use of 'white' fertilizers in this region should be rejected.

However, the best types and amounts of fertilizer to use for a particular crop in a given area should be decided on the basis of sufficient information obtained through soil and plant-tissue sampling and analysis. Only when such analysis has been done, is it possible to prescribe the best-suited crop for a given soil, and also the appropriate remedies for treating or reclaiming chemically degraded soils.

The people directly in touch with farmers and currently handling inorganic fertilizers are stockists and frontline extension staff. Unfortunately, few stockists are well informed about fertilizers, and therefore farmers do not get the best advice from them. We hope this book will provide the necessary background information for trainers and extension workers, and through them farmers and traders, to be able to make appropriate choices for their areas.

A further reason for the continuing decline in soil fertility in eastern Africa is the removal of subsidies as part of World Bank/IMF-prescribed liberalization or 'market orientation and globalization' strategies. Few farmers in eastern Africa can afford the resulting high fertilizer prices. By comparison, 50% of European and American farmers' incomes, for example, originate from direct government payments and subsidies. One can, therefore, make a case for a proportion of such subsidies being directed towards lowering fertilizer prices for the region. Such support would promote substantial growth in agricultural production and rural incomes, and thus make a direct contribution to poverty reduction for a large proportion of the population. It is difficult to say where or how such money should be raised, but the question of subsidies for fertilizers must be addressed by agricultural policy makers in our countries.

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Preface

The eastern Africa region faces serious and worsening problems of food security, decreasing per capita food production and massive poverty. Agriculture in this region is dominated by smallholder farmers. Yield levels on these farms are generally very low for a variety of reasons. One important reason is the declining soil fertility, and this forms the major theme of this book. Currently the different countries have policies aiming at giving increased attention to achieving improved productivity and better farm incomes as part of their national poverty reduction strategies. This book should provide useful information to extension workers and their trainers in giving the necessary advice to farmers.

The book is arranged in six chapters. The first chapter introduces the subject and argues for broad multi-faceted action programmes to deal with the problem of consistently low yields on small-scale farms. Chapter 2 presents basic information on soil properties, soil fertility and plant nutrient needs. This is important in designing possible solutions for specific field situations. Chapter 3 gives some practical ways of improving and maintaining soil fertility, including organic and inorganic methods, and suggests the need for an integrated approach that uses both organic and inorganic materials while ensuring effective soil moisture management. Chapter 4 contains case studies from Uganda, Rwanda, Tanzania, Kenya, Ethiopia and Zambia illustrating farmers' practical experiences in solving soil fertility problems. Chapter 5 is a brief look at the role of agroforestry in land productivity, while Chapter 6 highlights the importance of improved tillage.

Some major technical subjects related to improved land productivity, such as soil and water conservation and irrigation, are not covered in this book. These topics need to be presented separately so as to adequately cover their technical and organizational aspects.

It is also recognized that to adequately address soil fertility and land productivity national level action programmes are necessary, focusing on such key issues as the development of a suitable policy and legal environment; improved marketing, processing and storage; provision of rural and farm credit and rural infrastructure; focused research and effective extension services; and strong farmer organization and cooperation. Although these subjects are outside the scope of this book, they should be taken as part of an integrated approach to addressing food security and rural income growth.

Acronyms

ASN	Ammonium sulphate nitrate
CAN	Calcium ammonium nitrate
CEC	Cation exchange capacity
DAP	Di-ammonium phosphate
DM	Dry matter
EC	Electrical conductivity
ECe	Electrical conductivity of extract
ESP	Exchangeable sodium percentage
FAO	Food and Agriculture Organization of the UN
FYM	Farmyard manure
ICRAF	International Centre for Research on Agroforestry
IIED	International Institute for Environment and Development
ISFM	Integrated soil fertility management
LAMP	Land Management Programme (LAMP/Sida)
LRNP	Legume Research Network Project (Kenya)
MAP	Mono-ammonium phosphate
MIRCEN	Microbiology Resource Centre (University of Nairobi)
MRP	Mijingu rock phosphate
NPK	Sodium, phosphorus, potassium (fertilizer)
RELMA	Regional Land Management Unit (Sida)
SAARNET	Southern Africa Agroforestry Research Network
SECAP	Soil Erosion Control and Agroforestry Project (Tanzania)
SSP	Single superphosphate
TSP	Triple superphosphate

Chapter 1

The crisis in land and agricultural productivity

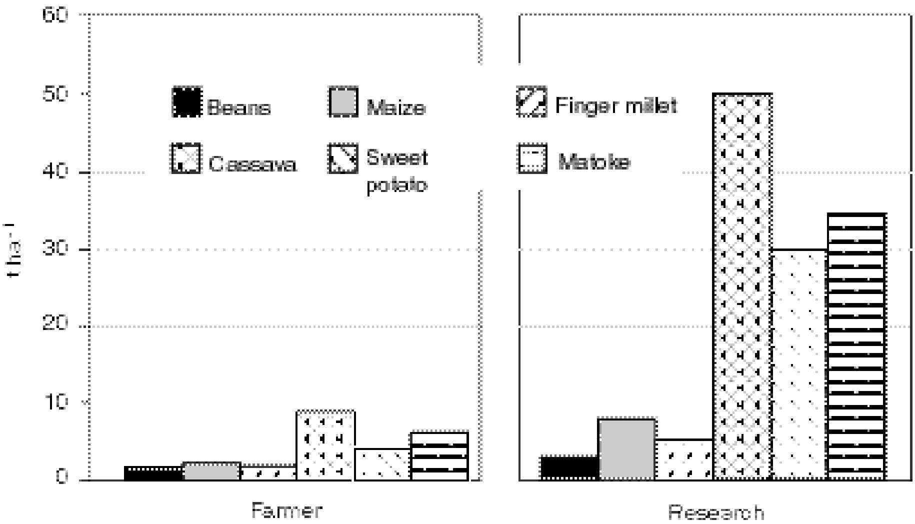
1.1 INTRODUCTION

Traditional subsistence, low-input, low-yield agriculture can no longer adequately cater for all food, fibre, cash, industry and other human needs in sub-Saharan Africa. 'Modern' or 'Green Revolution' market-oriented agriculture, that relies on adequate use of external inputs such as chemical fertilizers, herbicides, pesticides, high-yielding varieties, and farm mechanization (including irrigation) has resulted in dramatic agricultural yield increases in certain Third World countries, especially in Asia, in the last 30–40 years. But Africa has been bypassed by these developments.

Farmers in the eastern Africa region (defined here as Eritrea, Ethiopia, Kenya, Uganda, Tanzania, Zambia and Malawi, the seven countries which comprise RELMA's area of operation) are getting barely 25% of the yields that are attained at neighbouring research stations. The difference arises from the better supply, maintenance and management of plant nutrients, as well as improved tillage practices and good soil-moisture management, at research stations (Figure 1.1). Declining soil fertility, low soil moisture, soil salinity/sodicity, soil compaction and the formation of hardpans are major causes of low land productivity, which is itself manifested as low crop yields, low farm incomes and deepening rural poverty. There are worsening food deficits in many areas of the eastern African region. This has led to too much dependence on food aid (food grown in other countries using massive applications of fertilizers and crop-protection chemicals). The current high poverty levels can be reduced through effective action to raise soil fertility to levels that will bring crop yields closer to the potential for each ecological zone.

The substantial changes in productivity that are required call for the adoption of continuously changing technology. The question is how to manage these changes to suit resource-poor small-scale farmers in the short run. However, it is not debatable that production, and land productivity, must be consistently and sustainably improved

over many years. The long-term objective should be to achieve a significant net increase in nutrient levels, as well to improve other soil and production conditions, season after season.



Source: FAO 1999.

Figure 1.1 *Differences between farmer and research station yields*

1.2 WHY GIVE PRIORITY ATTENTION TO SOIL FERTILITY?

Smallholder farmers are unable to significantly raise production using only the organic manures available locally. There is poor biomass production (because of low soil fertility and often inadequate rainfall), and therefore little availability of organic materials for composting or for direct incorporation into the soils. The rate of accumulation of soil organic matter is also reduced by the very rapid mineralization that occurs in the prevailing hot climates. Termites also consume much of the organic matter, especially in semi-arid areas.

Competition between uses prevents the accumulation of organic matter in the soil. Most crop stover is removed from the farm as livestock fodder. Animal manures are often not returned to the originating farm. This combines with continuous cropping to cause serious soil mining and fertility decline.

Land productivity must be raised drastically and rapidly to stem the worsening rural poverty that results from declining yields. This will require significant increases in the use of organic and inorganic fertilizers.

1.3 WHAT IS SOIL FERTILITY AND HOW DOES IT DECLINE?

Soil fertility is the capacity of the soil to support the growth of plants on a sustained basis, yielding quantities of expected products that are close to the known potential.

Such productive capacity requires the provision of adequate and balanced amounts of nutrients to ensure proper growth of the plants. Other necessary soil factors must be favourable to promote proper nutrient uptake, and therefore adequate growth, production and yield. Some of these are soil moisture and temperature, aeration, water-holding capacity, a pH that should be near neutral, an absence of hardpans that otherwise would inhibit root growth, adequate organic matter, and other conditions that promote the growth of soil micro-organisms.

The recognized forms of soil degradation are erosion; physical, chemical and biological soil degradation; salinization and pollution. Chemical degradation includes salinization, sodication, acidification and the depletion of plant nutrient content in the soil. Biological degradation is loss of soil organic matter and soil biodiversity. It influences both soil physical properties and nutrients, while erosion is a cause of both physical and biological degradation and loss of nutrients. All these forms of degradation lead to a lowering of soil fertility and land productivity. Farmers get less and less from the same area of land, or yields have stagnated at very low levels. This problem is now recognized as being one of the major contributors to the persistent food deficits and high poverty levels in the eastern Africa region.

It is estimated that countries in the region need to increase agricultural production at least threefold within a generation. This level of increase is required to eliminate the current deficits, allow for better nutrition, obtain a significant marketable surplus to improve cash incomes, and to accommodate additional demand created by the growing population.

Because of low production at the farm level, the majority of the people in the eastern Africa region live below the poverty line (that is, on one US dollar per person per day according to World Bank standards). With these exceedingly low incomes, they are unable to afford the very basic needs of food, clean water, health services, proper shelter and education.

1.4 MAIN CAUSES OF POOR LAND PRODUCTIVITY

1.4.1 Declining plant nutrient status

Soils are rapidly losing the ability to supply the nutrient elements in the amounts, forms and proportions required for optimum plant growth.

1.4.2 Very little use of organic and inorganic fertilizers

Plant nutrients that are removed through harvested crops and forages (or through erosion) are not replenished. For example, Uganda imports only about 10,000 tonnes of fertilizer annually. Kenya's imports have dropped from around 300,000 tonnes to just 100,000 tonnes per annum in the last two decades. In all the eastern Africa countries, the bulk of the imported fertilizer goes to cash crops such as coffee, tea, sugar cane, tobacco and commercial horticulture; very little is used on food crops. The region depends on imported mineral fertilizers. There are deposits of rock phosphate, notably in

Uganda (at Tororo) and Tanzania (Mijingu), but these have not been adequately exploited.

The use of organic manure is often very low, or the material is collected, stored and applied poorly, thus seriously reducing its effectiveness. Often livestock are turned into the fields after harvesting, or the crop residues are removed from the field as fodder or fuel. In some cases, animal dung is collected, dried and used as fuel for cooking. All these actions lead to continuous removal of plant nutrients. Under these conditions, the production of sufficient food by individual families, improvement of rural incomes, and the reduction of food imports at the national level will depend heavily on renewed attention to soil fertility. The supply and use of sufficient amounts of inorganic fertilizers, and the proper use of organic manure, are important elements in this process.

1.4.3 Lack of attention to soil acidity

Leaching of bases and the use of acidifying fertilizers has led to the development of acid conditions, especially in highland areas. This limits the availability of plant nutrients in the soil, leading to reduced productivity of the soils. There is very little use of liming materials to minimize acidity.

1.4.4 Poor conservation and management of rainwater

Adequate soil moisture is necessary for the proper uptake of plant nutrients. Farmers are not harvesting and conserving rainfall runoff efficiently for agricultural production, and there is very little supplemental irrigation.

1.4.5 Poor tillage practices

Poor tillage practices cause hardpans that limit water infiltration into the soil, leading to wastage of rainwater. Poor tillage also fails to effectively control weeds.

1.4.6 Tree growing is not focused on the improvement of soil fertility

Many farmers are not yet familiar with modern agroforestry practices. Deliberate use of legumes for soil fertility maintenance is not common.

1.4.7 Excessive soil erosion by water and wind

Good topsoil is lost, and along with it considerable quantities of plant nutrients, ending up in rivers and other water bodies. Lake Victoria, for example, is experiencing high levels of eutrophication, which encourages heavy invasions by waterweeds.

1.4.8 Land fragmentation

Very high population densities, especially in the highland areas, have led to subdivision of land into small units that are unviable economically. This leads to loss of agricultural land and reduced production.

1.4.9 Poor land-use planning

A failure to practise crop rotation or fallow systems, as well as overgrazing (caused by keeping excessive numbers of livestock) leads to degradation and reduced land productivity.

1.4.10 Land-tenure problems

Land users may not be willing to invest in long-term land improvements if they are not sure of reaping the benefits from such work.

1.4.11 Inadequate extension services and infrastructure

Poor or inadequate back-up from extension agents, poor infrastructure, absence of credit facilities, inefficient marketing channels, and lack of information on production possibilities and the likely benefits are all constraints. The results are a lack of motivation to invest in soil fertility improvement.

1.5 ACTION NEEDED TO IMPROVE SOIL FERTILITY AND PRODUCTION

Action should be initiated to develop the necessary approaches and activities to deal with the problem of poor and worsening land productivity. Below are some potential areas for attention in the search for better land productivity.

1.5.1 Building up soil fertility as capital for production

Concerted and well-planned action needs to be taken to build up soil fertility on small-scale farms. The farmers and extension workers require appropriate knowledge and practical techniques on how to deal with the problem of consistently low yields. Effective participation of the farming community in development programmes is a major precondition for sustainable development in agriculture to take place. The aim should be to activate and enhance local capacities to adapt to changing conditions and to improve the efficiency of resource use. The improvement can be enhanced through more efficient research and extension programmes, especially if farmers are more fully involved in the identification of problems and opportunities and the design of possible solutions.

The following are important action points:

- Developing specific activities to enhance plant nutrient levels as a long-term programme through consistent use of adequate inorganic and organic fertilizers. According to World Bank figures, Africa (excluding South Africa) uses only 14 kg of fertilizer per hectare compared with 150–200 kg in East Asia and Europe. The famous European and American food mountains of the 1980s and 1990s were not built on a few occasional wheelbarrows of cattle dung!
- Giving adequate attention to the problem of soil acidity (low pH levels) and finding ways of promoting better plant nutrient availability and uptake (increasing base saturation and cation exchange capacity). Research work is required on the application of lime and other soil amendments. Wider use of organic fertilizers would help reduce the acidity problem.

- Developing and applying suitable rotations using legumes and green manure. The practice of putting livestock onto cultivated land after harvesting should be controlled to avoid damage to legume green manure and cover crops, as well as physical soil and water conservation measures.
- Promoting agroforestry and farm forestry for better soil fertility and increased land productivity to answer multiple needs at the farm level and beyond.
- Creating programmes to deal with the issues of tillage and depth of root bed to create sufficient storage capacity for plant nutrients and water. The root bed must be increased from the current 'hoe depth' of 10–15 cm to at least 25–30 cm. Farmers know that deeper tillage brings up too much infertile sub-soil to the surface. However, the depth should be increased gradually, each operation ensuring addition of sufficient organic and inorganic nutrients into progressively lower layers of the soil. Issues of the required energy and the development of new or improved tillage systems and equipment need to be dealt with as crucial elements in the process.
- Adopting improved methods of tillage to lessen the problem of hardpans and plough soles. This will greatly enhance the available soil moisture and therefore improve crop growth. Conservation tillage (see Chapter 6) also prevents unnecessary inversion and loosening of the soil, thus reducing erosion and promoting moisture storage.
- Promoting the efficient conservation and management of available rainfall to enhance soil moisture and crop production.
- Developing efficient systems of irrigation that increase production without degrading the soil.
- Integrating livestock in the farming systems and promoting better management of crop residues and organic matter.
- Adopting soil conservation measures that are simple, effective and affordable.

1.5.2 Modernizing agriculture

Serious efforts are needed to modernize agriculture. The objective should be to produce not just for home and national consumption, but also to achieve significant surpluses. In other words, greatly improved production technologies and techniques are required to elevate crop and livestock production to a level that covers all subsistence needs besides generating marketable surpluses. The process of modernization must include a shift from mere subsistence production to a cash-oriented agricultural industry that will generate export products for the eastern and southern Africa region, Europe and other markets, besides adequately meeting local demand.

The necessary improvements will require that farmers abandon the current low-input, low-output mode of production and adopt modern production processes that employ high-yielding technologies. Time is against the region. There is an urgent need to take advantage of scientific advancements, borrowing wisely from elsewhere. For example, chemical fertilizers should be used in much larger amounts than at present, and in a judicious manner to avoid harmful effects on the environment. African countries can never eradicate poverty without the use of improved technology that focuses strongly on raising soil fertility.

1.5.3 Expanding and diversifying markets

Through appropriate national policies, agricultural production must be market oriented while giving farmers the necessary support, as is done elsewhere in the world. The globalization and liberalization of world trade have made African smallholders vulnerable in the face of competition from other countries where farmers are accorded various forms of subsidies. African countries also need to promote adequate training and information capacities for institutions to improve the production and marketing knowledge available to farmers and extension workers. Some of the specific actions required are:

- Diversification of crops grown to include greater attention to high-value crops such as fruits and horticulture. Currently, the majority of farmers devote their farms to food crops and low-yielding livestock. To create a sound farm income base, enterprise diversification is required, as well as improvements in production methods.
- Promotion of local processing for animal and crop products to add value and to increase shelf life and reduce spoilage. There is very little local processing of agricultural produce. This leads to continued poor financial returns at the farm level, as well as restricting the opening up of wider market possibilities.
- Moving into non-traditional markets. This will require intensified research in processing and identification of more market niches as part of overall support to farmers. Organic farming is a good example. It is a specialized production system that targets special market niches where premium prices can be obtained. Vegetables and cereals are the prime candidates for premium prices ranging from 20 to 200%, depending on the market (Lampkin 1990). Out of 130 countries that are producing organic foods, 50% are from the developing world. Development of organic production in the eastern Africa region will require significant investments in time and capital, as well as in the training of both farmers and extension workers. There is also a need for the formation of strong farmers' organizations to champion the interests of organic food producers, to promote 'cleaner' production and to access outside markets.

1.6 CONCLUSION

The problem of declining soil fertility is now widely recognized and the causes, which are many, have been identified.

The following chapters give the reader both theoretical and practical information that is important for understanding how soil fertility can be improved. Chapter 2 provides the basics for understanding the soil and the ways in which fertility and plant nutrient needs can be assessed. It also discusses problem soils and how they should be managed. Chapter 3 explains the main ways of maintaining and improving soil fertility, using both organic and inorganic fertilizers. Chapter 4 presents case studies based on farmers' own experiences in using legume green manure or cover crops for soil fertility improvement. Chapter 5 describes the particular role that agroforestry can play in raising soil fertility and land productivity. Chapter 6 addresses the subject of tillage, which is now seen to warrant much more attention than it has received in the past.

Two important subjects which are not covered in this book are soil and water conservation and irrigation. Most countries served by RELMA have their own manuals on soil and water conservation and on irrigation. Soil fertility is the prime focus of this book because low fertility is now thought to be the most widespread cause of declining yields from agricultural land within the region.

Chapter 2

Soil properties, plant nutrients and soil fertility

2.1 INTRODUCTION

This chapter is intended for the reader who wishes to have a better understanding of soil properties and the way in which they affect plant growth. There is a great range of soils in the eastern Africa region that vary in origin and depth as well as in physical, chemical and biological characteristics. Some have serious problems which may not be visible to the eye but nevertheless limit the potential for crop production. It is not easy for the layman to evaluate soil without the help of laboratory analysis, and even understanding the significance of the results from a laboratory can be daunting without the assistance of a specialist. However, this chapter will help to bridge the gap between the knowledge available to the soil scientist and that which the layman needs in order to manage the soil on his farm more effectively.

2.2 SOIL PROPERTIES AND CHARACTERISTICS

In this section, consideration will be given only to those soil properties that have an important bearing on soil fertility.

2.2.1 Functions of the soil

Soil is the unconsolidated cover of the earth, made up of solid particles, water and air and capable of supporting plant growth. Thus, one of the most important functions of the soil is to serve as a natural medium for plant growth. The solids are made up of mineral and organic components. The mineral particles are sand, silt and clay, while the organic components consist of plant and animal residues that are readily decomposed. Clay and organic matter are chemically active, have the ability to adsorb cations, and are thus important as far as plant nutrition is concerned. Water and air occupy the pore spaces between the solids. In addition, soil contains micro-organisms which assist in the decomposition of plant and animal residues. Other microbes, e.g.

Rhizobium bacteria, are important in assisting certain plants to fix nitrogen from the air.

Nutrient supply

The soil is the source of essential nutrient elements like the macronutrients nitrogen (N), phosphorus (P), potassium (K), calcium (Ca), magnesium (Mg) and sulphur (S) and the micronutrients manganese (Mn), iron (Fe), boron (B), zinc (Zn), copper (Cu), molybdenum (Mo) and chlorine (Cl). Nutrients become available to plants through mineral weathering and organic-matter decomposition. Usually the nutrients are absorbed from the soil solution or from colloidal surfaces as cations and anions. (See Appendix 2.)

Plant support

Proper anchorage of plant roots into the soil is essential for the plants to remain upright and to flourish. Soil factors which influence root penetration are, among others, structure, bulk density and the degree of saturation. Root development requires pore spaces for penetration and oxygen for respiration. The carbon dioxide produced during respiration must diffuse out of the soil.

Moisture retention

Soils must have good moisture-retention qualities for sustained plant growth. The moisture held in the soil should be readily available to the plants. The rate of uptake of nutrients depends on an adequate supply of water and oxygen to the soil. Soils must be sufficiently moist (but not waterlogged) to satisfy evaporative demands, to maintain photosynthesis and transpiration and to facilitate the uptake of nutrients by the plants.

2.2.2 Soil profiles and horizons

Different soils have distinctive profiles with distinct horizontal layers or horizons that differ from each other in physical, chemical and biological properties or characteristics, such as colour, structure, texture, consistency, kinds and numbers of organisms present, degree of acidity or alkalinity (Plate 1).

Many roots occur in the topsoil where there is enough supply of nutrients, water and air. Such soil profiles may take more than 100,000 years to develop.

There are five major master horizons or layers, namely: O, A, B, C and R, as described in Table 2.1.

Plate 1: Soil profile showing horizons and plant roots

***Table 2.1** Designations and properties of the major soil horizons*

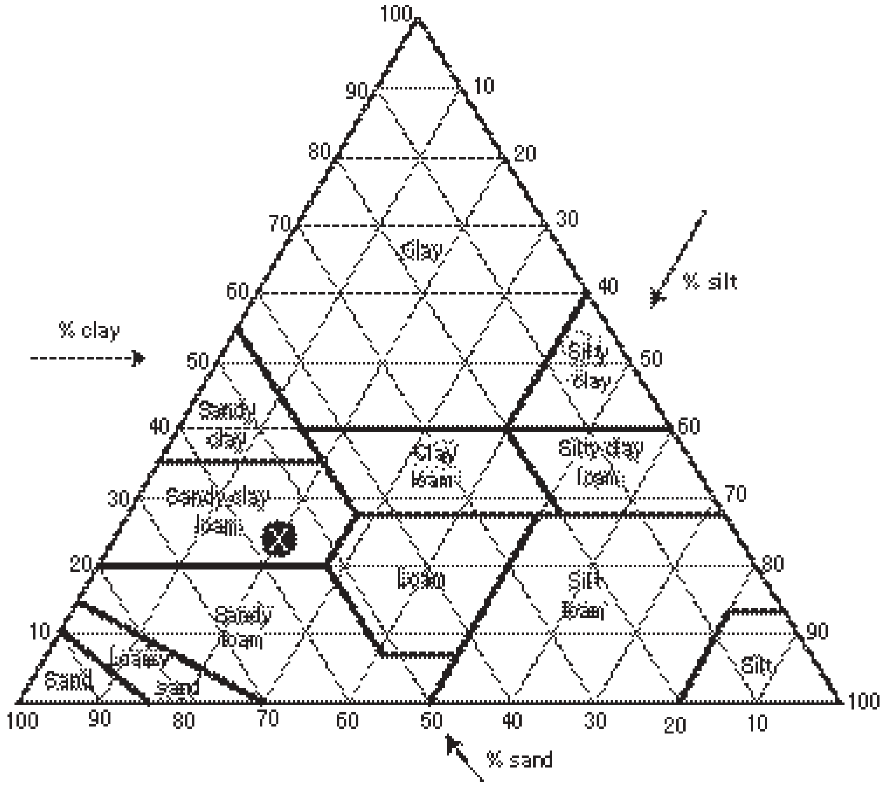
Horizon designation	Description
O	Organic horizons of mineral soils. Horizons: (i) formed or forming in the upper part of mineral soils above the mineral part; (ii) dominated by fresh or partly decomposed organic material. These horizons can be found in mangrove forests and swampy areas. Few soils in the eastern Africa region, therefore, have this horizon.
A	Mineral horizons consisting of: (i) horizons of organic matter accumulation formed or forming at or adjacent to the surface; (ii) horizons that have lost clay, iron or aluminium to the underlying horizons with resultant concentration of quartz or other resistant minerals of sand or silt size; or (iii) horizons dominated by (i) or (ii) above but transitional to an underlying B or C. Most soils in the region are characterized by an A horizon, although in some cases this has been lost or truncated through erosion. This horizon is often damaged through manipulation by man.
B	Horizons which are dominated by an illuvial concentration of silicate clay, iron, aluminium or humus, alone or in combination. The B horizon has more clay than the A horizon and thus appears more compact and dense than the overlying horizon. Most water for plant uptake is stored in the B horizon. This horizon dominates most soils of the region.
C	A mineral horizon or layer, excluding bedrock, that is either like or unlike the material from which the profile is presumed to have formed and is relatively little affected by soil-forming processes.
R	Underlying consolidated bedrock, such as granite, sandstone or limestone.

2.2.3 Soil texture

Soil texture refers to the relative proportion of stone, gravel, sand, silt and clay in a specified quantity of soil. Sand particles are 2.00–0.05 mm in diameter, silt 0.050–0.002 mm and clay <0.002 mm. Soil texture determines soil workability, water-holding capacity, soil structure and nutrient retention. Compared to sandy soils, clay soils hold more water and retain nutrients. Clay particles are lighter than sand particles, and once detached by erosion they are easily transported. Therefore unchecked erosion leads to a loss of soil productivity. Great care should be taken when working on soils that are susceptible to erosion and with low soil-loss tolerance (such as shallow soils on sloping land). The classification of soils according to their texture is usually given in the form of a textural triangle (Figure 2.1).

2.2.4 Soil structure

The arrangement of individual soil peds or aggregates in relation to each other determines the structure of the soil. Soil structure is one of the most important physical properties of a soil. Air and water movement within the soil, aggregate stability and workability largely depend on the type of soil structure. Well-structured soil provides both large and small pores, which are desirable for water uptake and plant growth. The different types of structure are shown in Figure 2.2.



How to use the textural triangle
A textural triangle is used to determine the soil textural name. To describe a soil for which a texture analysis has been done, select the values for clay and sand (or silt) and follow the direction shown by the arrows until the lines intersect. For example, point X represents a sandy clay loam that has 55% sand, 20% silt and 25% clay. Texture can also be determined by 'feel' (see Appendix 2).

Figure 2.1 *Soil textural triangle*

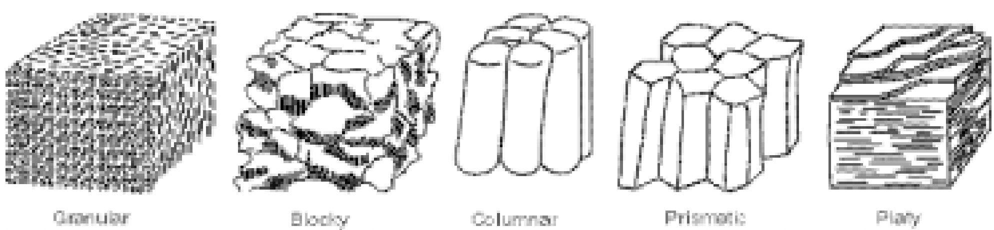


Figure 2.2 *Main types of soil structure*

Soils with a high sand content (>70%) are characterized by a single-grain structure as there are no binding substances holding the particles together. Such a soil cannot hold much water; neither can it retain nutrients due to leaching. Addition of organic matter to the soil improves the structure and increases its capacity to supply nutrients to plant roots.

2.2.5 Water-holding capacity

Water-holding capacity is related to soil texture and structure. Fine-textured soils are able to retain more of the available water than coarse-textured soils. Coarse-textured soils are prone to leaching as they cannot hold nutrients in the absence of clay. However, other factors, such as tillage, also affect the water-storage capacity of a soil. For a soil to hold sufficient water for plant growth, it must have a good structure, which can be attained if the soil has high amounts of organic matter. Good tillage practices also help to retain soil moisture, especially where hardpans and plough soles are regularly broken to improve rainfall infiltration.

2.2.6 Permeability and hydraulic conductivity

Permeability is a measure of the ease with which liquids and gases can pass through the soil. Hydraulic conductivity refers to the ease of passage by water and is related to soil texture and structure. In soils with abrupt horizon changes, the corresponding changes in hydraulic conductivity values can have serious effects on the infiltration and percolation of rainfall, or irrigation water, and on the drainage of excess water through the profile. As a rule of thumb, a horizon with a hydraulic conductivity value less than 10% of that of the overlying layer should be regarded as effectively impermeable. Heavy clay soils have low hydraulic conductivity values compared to light-textured soils. Similarly, soils with good structure have high hydraulic conductivity values. The FAO classification for hydraulic conductivity values is summarized in Table 2.2. Hydraulic conductivity is normally designated as 'K' (and is measured as metres per day or cm per hour).

***Table 2.2** Hydraulic conductivity (K) values*

Hydraulic conductivity (K)		Conductivity class
(m day^{z})	(cm h^{-1})	
<0.2	<0.8	Very slow
0.2–0.5	0.8–2.0	Slow
0.5–1.4	2.0–6.0	Moderate
1.4–1.9	6.0–9.0	Moderately rapid
1.9–3.0	8.0–12.5	Rapid
>30	>12.5	Very rapid

Source: Landon 1991.

Soils with K values below 0.1 m day^{-1} require drainage and sub-soiling to improve soil-water uptake. K values of 0.1–1.0 m day^{-1} are the most critical for drainage design. Above 1.0 m day^{-1}, field drainage is unlikely to be required.

2.2.7 Bulk density and porosity

Bulk density

Bulk density refers to the density of a soil, i.e. the mass of mineral soil divided by the overall volume it occupies (or the weight per unit volume of undisturbed soil). Bulk density measurements are used as indicators of problems of root penetration, soil aeration and water intake in different soil horizons. There is a tendency for bulk density values to rise with depth as the effects of cultivation and organic matter decrease. Even in soils with similar texture, there are usually large differences in bulk density values depending on soil organic matter levels and soil structure. Soils with high organic matter content and good structure have low bulk density, indicating that infiltration rates are high for such soils, while workability is equally good. Bulk density values can vary from 0.96 to 1.65 g cm^{-3} (Table 2.3). High values indicate hindrance to root penetration (see Section 6.3.2).

Table 2.3 *Bulk density and porosity relationships with soil texture*

Texture	Bulk density (g cm^{-3})	Porosity (% volume)
Sand	1.55–1.80	32–42
Sandy loam	1.40–1.60	40–47
Loam	1.35–1.50	43–49
Clay loam	1.30–1.40	47–51
Silty clay	1.25–1.35	49–53
Clay	1.20–1.30	51–55

Source: Landon 1991.

Porosity

Soil porosity is a measure of the total pore space of a given soil. Porosity influences aeration, water movement and root penetration in soils. Soil porosity can be broadly classified in terms of macro- and micropores. The compaction of soils through tillage or other operations increases the micropores and decreases the macropores. This reduces the total pore space, thus increasing bulk density. Compacted soils (with high bulk density) are less aerated, and root penetration is restricted. Rainfall infiltration is also hindered, thus reducing the moisture available to crops.

Figures 2.3 and 2.4 show the results of tests for bulk density and saturated hydraulic conductivity of soil samples from Sakila, Mkonoo and Ngorbob in Arusha, Tanzania. These figures illustrate the presence of hardpans between 20 and 30 cm depth. The hardpan limits water infiltration and root penetration. This reduces crop growth and leads to poor yields.

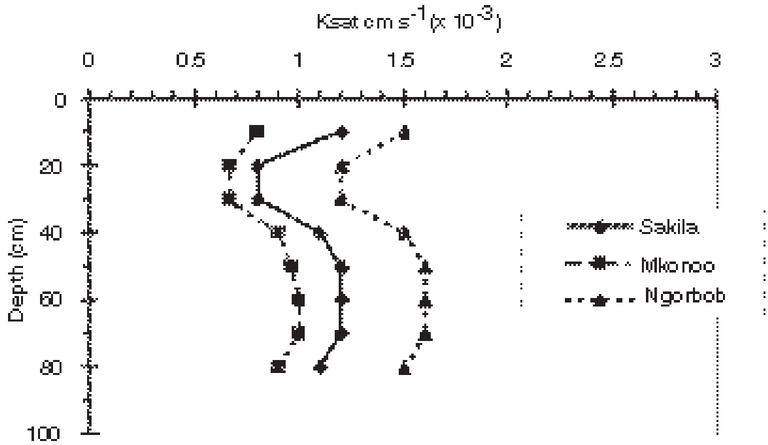
2.2.8 Soil reaction (pH)

Soil reaction is the condition of soil acidity (low pH) or alkalinity (high pH; see Table 2.4). Although there are plants that thrive in acid or alkaline media, most crops perform best in a very slightly acid soil (pH 6.5–6.8). Values of pH less than 5.5 may lead to aluminium toxicity, unavailability of phosphorus (due to fixation) and some of the soil micronutrients such as molybdenum , and reduced biological activity.

Table 2.4 *Describing soils according to pH values*

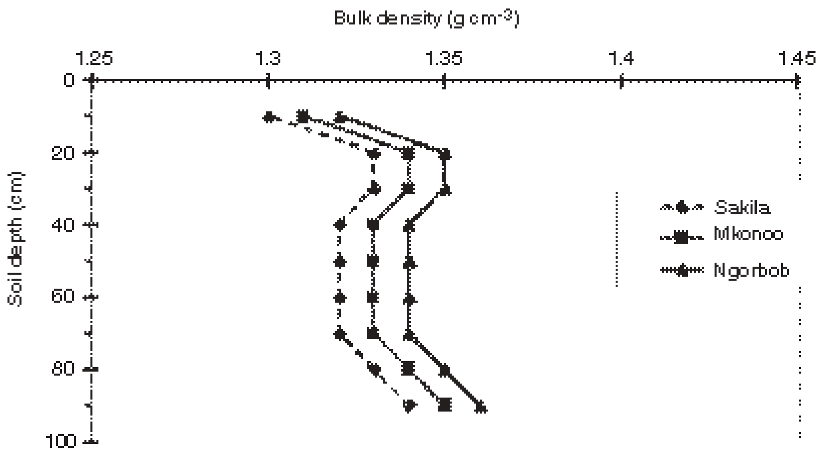
Soil condition	pH value	pH scale
Extremely acid	<4.5	Low pH
Very strongly acid	4.5–5.0	↑
Strongly acid	5.1–5.5	
Medium acid	5.6–6.0	
Slightly acid	6.1–6.5	
Neutral	6.6–7.3	
Mildly alkaline	7.4–7.8	
Moderately alkaline	7.9–8.4	
Strongly alkaline	8.5–9.0	↓
Very strongly alkaline	>9.1	High pH

Source: Kanyanjua et al. 2002.



Source: Mburu et al. 2000.

Figure 2.3 *Saturated hydraulic conductivity (Ksat) for soils from Arusha, Tanzania*



Source: Mburu et al. 2000.

Figure 2.4 *Bulk density for soils from Arusha, Tanzania*

As can be seen in Figure 2.5, at extreme ends are acid soils and alkali or sodic soils. Certain acid soils may show a pH of 3.5 or less, while some alkaline soils may reach a pH near 11.

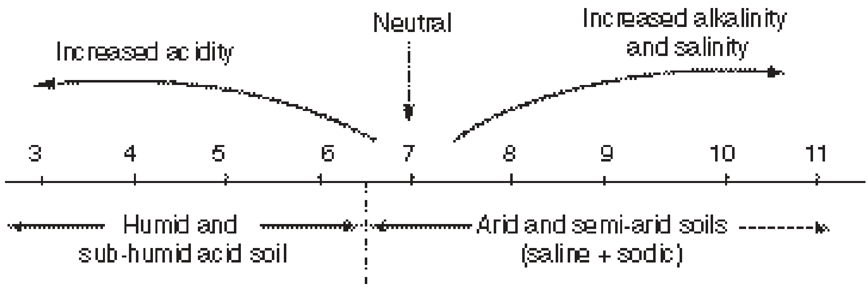


Figure 2.5 *Ranges of soil pH*

For pH values of >8.0, some of the micronutrients and phosphorus become unavailable to the plants, biological activity is reduced and soil becomes saline and/or sodic. Soils with low and high pH are common in high- and low-rainfall areas, respectively. Table 2.5 gives the optimum pH ranges for different types of crops.

Table 2.5 *The pH tolerance limits for different types of crops*

Crop	Optimum pH	Tolerance range
Cereals		
Maize	5.5–7.0	5.0–8.0
Sorghum	5.5–6.5	5.0–8.5
Wheat	6.0–7.0	–
Citrus	5.5–6.5	5.0–8.0
Oil crops		
Groundnut	5.3–6.6	5.0–7.0
Soybean	6.0–7.0	4.5–7.5
Pulses		
Beans, cowpea	6.0–7.0	5.5–7.5
Root crops		
Irish potato	5.0–5.8	4.5–7.0
Vegetables		
Cabbage, onion	–	6.0–7.5
Tomato	–	5.0–7.0

Source: Landon 1991.

Common causes of low pH

Strongly acid soil is found in areas that are intensively leached and badly eroded. Acid soil is also low in basic cations such as Ca, Mg, K and Na. Although some soils are developed from acidic materials, most soil acidity is caused by leaching and continuous use of acidifying fertilizers. As water containing hydrogen cations from various weak acids (such as carbonic and organic acids) moves through the soil, some of the hydrogen cations replace adsorbed exchangeable cations, which are then leached out of the upper horizons to deeper horizons of the profile. Strongly acidic soils are not productive for most crops. In acidic soils, the majority of crops yield less than their potential because of one or more of the following:

- Aluminium and manganese toxicity
- Deficiency of basic cations and molybdenum
- Phosphorus fixation.

The addition of lime raises the soil pH thereby eliminating the major problems of acid soils. On the other hand, some plants, such as tea, thrive in acidic rather than neutral conditions. It is possible to increase soil acidity by applying acid-containing fertilizers. A soil fertility trial involving some 90 farms in Kirinyaga District of Kenya conducted between 1999 and 2001 by Gachene and others (unpublished) showed that soil acidity is a major problem in the high-rainfall zones (Table 2.6).

Table 2.6 *Soil pH for soil fertility trial sites in Kirinyaga District, Kenya*

Agroclimatic zone (ACZ)	No. of farms	pH–water	pH–CaCl
Lower highland zone (LH1) (tea/dairy zone)	10	4.30	3.80
Upper midland zone (UM1) (coffee/tea/dairy zone)	7	4.91	4.30
Upper midland zone (UM2) (maize/coffee zone)	10	5.55	4.97
Upper midland zone (UM3) (marginal coffee)	20	5.93	5.10
Lower midland zone (LM3) (cotton zone)	10	5.98	5.18
Lower midland zone (LM4) (marginal cotton zone)	27	6.63	5.90

Due to the extreme pH conditions in the highland zones, crop yields have dropped drastically. Addition of lime in the trial sites has led to marked improvements in yields.

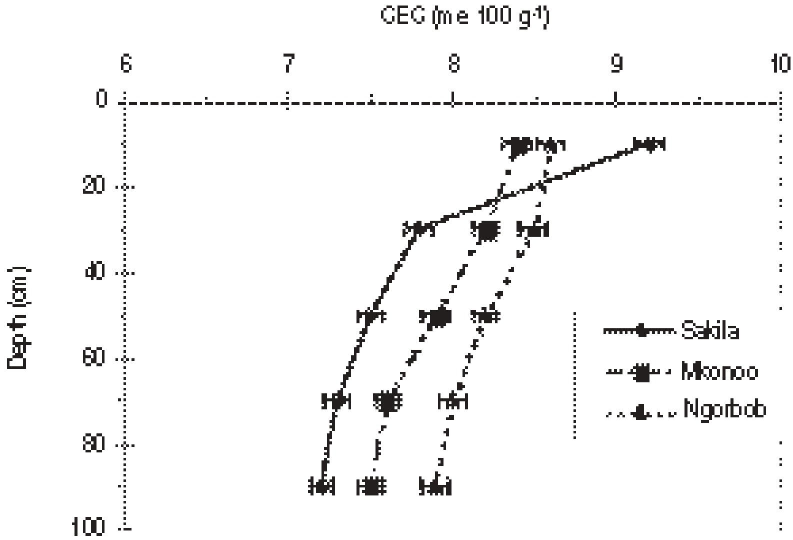
2.2.9 Cation exchange capacity

Cation exchange is the interchange between a cation in solution and another cation on the surface of clay or organic colloids. It indicates the ability of a soil to hold cations such as K and Ca. Cation exchange capacity (CEC) is the sum total of exchangeable cations that a soil can adsorb. For most soils, organic matter is the main component with the greatest CEC. The CEC of soils is affected mainly by the amount and kind of organic matter and clay. Sand and silt contribute little to the CEC of soils.

CEC depends on the texture, type of clay and amount of organic matter in the soil, being highest in clay soils and lowest in sandy soils, with silt being in between. Soils with a CEC of <16 meq 100 g^{-1} soil are considered not to be fertile. Such soils are usually

highly weathered. Fertile soils have a CEC of more than 24 meq 100 g^{-1} soil. Most soils in the eastern Africa region are dominated by kaolinitic types of clay whose CEC values are between 10 and 20 meq 100 g^{-1}. Organic matter has a CEC ranging between 200 and 300 meq 100 g^{-1} soil. This shows the importance of soil organic matter.

As an example, the results of CEC analysis of soil samples from Arusha, Tanzania (Sakila, Mkonoo and Ngorbob villages), as given in Figure 2.6, indicate that the CEC of all the samples was very low. This is a reflection of low fertility of the soils as a result of high rates of erosion. Addition of organic matter to the soil would increase the CEC and hence improve the soil fertility.



Source: Mburu et al. 2000.

Figure 2.6 *Cation exchange capacity (CEC) for soils from Arusha, Tanzania*

2.2.10 Electrical conductivity and exchangeable sodium percentage

Electrical conductivity

In order to assess the salinity hazard of a soil, electrical conductivity (EC) measurements are carried out. The salt content can thus be estimated from the electrical conductivity of a soil suspension in distilled water. This is expressed in millimhos cm^{-1} (mmhos cm^{-1}). In laboratory analysis, a saturated soil paste is used (ECe = electrical conductivity of extract). The classification shown in Table 2.7 is used for ECe.

Table 2.7 *ECe and salinity classification.*

ECe (mmhos cm^{-1})	Salinity class
0–4	Non-saline
4–8	Slightly saline
8–15	Moderately saline
<15	Strongly saline

Source: Landon 1991.

Exchangeable sodium percentage

Exchangeable sodium percentage (ESP) is the degree of saturation of sodium in the soil exchange complex. High ESP values are reflected in soils usually containing significant amounts of exchangeable sodium and having pH values above 8.5 (Table 2.8). Under wet conditions, soils high in ESP will disperse, and this will have negative effects on soil aeration, infiltration and permeability.

Table 2.8 *Soil sodicity classification*

ESP (%)	Sodicity
0–6	Non-sodic
6–10	Slightly sodic
10–15	Moderately sodic
>15	Strongly sodic

Source: Landon 1991.

The influence of ECe, ESP and pH on crop growth is summarized in Table 2.9. The classification and other management aspects of soils with salinity and sodicity problems are discussed in Section 2.5.

Table 2.9 *Influence of ECe, ESP and pH on crop growth*

ECe (mmhos cm^{-1})	ESP (%)	pH	Remarks
0–4	<6	<8.5	No injury to crop
4–8	6–15	8.5	Maize, rice, soybean slightly affected
8–15	15–30	8.5–9.0	Only cotton and barley may perform well
15–30	30–50	9.0–9.5	All crops strongly affected. Only a few species can survive

Source: Landon 1991.

2.2.11 Soil organic matter

Soil organic matter is important in physical, chemical and biological soil processes. A decrease in organic matter content is an indicator of a lowered soil quality. This decline can be checked by leaving and incorporating crop residues in the soil and by adding organic manures to the soil. The removal of crop residues, as is commonly practised in many parts of sub-Saharan Africa, hastens the rate of organic matter decline. The rate of organic matter decline is also higher in semi-arid environments due to high rates of decomposition and mineralization.

Organic matter in the soil enhances it in many ways. The organic matter builds and improves soil structure, thereby improving soil drainage, infiltration of water into the soil, aeration and water-holding capacity. The improved soil structure results in well-developed plant root systems and healthier, more disease-resistant crops. Soil organic matter increases the cation exchange capacity of a soil and provides a neutralizing or buffering effect on soil pH (preventing rapid changes in pH). Soils that are high in

organic matter content have water-stable aggregates that bind soil particles together and are resistant to being broken down by the impact of raindrops.

One of the indicators of high-quality manure is the carbon:nitrogen ratio (C:N ratio). A high ratio means low quality (less nitrogen due to the slow rate of decomposition and mineralization). For example, maize stover with an average C:N ratio of 60:1 takes a long time to decompose compared to vegetable waste which has a ratio of 12:1 (and therefore very rapid decomposition and faster release of nitrogen). From the previously mentioned example of the 1999–2001 Kenya trial, the farmyard manure (FYM) from Kirinyaga with C:N ratio of 10:1 is seen to be of good quality (Table 2.10). Note the high pH values of the FYM compared to soil samples from the same area (Table 2.6). The FYM is also well supplied with essential plant nutrients. Hence, application of manure can reduce soil acidity (that is, raise soil pH). Manure has multiple beneficial effects on the soil, and it is always recommended for increased land productivity.

***Table 2.10** Farmyard manure analysis data for soil fertility trial sites in Kirinyaga District, Kenya*

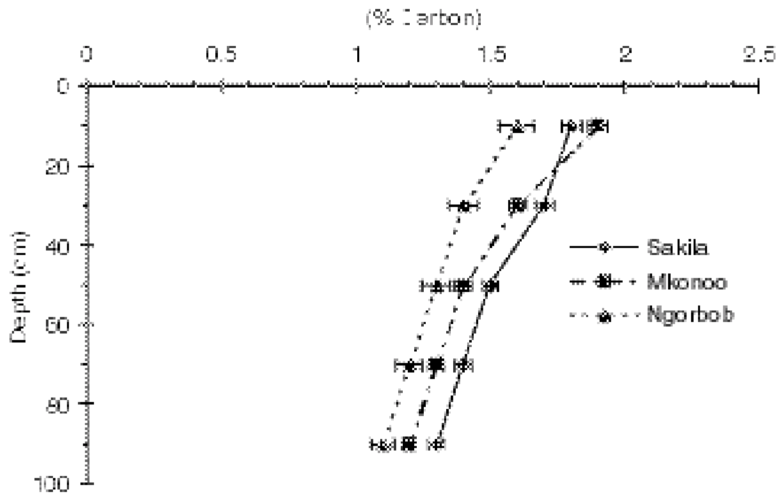
ACZ	No. of samples	pH–water	pH–CaCl	% N	% C	C:N ratio	K/meq
LH1	10	7.34	6.28	1.30	13.27	10:1	47.82
UM1	7	7.90	7.40	1.10	11.96	10:1	54.44
UM2	10	7.85	7.11	1.09	10.81	10:1	34.77
UM3	20	8.24	7.57	1.10	10.57	10:1	58.61
LM3	10	9.39	8.72	1.33	13.37	10:1	70.52
LM4	27	8.29	7.30	1.23	12.70	10:1	59.06

Notes: ACZ = agroclimatic zone. For key to ACZ column see Table 2.6.

During field investigations in the region, it has been noted that many farmers do not apply FYM on their farms, and often it is used as household fuel (Plate 2). Often those who use manure lack proper collection and storage facilities and general management skills. Some farmers argue that manure increases the problem of weeds. The use of manure will, of course, require improved weed control, especially early weeding to prevent an increase in weed seeds in the soil. But weeds are a minor disadvantage compared with the likely benefits of significant increases in crop yields.

Plate 2: Manure preserved for use as fuel, Amhara Region, Ethiopia

Soils sampled in the three areas in Arusha, Tanzania (Figure 2.7) had moderate amounts of organic matter (soils in semi-arid areas often have organic carbon contents below 1%, while a level above 2% is considered adequate). Organic matter is the major agent that stimulates the formation and stabilization of granular and crumb-like soil aggregates. As organic residues decompose, gels and other viscous microbial products, along with associated bacteria and fungi, encourage crumb-structure formation.



Source: Mburu et al. 2000.

Figure 2.7 *Percent organic carbon for soils from Arusha, Tanzania*

Manure stimulates growth in populations of soil micro-organisms, and these interact to limit the development or activity of pathogenic bacteria or fungi, while macro-organisms like chafer grubs feed on a variety of soil flora and fauna. Soil organic matter also stores and supplies nutrients and improves the workability of the soil. Organic materials and agronomic practices that can be used to increase soil organic matter are discussed in Chapter 3. Some sources of organic matter are shown in Table 2.11.

Table 2.11 *Sources of organic matter*

Source and/or type of organic matter	Constraints
FYM	Usually available only in small quantities; expensive to purchase; bulky to transport; high labour requirements during application
Green manure cover crops	Takes land that is needed for food crops (farmers may view this as a loss of a cropping season)
Crop residues	Not returned to the soil (used as fodder or fuel); termite attacks
Urban wastes or garbage	Might have heavy-metal and other poisonous contamination, or harmful bacteria; limited application due to cultural restrictions on use of human waste
Kitchen wastes	Quantity low
Shrub or tree cuttings and prunings	High labour requirement; trees/shrubs compete with arable crops; inadequate amounts

Soil flora and fauna

Soil supports a wide range of macro- and micro-organisms. These play a major role in nutrient cycling, addition of organic matter, e.g. through litter fall, decomposition of organic matter, soil aeration, soil structure, and general soil admixturing. Others, like *Rhizobium* bacteria, are useful in assisting legume crops to fix nitrogen from the air, which is then utilized by the plants. Earthworms and other macro-organisms have an important role to play in the creation of humus from organic residues (see Section 3.2.8).

2.3 PLANT NUTRIENT ELEMENTS IN THE SOIL

Crops, like all other living things, require nourishment in order to grow, reproduce and survive. In order for crops to give the highest possible yields, each plant nutrient element that is essential for its growth must be available in optimum amounts. The first increments of the nutrients in short supply give the greatest yield increases. This is well illustrated with the general (growth) response curve in Figure 2.8.

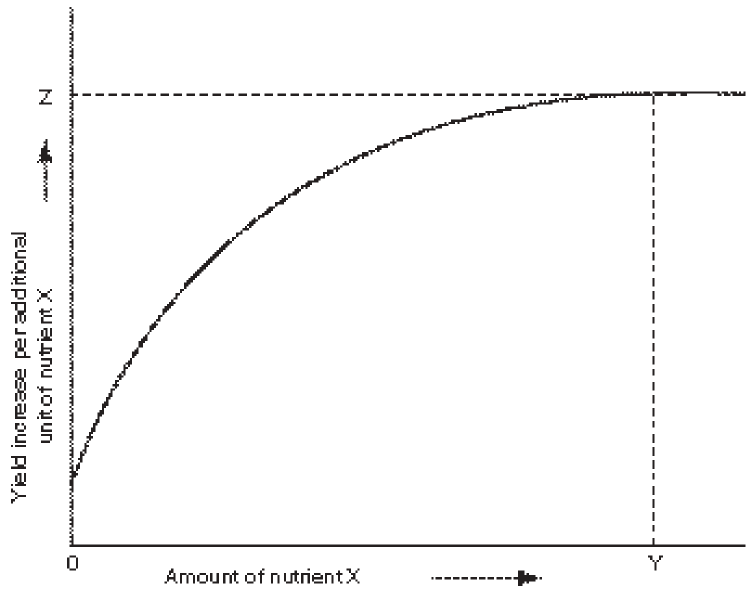


Figure 2.8 *The general growth response curve*

Note: From the growth response curve, maximum yield is the yield the crop can achieve from the addition of enough nutrient X given that all other factors and growth conditions are not limiting. As the maximum yield is approached (quantity Z), further increases of the nutrient X bring only small yield increases. Addition of the nutrient beyond amount Y will not raise yields above the level Z. There is luxurious consumption beyond point Y without any additional benefits in yields.

The types and quantities of nutrients must be correctly balanced and applied in order that the crop is vigorous and healthy. Different crops require different types and amounts of nutrients. Major or macro-elements are needed in large quantities, while trace or minor or micro-elements are required in small quantities. The elements must be present in forms usable by plants and in concentrations that are optimal for plant growth. However, some of the nutrients, when present in excess amounts are toxic to the plant, for example manganese, aluminium and sulphur.

Seventeen elements have been found to be essential for plant growth. The elements as listed below, are categorized into macro- and micro- (trace) elements.

Macro-elements	
Carbon (C), Hydrogen (H_2), Oxygen (O)	Derived from air and water
Nitrogen (N), Phosphorus (P), Potassium (K), Calcium (Ca)	Derived from soil solids, and some from air
Magnesium (Mg), Sulphur (S)	Derived from soil solids
Trace elements	
Iron (Fe), Molybdenum (Mo), Copper (Cu), Zinc (Zn), Manganese (Mn), Cobalt (Co), Boron (Bo), Chlorine (Cl)	Derived from soil solids

The macronutrient elements N, P and K are required in large quantities, while other elements (micronutrients) are required in very small quantities. The secondary nutrients S, Ca and Mg are required in intermediate quantities. Section 2.4.2 describes symptoms of nutrient deficiencies.

2.4 DETERMINING THE FERTILITY STATUS OF A SOIL AND THE NUTRIENT NEEDS OF A CROP

Plant nutrient sources include soil reserves (from weathering of rocks), crop residues, as well as organic and inorganic fertilizers that are added to the soil during the growing season. In order to make a decision on which type of fertilizer to use, a number of observations or tests must be carried out. Farmers have their own ways of assessing fertility, as indicated below, and observations on crop growth will often indicate which nutrients are deficient. More accurate information can be obtained from soil and plant tissues tests. How these should be carried out is indicated in Section 2.4.5.

2.4.1 Farmers' observations on soil fertility and plant growth

The proliferation and dominance of a particular grass, weed or shrub can indicate the soil's fertility status. For example, the weed striga thrives in infertile soils. It is suppressed by application of organic and inorganic fertilizers. The visual (field) observation method, however, does not quantify the amount of nutrient in the soil. It is too general and does not tell us which nutrients are in the soil and in what quantities or proportions. Generally, dark-coloured soils are assumed to be fertile and high in soil organic matter. Soils with a loamy texture are also assumed to be more fertile than sandy soils. Farmers have their own ways of judging the fertility status of soils, as seen in the example in Table 2.12.

Table 2.12 *Farmers' assessment of soil fertility, Kirinyaga District, Kenya (% of farmer respondents)*

Indicators of good, fertile soil	%	Indicators of infertile soil	%
Good yields	53	Low yields	40
Healthy, vigorous, green crops	50	Stunted, poor and weak crops	48
Nature of soil: colour, depth	44	Yellow colour of crops and weeds	10
Presence of certain trees and shrubs	3	Certain weeds, especially hardy grasses	48
Heavy pest infestation	3	Nature of soil, colour, stoniness	52
Crops withstand drought	2	Presence of certain trees and shrubs	2
Weeds grow well	11	Erosion signs	1
Presence of certain weeds,		Crop and weed failure	18
e.g. *Commelina* sp., *Galinsoga* sp.	48	Crops wither quickly in drought periods	100

Farmers also listed some 36 possible causes of soil fertility decline. The first six are given in Table 2.13.

Table 2.13 *Causes of soil fertility decline according to farmers*

Causes of soil fertility decline	Frequency	%
Non-application of manure	50	56
Soil erosion	44	49
Continuous cropping	37	41
No crop rotation	19	21
Harvested crop and stover removal (nutrient mining)	6	7
Lack of fertilizer and manure	5	6

Cassava, grass, loquat, Napier grass, sweet potato and trees were some of the 24 types of crops mentioned as being grown on infertile soils by the Kirinyaga farmers.

2.4.2 General symptoms of plant nutrient deficiency

Observing a growing crop to identify nutrient deficiencies

Symptoms observed in a plant could be a result of nutrient deficiencies, diseases or pest damage. It is, therefore, important to start with a close examination of the plant leaves, stem and roots to check for insects or signs of diseases. There are some general clues to nutrient deficiencies. Visual observations assume that what is deficient in a crop is symptomatic of what is lacking in the soil. Observations are made mostly on the leaves, but sometimes on the stem. A nutrient deficiency is suspected when the plant shows any of the following characteristics:

- Very poor initial growth
- Stunting in early growth
- Restricted or abnormal root growth
- Maturing too early or too late
- Growth markedly different from crops growing close by
- Poor-quality products: appearance, taste, firmness, moisture content
- Leaf symptoms that may point to deficiencies of specific nutrients.

Terms used to describe nutrient deficiency conditions

Chlorosis

Chlorosis is the generalized yellowing of leaves caused by the direct or indirect effect of the deficiency on the process of photosynthesis. When photosynthesis and chlorophyll (the green pigment) are reduced, other coloured compounds can then become dominant and more visible. The leaves turn white if there is a drastic reduction of chlorophyll.

Necrosis

This is the death of the entire plant or parts of the plant that are affected by the deficiency. The affected tissue becomes brown and dies.

Inter-veinal chlorosis

In inter-veinal chlorosis the leaves become yellow in between the veins, but the veins themselves remain green, in grasses forming coloured stripes.

Firing

Firing means yellowing followed by rapid death of the lower leaves of the plant starting from the bottom (like the effect of fire).

2.4.3 Specific symptoms of nutrient deficiencies by observation

It should be noted that visual observation of deficiency symptoms is done when the damage to the crop has already occurred. Nevertheless, observations should assist the farmer when planning the nutrient requirements of the subsequent crops. A summary of information on nutrient deficiency symptoms is given in Table 2.14.

Nitrogen (N)

Nitrogen is an essential component of amino acids, and thus of all proteins, and is needed for all cell division and reproduction. Plants that are deficient in N are generally stunted and very light green or yellowish (chlorotic) (Plates 3 and 4). Chlorosis of the entire leaf blade is followed by necrosis and leaf drop.

Plate 3: N deficiency in bean leaves

Plate 4: N deficiency in maize (right of picture)

This yellowing usually appears first on the lower leaves because N in the lower (older) leaves is translocated to new growing areas of the plant in case of insufficient supplies from the roots. The lower leaves may drop off before the topmost leaves have lost their intense green colour. However, this should not be confused with yellowing due to lack of sunlight needed for photosynthesis. Plant growth is reduced and/or stunted.

Phosphorus (P)

Phosphorus is needed for cell division and for reproduction, and therefore deficiency causes slow growth. P promotes root establishment and formation as well as flowering. P deficiency is manifested as a purple pigment or dull-bronzed leaves (especially on the underside of lower leaves), petioles and stems (Plate 5). The older leaves are affected first because P tends to be translocated from the older to the new-growth leaves when in short supply. Not all crops show this purpling: some examples are cotton, soybean and potato. However, all crops show signs of stunted growth and delayed maturity, and fruit often drops prematurely. Flowering and fruiting are limited and plants are slow to form new roots and establish. Seedlings may not develop past emergence. Cotyledons may yellow, shrivel and fall off.

Plate 5: Phosphorus deficiency in young maize leaves

Potassium (K)

Potassium increases the plant's vigour and disease resistance, producing strong, stiff stems. K also promotes production of sugar, starches and oils, increases the size of grains and fruits and improves the overall quality of the crop. Potassium deficiency results in reduced vigour, increased disease problems, as well as small fruit with thin weak skins. Deficient leaves are usually curled and show a light green to a 'burned' or 'scorched' effect along the leaf margins and tips. Older leaves show deficiency symptoms first (Plate 6).

In severe cases, the dead areas may fall out leaving ragged edges. In maize and other grasses, 'firing' starts at the tips of leaves and proceeds down to the leaf stalks, leaving the midribs green. Plants tend to bend and break over and lodge due to weak stems or leaf stalks, and also show general stunted growth. Seeds and fruits become small and shrivelled.

Plate 6: Potassium deficiency in mango leaves

Calcium (Ca)

Calcium is a part of cell walls and regulates cell-wall construction. Cell walls give plant cells their structural strength. Since Ca is relatively abundant in soils, it is usually difficult to notice a deficiency unless critical limits are attained. Unlike P and K, Ca is immobile, and therefore deficiency signs are first seen in young leaves and roots, which become crooked, wrinkled, short and bunched together. The stems become weak and, due to N concentration in the young leaves, become dark green initially. Deficiency may show as sudden collapse of young leaf petioles or stems, followed by leaf death. In extreme cases, the leaves of terminal buds curl, turn light green then die. When Ca deficiency is moderate to acute, plants have grossly deformed terminal leaves and branches. Leaves may show spotted or necrotic areas near the midrib. In tomato fruit, the deficiency is manifested as 'blossom end rot'. Ca deficiency will also show up as weak stems as well as a reduction of any new growth from the growing points.

Magnesium (Mg)

Magnesium is a key element in chlorophyll, and is therefore essential in the photosynthesis process. Deficiency symptoms appear on older leaves in the latter part of the growing season. Since Mg is a constituent of chlorophyll, deficiency results in the yellowing (chlorosis) of leaves, initially between the veins, and then the leaves turn reddish purple as deficiency becomes severe. Necrosis may develop between the veins or along leaf margins or tips. Curling or dropping of leaves may also occur. Stem strength is influenced by Mg.

Sulphur (S)

Sulphur occurs in certain amino acids and all proteins. It is a part of the flavour compounds in mustard and plants in the onion family. Sulphur deficiency symptoms are somewhat similar to those of nitrogen. However, with diminishing supply of S, small, spindly and yellowish younger leaves stand in contrast to the normal older leaves.

Zinc (Zn)

In zinc-deficient plants, terminal growth is affected first, causing severe retardation of leaf and shoot growth and resulting in small leaves, short internodes, rosettes of leaves or excessive side branches. Inter-veinal chlorosis is typical, and leaves may also become bronzed or develop rusty-brown flecks. Zn deficiency is easily recognizable in maize within two weeks of emergence. The upper leaves show a broad band of yellowing on either or both sides of the midrib. As deficiency becomes severe, leaf edges crinkle and reddish purple pigment is noticed. Stunting and shortening of the internodes can also be noticed. Small, thin, yellow leaves, as well as low yields, are symptoms of Zn deficiencies.

Manganese (Mn)

Manganese is crucial in the plant's enzyme systems, and for the synthesis of chlorophyll and assimilation of nitrate. Deficiency symptoms are similar to those of Fe in the early stages. Manganese deficiency is manifested by a mottled chlorotic appearance on the leaves (brownish, black or grey spots next to the veins), and growth is stunted. There may be patches with stunted growth and pale green to yellow foliage within an apparently healthy crop. In the more acute stages of Mn deficiency, light green parts may become white. Necrosis develops near the edges and tips of older leaves and extends to the base, causing leaf death and shedding of leaves. Twig growth is also reduced in most fruit crops.

Boron (Bo)

Boron affects the absorption of other nutrients and is important in sugar transport within the plant. It also affects the germination of the pollen tube once the pollen grains land on the stigma. Without this germination, the pollen is not available, seeds are not fertilized and fruits abort. In Bo deficiency, terminal growth shows rosetting, dieback, discoloration and failure to elongate. Leaves may curl, wrinkle, thicken or become brittle. Petioles or stems may be corky, cracked or show water-soaked dead areas. Fleshy parts of fruits, tubers or roots may show brown flecks, necrosis, cracks and dry rot. Multiple buds may develop with a lack of Bo, leaves are small, and heart rot and corkiness can develop.

Molybdenum (Mo)

Molybdenum helps the plant use nitrogen. Molybdenum is also essential for N fixation by N-fixing bacteria in legumes. Plants lacking sufficient Mo become N deficient. Pale green leaves have rolled or cupped margins (leaves may fail to unroll). Tubers may fail to develop, and seeds or glumes of grains do not fill out. The symptom is easily noticeable in the cabbage/brassica group where leaves become cup-shaped presenting a rolled appearance, then twist in later stages. Chlorosis is also noticed.

Chlorine (Cl)

Chlorine is present in plants in small quantities and takes part in the photosynthetic reactions in which oxygen is liberated. It is seldom deficient under natural conditions. Chlorosis, then wilting, and death of leaves are some of the signs of deficiency.

Table 2.14 *Summary of various nutrient deficiencies by observation*

Description of condition	Nutrient deficiency suspected
The whole leaf blade is chlorotic (and chlorotic foliage is the dominant symptom)	• Nitrogen if only the lower leaves are chlorotic, followed by necrosis and leaf drop • Sulphur if all leaves (young and old) are chlorotic
Inter-veinal chlorosis of leaves (where chlorotic foliage is the dominant symptom)	• Magnesium where only the recently mature or older leaves have inter-veinal chlorosis • Iron if only the younger leaves exhibit inter-veinal chlorosis, and if this is the only symptom • Manganese if chlorotic foliage is the dominant symptom, inter-veinal chlorosis on younger leaves, and grey or tan necrotic spots in chlorotic areas • Copper if the younger leaves have *inter-veinal* chlorosis, the tips and lobes of leaves remain green followed by *veinal* chlorosis, and then the whole leaf blade rapidly becomes chlorotic, and if this is the dominant symptom • Zinc if the dominant symptom is chlorotic foliage; young leaves are very small (sometimes missing leaf blades altogether), and internodes are short giving a rosette appearance
Leaf chlorosis not dominant. Symptoms appear at base of plant	• Phosphorus where initially all leaves are dark green followed by stunted growth and purple colouration developing particularly in older leaves • Potassium if the margins of older leaves become chlorotic and then burn (sometimes small chlorotic spots progressing to necrosis appear scattered on older leaves)
When leaf chlorosis is not the dominant symptom, and symptoms appear at top of plant	• Boron where terminal buds die, giving rise to lateral vegetative shoots; younger leaves become very thick, leathery and chlorotic; rust colour, cracks and corking occur on young stems, petioles and flower stalks; young leaves are crinkled • Calcium if margins of young leaves fail to form, sometimes yielding long thin leaves; growing points fail to develop leaving a blunt end; light green colour or uneven chlorosis of young tissue; root growth is poor (i.e. roots are short and abnormally thickened)

2.4.4 Mobility of plant nutrients

Nitrogen, phosphorus and potassium (NPK) can move from places where they are stored to places where they are needed within the plant. Deficiencies are therefore noticed first on older leaves. On the other hand, deficiencies of immobile elements are noticed first on younger leaves. Calcium and boron are always plant-immobile nutrients. Sulphur, chlorine, copper, zinc, manganese, iron and molybdenum are intermediate in plant mobility (see Table 2.14). Under certain circumstances the intermediate elements are mobile. Under good nitrogen availability, these elements are mostly immobile.

Soil and plant tissue analysis help to give a more accurate assessment of the status of the available or deficient plant nutrients than mere observation of the plants. Hence, such an analysis provides a good guide to the farmer for the wise and efficient use of fertilizers or soil amendments. It is recommended, therefore, that farmers should have their soils evaluated every four years. In order to get useful recommendations from the results, however, the soil and plant-tissue sampling techniques must be carried out correctly. Details are given in Section 2.4.5, below. (See also Appendix 6.)

2.4.5 Soil and plant-tissue sampling and testing

Soil sampling

Soil sampling should be carried out one to two months before the beginning of the rains to give time for laboratory analysis, and to allow the farmer to include any new recommendations that result from it in the next planting season.

Planning the activity

Equipment and materials:

- Flat hoe, spade or auger
- Clean plastic basin or pail or clean plastic sheeting (about 0.5 m^2)
- Labels (plain sheets of paper) and a pencil
- Plastic bags big enough for one kilogram of soil
- String for tying sample bags.

Make a diagram of the field concerned showing the position of the separate sampling blocks (see Figure 2.9).

- A diagram of the arrangement of blocks within the total area should be made (indicating approximate length), and each block should be numbered
- If the total area is large, divide it into fields and have a diagram indicating numbered fields and sampling blocks (you can use letters for fields and numbers for the blocks)
- Indicate the slope direction of the field on the sketch.

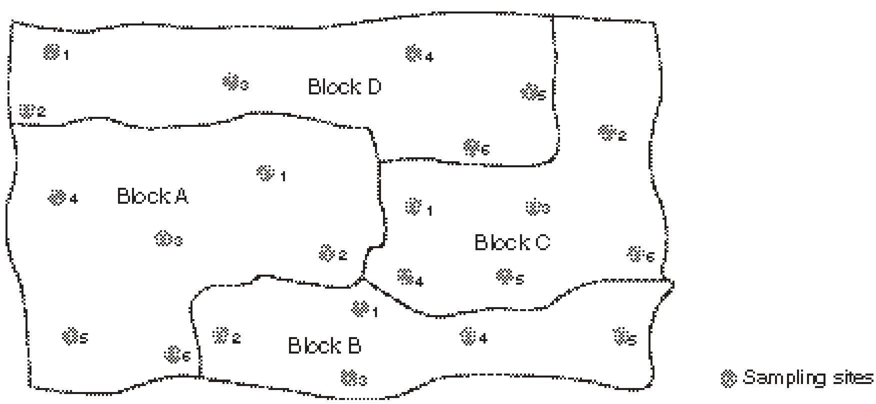


***Figure 2.9** Sketch map showing sampling sites (an example)*

Divide the sample area into equal blocks, or into various sections within which the soil and land appear to be uniform:

- Within a block the soil colour should be the same
- Sandy and clay soils should be sampled separately
- Higher and lower parts of a slope should be sampled as separate blocks
- Fields with different previous treatments or cropping history should be sampled separately
- If the area is large, a farm plan helps to indicate logical blocks to sample separately
- Avoid sampling along footpaths or from anthills, close to tree trunks, crop-residue or leaf-litter heaps, trash and rubbish piles, FYM pits, charcoal burning sites, and other areas which are not representative of the whole farm.

Based on soil differences, crop performance or slope positions, land blocks A, B, C and D are sampled and bulked separately. A number of samples (e.g. 1, 2, 3, 4, 5 and 6 for Block A) are collected and mixed thoroughly. Then one final sample weighing 0.5–1 kg is drawn from the mixture. Other blocks are sampled similarly to obtain separate samples. These final samples are put into well-labelled plastic containers for transfer to the laboratory. After a few weeks, the soil fertility data, interpretations and recommendations will be sent to the farmer for implementation.

Taking the samples

1. Within each block, collect at least five sub-samples. Dig out samples from the rooting zone of the crop. For shallow-rooted crops, soil samples should be taken at 0–30 cm, while a soil depth of 0–40 cm is recommended for deep-rooted crops. The sampling holes should be arranged in a zigzag manner, and in such a way that the five samples represent the whole block. If after taking five samples the block is not fully covered, take more samples.
2. Put the samples from the same depth increment into the basin/pail (or plastic sheeting), break up clods and mix the soil thoroughly (this is the composite sample).
3. Using a small cup, take sub-samples from the composite sample and put them into a plastic bag. The total sample should be about 1 kg; at least 500 g of soil will be sufficient for laboratory analysis.
4. Using a pencil, write the field and block numbers on a label and put it inside the bag. Leave the bag in the block until all the blocks are sampled.
5. Move to another block and repeat the steps above.
6. When all the units have been sampled, the samples are collected from each block, following the diagram and checking that each sample has a label matching the diagram.

Sending samples

- Samples should be sent to the nearest laboratory for analysis soon after sampling.
- If for some reason the samples cannot be sent immediately, then store the bags in a safe place. The bags should be always closed to avoid any contamination.
- If the plastic bags used are not strong enough, double them up for transportation.

Indicate the following information:

1. Name of the farmer and location of the farm (e.g. village, location, ward, county, district)
2. Topographic position of the farm (e.g. hilltop, upper slope, lower slope, valley). Include this information on the field diagram
3. History of land use for the previous five years. What were the crops grown, and any soil amendments applied. For example, was manure or fertilizer applied, if so what and when? Were crop residues removed after each crop? If not, what happened to the residues?
4. Indicate the crops for which recommendations are required.

Note that poorly collected and wrongly labelled soil samples will give wrong information on the analysis!

Plant-tissue sampling and analysis

Plant-tissue analysis is the determination, usually by chemical analysis, of the amount of each essential element (or nutrient) in an oven-dry sample of plant material taken from a nominated part of the crop plant at a specified time in the crop cycle. This plant analysis complements soil-sample analysis. The concentration of nutrients in plant tissue depends on the plant part sampled and the time of sampling (the time of day).

Plant analysis is useful for determining the nutritional status of deep-rooted crops, e.g. fruit trees, where soil samples would otherwise be difficult to obtain; diagnosing the causes of poor crop growth; evaluating the effectiveness of fertilizers; monitoring the nutrient status of crops throughout the growing season; and understanding and incorporating the factors that are important for the quality of many crops.

Generally, a young but mature leaf is selected for sampling. The sample should contain material from as many plants as possible to provide a sufficient amount for analysis (weight of sample to be 1 kg fresh weight). Table 2.15 shows the sampling techniques for some important crops, while the Appendix 6 table can be used as a general guide for assessing the critical nutrient levels once the tissue analysis has been done.

Caution: Do not sample diseased plants, or plants that have recently been sprayed with chemicals. This will give wrong results!

Table 2.15 *Plant part to be analysed and timing of sampling*

Crop	Plant part	Timing
Cereals		
Maize	Blade opposite and below the cob	At silking
Rice	Upper leaves	Before flowering
Wheat, barley, oats	Whole plant from the base of the stem (above the ground)	Before flowering
Root crops		
Cassava	4th and 5th youngest leaves	4 months after planting
Irish potato	Fully developed leaves	At flowering
Sweet potato	Youngest mature leaf	At mid-crop period
Yam	Leaf with petiole	3rd month after planting
Food legumes		
Beans	Fully developed leaves	At flowering
Cowpea	Whole shoot	At early flowering
Groundnut	Fully developed leaves	At flowering
Soybean	Upper fully developed leaves	At flowering
Vegetables		
Carrot	Whole shoot	At mid-crop period
Cucumber	Fully developed leaves	At flowering
Eggplant	5th youngest leaf	60 days after planting
Okra	Fully developed leaves	15 weeks after planting
Onion	Youngest mature blade	At mid-crop period
Sweet pepper	Fully developed leaves	At mid-crop period
Sweet corn	5th leaf from tips	At mid-crop period
Tomato	Fully developed leaves	At fruit set
Fruit crops		
Avocado	Fully developed leaves	At crop flush
Banana	Strips of young, fully developed leaf blades	During active growth
Mango	5th leaf from base of current flush	After harvest
Orange	Fully developed leaves of young branches	Productive trees
Pawpaw	Petiole of youngest mature leaf	At flowering
Pineapple	Youngest mature leaf	At 6, 3 and 1 month prior to flower induction
Watermelon	Young fully developed leaves	At mid-crop period
Tree crops		
Cocoa	Young fully developed leaves	Productive trees
Clove	Young mature trees	Productive trees
Coconut	14th leaf (counting from the first fully opened leaf)	Productive trees
Coffee	Fully developed leaves on branches carrying cherries	Before application of fertilizers
Tea	Two leaves plus buds	At plucking
Cash crops		
Sugar cane	Leaf	3–6 months after planting
Tobacco	Fully developed leaves	At mid-crop period
Spices		
Chillie	Young mature leaves	Early fruiting
Pepper	Young fully developed leaves	At mid-crop period
Fodder crops		
Grass	Whole shoot above 5 cm	At first flowering
Legumes	Whole shoot	At flowering

Source: Dierolf et al. 2001.

2.5 PROBLEM SOILS: OCCURRENCE, CHARACTERISTICS AND MANAGEMENT

This section provides an overview of the soil resources in the eastern Africa region with special emphasis on problem soils. The variation in geology (parent material), coupled with variation in relief and climate have resulted in the formation of a wide range of soils in the region, with accompanying variations in constraints to crop production. Thus, when planning for sustainability, it is essential that the distribution, extent, limitations and potentials of different soil types be appreciated. The soil resources vary greatly. They range from sandy to clayey, shallow to very deep and low to high fertility. Most of these soils, however, have serious constraints. The problem soils described in this section are those with salinity, sodicity, acidity, drainage and fertility problems.

2.5.1 Soils with salinity and/or sodicity problems

Occurrence

A substantial proportion of the eastern Africa region's arid and semi-arid soils are either saline or sodic, or both. They are generally found on flat to very gently undulating topography. The weathering of primary minerals is the indirect source of most of the soluble salts. Ocean, surface and groundwater may also be the main source of soluble salts when they are used for irrigation.

Salinization is the accumulation of soluble salts within the soil profile, whether by natural processes or resulting from improper irrigation. Sodicity (alkalization) is brought about by prolonged or repeated saturation with water in which sodium predominates over the other cations.

Soils classified as Solonchaks have salinity problems, while those classified as Solonetz have sodicity problems.

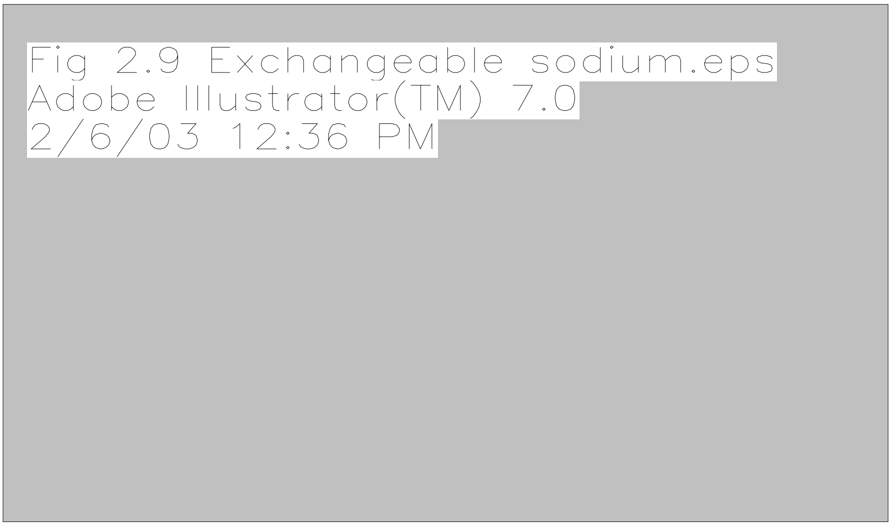
Characteristics of a saline soil profile

A saline soil profile has a pH below 8.5, and often has white salt crystals (which can be seen precipitated on the sides of the profile pit), or otherwise a white salt crust covering the ground, or a very loose 'fluffy' surface caused by the growth of long needle-like crystals of sodium sulphate.

Characteristics of a sodic soil profile

Sodic soils have an exchangeable sodium percentage exceeding 15, while the pH ranges from 8.5 to 10.0. These soils also have a thin, coarse-textured A-horizon (topsoil) from which clay has been eluviated (removed) to the underlying horizons. The A horizon overlies a compact, heavy-textured B horizon (sub-soil) because of clay eluviation (movement) from the topsoil to the sub-soil. The accumulation of sodium ions in the soil has a negative effect on the soil structure. This results in dispersion of clay colloids and destroys the soil structure.

The following is an example. The concentration of sodium ions in soils from Mkonoo and Ngorbob villages in Arusha, Tanzania, was found to increase with depth (Figure 2.10). These are the two areas where serious tunnel erosion was noted. The tunnels quickly develop into gullies that are difficult to control (Plate 7). The high level of sodium ions causes dispersion of clay colloids, which leads to the collapse of the soil structure. The situation is especially critical where water-harvesting systems may be planned by constructing water pans or ponds. In Ngorbob there were already a number of small water ponds constructed by manual excavation. There was high seepage loss through tunnels. Such structures need lining either with synthetic material or dressing the floor with stable soil imported from outside the area.



Source: Mburu et al. 2000.

Figure 2.10 *Exchangeable sodium (me/100 g) for soils from Arusha, Tanzania*

Plate 7: Subsidence caused by underground erosion (piping or tunnelling)

Plate 8: Gullies in sodic soils

Note that due to poor soil structure, sodic soils are characterized by gullies, which are hard to reclaim (Plate 8). Typically there is a columnar structure with rounded tops in the B horizon (Plate 9). This structure is very unstable and collapses upon wetting. Sodic soils have low permeability due to a heavy textured B horizon.

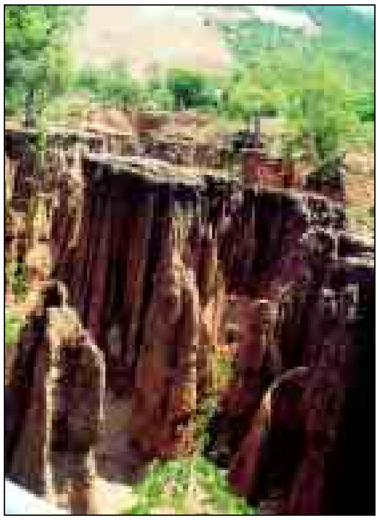


Plate 9: Columnar structure in sodic soils

Use and management of saline and sodic soils

A high level of soluble salts and/or exchangeable sodium in the soil is toxic for some species of plants, and it also interferes with the structure of the soil, thus impeding root development. Phosphorus availability to the plant is also reduced.

Saline soils can be reclaimed by leaching out the excess soluble salts. Sodic soils can be reclaimed by use of organic matter (FYM and composts) or by use of chemicals to neutralize the soil reaction, to react with free soda (Na_2CO_3) and to replace exchangeable sodium by calcium. Gypsum is most commonly used for this purpose. It is always advisable to leave saline or sodic soils under natural vegetation as it is expensive to reclaim them for crop production.

2.5.2 Soils with acidity problems

Soils of the highland and mountainous areas in eastern Africa often have acidity problems. They are found in high-rainfall areas, especially in the coffee and tea/pyrethrum zones, for instance on the slopes of Mt. Kenya and the Aberdare Mountains in central Kenya, and the high-altitude areas of Arusha and Moshi on the slopes of Mts. Kilimanjaro and Meru in Tanzania, and parts of Eastern Province, Zambia. The major soils found in the highlands and mountainous areas of eastern and southern Africa with acidity problems are Andosols, Nitisols, Acrisols, Alisols, Lixisols, Luvisols and Ferralsols.

Andosols (young volcanic soils)

Andosols occur in high-rainfall areas with steep topography, e.g. around Mt. Kenya and Mt. Kilimanjaro.

Andosols are porous, have a low bulk density and high water-storage capacity (Plate 10). Andosols occurring in the wetter regions (over 1,000 mm of rainfall per annum) are exposed to excessive leaching.

One of the limiting factors of these soils is P-fixation due to high levels of Al, and due to high leaching of soluble bases the soils are also acidic (low pH). Such conditions favour P-fixation, making it no longer available to the plants. Problems with soil micronutrients, especially Mo, are also common. Application of lime and organic and inorganic fertilizers is necessary in order to maximize agricultural production. Erosion may be a serious problem as these soils often occur on steep slopes. In these areas, the soils are mainly under tea, pyrethrum, temperate crops, and dairy farming (Plate 11).

Plate 10: Andosol, Kijabe, Kenya (monolith: Kenya Soil Survey)

Plate 11: Tea on small-scale hillside farms in central Kenya

Nitisols

Nitisols occur in the highlands and on volcanic foot slopes. They are found extensively in the central highlands of Kenya, some areas of the Ethiopian highlands, and around Mts. Elgon and Kilimanjaro.

These Nitisols are developed from volcanic rocks. They have favourable moisture-storage capacity and aeration and characteristically are coloured red, dark red or dark reddish brown (Plate 12). The organic matter content, cation exchange capacity and percentage base saturation range from low to high. Most Nitisols are acidic, that is, they have low pH (<5.5) due to the leaching of soluble bases. Their physical and chemical properties compare favourably to those of most other tropical soils.

Plate 12: Nitisol, Muguga, Kenya (monolith: Kenya Soil Survey)

Nitisols are some of the best agricultural soils found in the region. Bananas grow well on Nitisols (Plate 13), and most of the coffee and tea in the region is grown on Nitisols (Plate 14). For optimal crop production, Nitisols require the addition of inorganic fertilizers and manure. Soil conservation measures are necessary as most of these soils occur in steep areas.

Plate 13: Bananas with conservation measures, Mbarara, Uganda

Plate 14: Coffee on a smallholding in central Kenya

Acrisols, Alisols, Lixisols and Luvisols

These types of soil occur on undulating to hilly topography, common in marginal coffee zones in the sub-humid areas.

These are soils whose profile is characterized by an increase of clay content in the B horizon (sub-soil) (Plate 15). Often the sub-soil is not very porous and this restricts rooting. Compared with the Nitisols, these soils have a relatively low water-storage capacity. Acrisols and Alisols found in the wetter areas are also characterized by low pH, Al and Mn toxicities and have low levels of available nutrients and nutrient reserves. However, the chemical properties of Lixisols and Luvisols are generally better than those of Acrisols and Alisols due to the absence of serious Al toxicity in the former.

In addition to applying organic and inorganic fertilizers to these soils to improve their fertility, erosion-control measures must be put in place as these soils have poor structure and can be highly erodible. The soils respond well to liming, fertilizer (especially N and P, and sometimes K) and soil organic matter application.

Plate 15: Acrisol, Thika, Kenya (monolith: Kenya Soil Survey)

Ferralsols

Ferralsols are found on gently undulating to undulating topography. These soils are rich in Fe and Al. They are highly weathered and leached and are therefore chemically poor. Their natural fertility is restricted to the topsoil as the sub-soil has a low cation exchange capacity. However, Ferralsols have an excellent capacity to hold moisture due to their favourable physical properties (Plate 16).

The fertility of Ferralsols is poor since most of the weatherable minerals are absent. Phosphorus and N are always deficient. Thus applying fertilizers, e.g. rock phosphate or superphosphates, and maintaining the soil organic matter content by use of green manures, FYM and mulching, are important management requirements. The good physical conditions and favourable topography favour intensive agriculture if the poor soil chemical properties are effectively dealt with.

Plate 16: Ferralsol, Tsavo, Kenya (monolith: Kenya Soil Survey)

2.5.3 Soils with drainage problems

Soils with drainage problems occur in relatively flat areas that are subject to waterlogging during the wet season. These soils are classified as:

- Planosols (vlei soils)
- Vertisols (black-cotton soils)
- Gleysols (mostly occurring in marshy areas and along river valleys and characterized by a grey or bluish colour)
- Histosols (peat soils found in valley bottoms and swampy areas).

Planosols and Vertisols

Planosols and Vertisols are found on very gently undulating to flat topography. They occur in both semi-arid and sub-humid environments.

These are poorly drained soils with very slow vertical and horizontal drainage due to an impermeable layer in the B horizon (Plate 17). The sub-soil has more clay than the top-soil and this drastic change in texture results in the formation of an impermeable layer in the sub-soil.

Plate 17: Planosol, Nyandarua, Kenya (monolith: Kenya Soil Survey)

Plate 18: Vertisol showing large cracks, Mwea, Kenya

A striking feature of Vertisols is their capacity to expand (swell) and contract (shrink) with changes in moisture content. When dry, the soils form wide cracks (Plate 18), which close upon wetting. When both wet and dry, workability is extremely poor. The chemical fertility of Vertisols is usually high except for N and P. Both Planosols and Vertisols have a high cation exchange capacity, the former in the sub-soil, but workability is extremely poor.

The cracking that occurs on Vertisols when they are dry affects the crops growing in them by tearing the roots, while waterlogging becomes a problem when the soils are wet (Plates 19a and b). Attempting to grow seasonal crops in these soils without supplemental irrigation often leads to crop failure. In Plate 19b the first crop failed due to excess water (waterlogging), and the replanted crop (appearing as patches of green) also failed to reach maturity, but this time due to lack of moisture later in the season. A characteristic feature of soils with drainage problems is lack of diversity in the soil fauna. The population of microbes is low due to prolonged waterlogging.

Plate 19a: Growing seasonal crops on Vertisols, Mwea, Kenya: Effect of drought

Plate 19b: Growing seasonal crops on Vertisols, Mwea, Kenya: Effect of waterlogging followed by drought

In Mwea-Karaba, Kenya, and Shoa region, Ethiopia, broad-bed and furrow systems (Chapter 6) have proved successful in the management of Vertisols (Plate 20). The furrows should have very slight slopes to avoid gullying. The permeability of the subsurface soil is low, hence the drains should be closely spaced. Root development is hampered by oxygen deficiency in wet periods and high density or compaction of the sub-surface soil, as well as lack of soil moisture.

Plate 20: Managing excess water on Vertisols with broad-bed and furrow systems: (left) Amhara, Ethiopia; (right) Mwea, Kenya

Large areas under Vertisols are used for growing paddy rice, sugar cane, cotton, teff and subsistence crops, and for grazing during the dry season (Plate 21).

Plate 21: Irrigated rice fields on Vertisols (Mwea, Kenya)

Gleysols and Histosols

Gleysols and Histosols occur along river valleys and on bottomlands (Plate 22). They are poorly drained soils and most have a low pH. The fertility of Gleysols is variable, while Histosols have a thick topsoil horizon that contains a high percentage of soil organic matter.

Like Planosols and Vertisols, Gleysols and Histosols need to be drained to allow for the cultivation of crops, but use of inappropriate drainage methods in wetlands may lead to destruction of biodiversity, loss of productive potential, and drying up of these valuable water reservoirs.

Liming and full fertilization with N, P, and sometimes K, are needed for high yields. During the dry season, Gleysols along river valleys are utilized for growing vegetables and horticultural crops, which have a high market value at such times.

Plate 22: Use of Gleysols: draining wetlands for agriculture in Rwanda

2.5.4 Soils with fertility problems

Virtually all the soils in the eastern Africa region have fertility problems. This may be due to an absolute deficiency of the main plant nutrients or, more often, the nutrients are locked or fixed in the soil due to various unfavourable soil conditions.

Low fertility and insufficient organic matter are the main soil characteristics that adversely affect crop production in the region. Most soils in the region (e.g. Ferralsols, Acrisols and Luvisols) are highly weathered, have low pH and toxic levels of aluminium, which interfere with nutrient uptake. Nitrogen and phosphorus are the most frequently limiting nutrients in these soils.

A decline in soil fertility has resulted from unchecked soil erosion and nutrient removal through harvest where there is no recycling of crop residues and no addition of inorganic fertilizers. It has been estimated that an average of 3 kg P, 42 kg N and 29 kg K per hectare is lost through crop harvests annually (Smaling and Nandwa 1997). The inherent capacity of a soil to provide plant nutrients can be supplemented through the application of organic and inorganic fertilizers and lime.

These soils with low fertility are used for growing a wide variety of subsistence and cash crops. The management options for restoring fertility are given in more detail in the following chapters.

Plate 23: A poor maize crop on K-deficient soils

Plate 24: A healthy maize crop on fertile soil

2.6 SOIL AND WATER MANAGEMENT

The main objective of good water management is to improve the availability of water to plants through activities that enhance infiltration of rainwater, increase the soil's water-holding and storage capacity, minimize evaporation from the soil and minimize soil loss and salinization.

Activities to achieve these objectives include measures to conserve water, including runoff water harvesting; crop rotations in which deep-rooted plants utilize water from deeper soil horizons; surface residue mulching and cover cropping to decrease evaporation; improved tillage to enhance infiltration and reduce surface runoff; application of fertilizer and organic manure to promote vigorous crop growth; and use of drought-tolerant crops in the drier areas.

Good soil and water management enhances nutrient uptake by the crop. Nutrient uptake may also be improved through external inputs of nutrients and/or by increasing the soil-water supply. Increased water supply increases the uptake of available N, and also raises the rate of mineralization of organic N. Thus, crops should be planted at the right time and irrigation (if available) should be used whenever crop growth is affected by lack of rainfall.

High crop yields have been recorded in situations where water is non-limiting. A study carried out at Machakos, Kenya, indicated that irrigation significantly increased total N uptake in irrigated plots, which was on average 10.5 times higher than in the rain-fed plots. Total dry-matter and grain yields were 10.8 and 34.4 times higher, respectively, compared with the rain-fed area (Table 2.16). This was attributed to enhanced nutrient uptake by the irrigated crop. Additional soil water from irrigation may have increased the N mineralization in the soil, thus increasing the N available to the plant.

Table 2.16 *Total N uptake, total dry-matter and grain yields of maize grown under different water regimes and N application rates*

Water regime	N level (kg ha^{-1})	Total N uptake (kg ha^{-1})	Dry matter (kg ha^{-1})	Grain yield (kg ha^{-1})
Rain fed	0	15.1	1,105	228
	50	11.2	900	96
	100	16.1	1,237	130
Irrigated	0	94.1	9,231	3,734
	50	164.3	12,680	5,899*
	100	171.1	13,249	5,958*

Source: Kamoni et al. 2000.

* Indicates that applying more than 50 kg N per hectare may not be economical where water (soil moisture) is not a limiting factor.

Good agronomic and/or vegetative measures are the key to effective soil and water conservation. Tillage operations should always be carried out on the contour, not up and down the slope. In many cases, conservation structures such as terraces may be necessary to complement the other measures. Conservation structures are particularly useful in the following situations:

- High-rainfall areas with annual cropping to check erosion occurring due to highly erosive rainstorms falling on bare soil before crop cover is established;
- Marginal rainfall areas where agronomic measures (e.g. crop-residue mulching) are more difficult to apply, and *in situ* moisture conservation is a priority;
- Deep, stable and well-drained soils (with no swelling and shrinking properties) and crusting soils (due to surface sealing and subsequent high generation of runoff);
- Dryland areas where there is a need for harnessing runoff water for replenishing groundwater flow (appropriate structures for this include retention and infiltration ditches); and
- Badly eroded steep lands with rills and gullies.

The contrast between land which is mismanaged and degraded and land which is well conserved is exemplified by Plates 25, 26, 27, 28 and 29.

The most widely used conservation structures in the region are diversion ditches, infiltration or retention ditches, various types of terraces, waterways and gully stabilization structures (e.g. check-dams and gabion weirs). Proper design and installation of these structures is essential for ensuring that they are effective in controlling surface runoff and minimizing maintenance requirements.

Plate 25: Degraded grazing land in Arusha, Tanzania

Plate 26: Poor coffee on degraded hill farms, central Kenya

Plate 27: Well-conserved, intensively farmed hillsides, central Kenya

Plate 28: Good terraces stabilized with grass on a small-scale farm, Machakos, Kenya

Plate 29: Well-laid out stone terraces, Amhara, Ethiopia

2.7 CONCLUSION

Understanding the soil is the key to its improvement. As has been shown in this chapter, there are many physical, chemical and biological properties of soil that affect the growth of plants. With a better understanding of the soil it becomes possible to plan the most cost-effective measures that target specific problems that limit production. Organic matter has been shown to play a strategic role in the maintenance and improvement of fertility, but inorganic fertilizers and soil amendments may also be needed. The next chapter explains what measures can be used and how they can be implemented to restore the soil and increase production.

Chapter 3

Maintenance and improvement of soil fertility

3.1 INTRODUCTION

On well-conserved farms with little soil erosion the greatest loss of plant nutrients is through the removal of harvested crops. Few farmers in the eastern Africa region can afford to apply the recommended rates of organic and inorganic fertilizers to compensate for the losses. In most situations, the farmer applies whatever is available, which is not necessarily the type and quantity that is appropriate for the specific needs of the crop.

Here we use the term 'fertilizer' to mean any organic or inorganic material of natural or synthetic origin which is added to a soil to supply one or more elements essential to the growth of plants. The nutrients in organic fertilizers are variable and in low concentrations, unlike inorganic (mineral) fertilizers whose nutrient concentration is high and known. Organic fertilizers raise the level of soil organic matter in the soil, and improve soil structure, aeration and water-holding capacity. However, organic fertilizers are bulky and require more labour for composting, transportation and application. To be effective they are also required in large quantities, and this is often a problem for small farners. In general, inorganic fertilizers release plant nutrients more rapidly than organic fertilizers, but there are exceptions such as rock phosphate which is slow acting, and plant teas (see Section 3.2.4) which are fast acting.

Organic materials are extremely important in maintaining soil fertility, but inorganic fertilizers are also needed where soils are deficient in certain elements or there is continuous export of nutrients from the farm through crop harvest, grazing or removal of crop residues. This chapter deals with both organic and inorganic fertilisers.

3.2 ORGANIC FERTILIZERS

Organic fertilizers are materials derived from plant and animal parts/droppings or residues which are applied to fertilize the soil. These include FYM, urine, compost, *boma* manure, green manure and crop residues, municipal garbage, and human fæces and urine.

Livestock play a very important role in recycling plant nutrients. On many African farms they provide the major conduit for nutrient flow to cropland. Grazing animals harvest nutrients from pasture, and if the dung and urine are collected at night some of the nutrients can be made available for crops. Animals which are fed on purchased feeds provide manure of higher quality than those which rely on grazing alone. The way in which the manure is collected, stored and used is therefore a matter of great importance for the maintenance of soil fertility.

There are many beneficial effects of applying organic manures. Organic matter in the soil improves soil physical conditions by improving soil structure. It also markedly increases water-holding capacity, improves soil structure and aeration, as well as regulating the soil temperature. Organic matter contains varying amounts of plant nutrients, especially nitrogen, phosphorus and potassium, which are slowly released into the soil for plant uptake. Organic matter in the soil assists in the formation of stable aggregates that are resistant to erosion, creates good conditions for microbial activity and improves the workability and cation exchange capacity of the soil.

3.2.1 Farmyard manure (FYM)

Farmyard manure (FYM) is the accumulation of animal droppings where the animals are enclosed during the night or in a zero-grazing unit. The accumulation of FYM may be enhanced by adding vegetative material as bedding, which also helps to absorb and store the nitrogen-rich animal urine. FYM is important in areas where crop residues are removed for animal feed. Unfortunately, few livestock pens on smallholder farms have shelters over them and therefore a lot of nutrients are lost before the manure is applied to crops. Additional losses occur during application. Therefore, if the manure is not managed well, its quality will rapidly decline.

Adding of bedding in a *boma* or zero-grazing unit improves aeration and increases the quality of the manure. The quality of FYM will also depend on the type of animal (Table 3.1), type of feeds given to the animals and the way the manure is stored. Animals feeding on plant materials grown on nutrient-rich soils are healthier, grow faster and produce nutrient-rich manure.

Fresh manure should not be used directly in the soil because the free nitrogen it contains can be harmful to plants. It is also likely to attract pests and cause weed proliferation. The safest way of using manure is to compost it before use to kill pathogens, harmful micro-organisms and weed seeds (see section on composting, below). Materials such as rock phosphate, bonemeal, eggshells, bloodmeal, fishmeal and dried seaweed can also be added to FYM to improve its quality.

Maximizing the beneficial effects of FYM

In order to maximize the beneficial effects of manure, the following points should be noted. When manure must be stored to await the planting season, it should be gathered into piles which are then kept under a suitable shelter, or are covered with a layer of soil, dry grass or crop residues to prevent nutrients from being washed away in

runoff water, or being leached downwards as rainwater percolates through the soil. Covering the manure also reduces loss of nitrogen to the air (volatilization).

Manure should be incorporated into the soil as soon as it is spread. This reduces nutrient losses through volatilization. Timing of application is important. Spreading and incorporation of manure should be done at least two weeks before planting to allow the process of nutrient release to be initiated to benefit the early stages of crop growth.

***Table 3.1** Nutrient content (NPK) in some commonly used organic materials*

Organic material	Nitrogen %	Phosphate %	Potash %
Cow manure	0.4–0.6	0.2	0.2–0.5
Horse manure	0.5–0.7	0.3	0.6
Goat manure	1.4	0.2	0.3–1.0
Sheep manure	0.7	0.3	0.4
Human waste	2.0	1.0	0.2
Pig manure	0.5	0.3–0.4	0.5–0.8
Poultry manure	1.1–1.5	0.8–1.3	0.5–2.7
Rabbit manure	1.1–2.4	1.2–1.4	0.6
Boma (mixed animals)	0.7	0.1	0.7
Compost (household)	0.5	0.2	0.8
Grevillea leaves	1.37	0.06	0.64
Bean trash	0.80	0.07	1.57
Banana stalks	0.73	0.18	4.10
Sugar cane trash	0.47	0.06	1.23
Banana leaves	1.30	0.10	1.72
Coffee husks	1.63	0.14	4.45
Sweet potato vines	1.73	0.48	6.63
Leucaena leucocephala	3.74	0.26	3.37
Napier grass	1.97	0.14	3.85
Lantana camara	2.50	0.26	1.93
Tithonia leaves	3.97	0.30	4.60
Cajanus	3.62	0.21	n/a
Jackbean	3.45	0.16	n/a
Crotalaria (‘marejea’)	4.45	0.16	n/a
Desmodium	3.44	0.15	n/a
Soybean	3.52	0.15	n/a
Lablab	4.02	0.18	n/a
Mucuna	3.56	0.17	n/a
Lima bean	3.79	0.13	n/a
Purple vetch	3.68	0.16	n/a
Groundnuts	3.25	0.18	n/a

Source: Bunyasi 1998; Gitahi and Mureithi 2002.

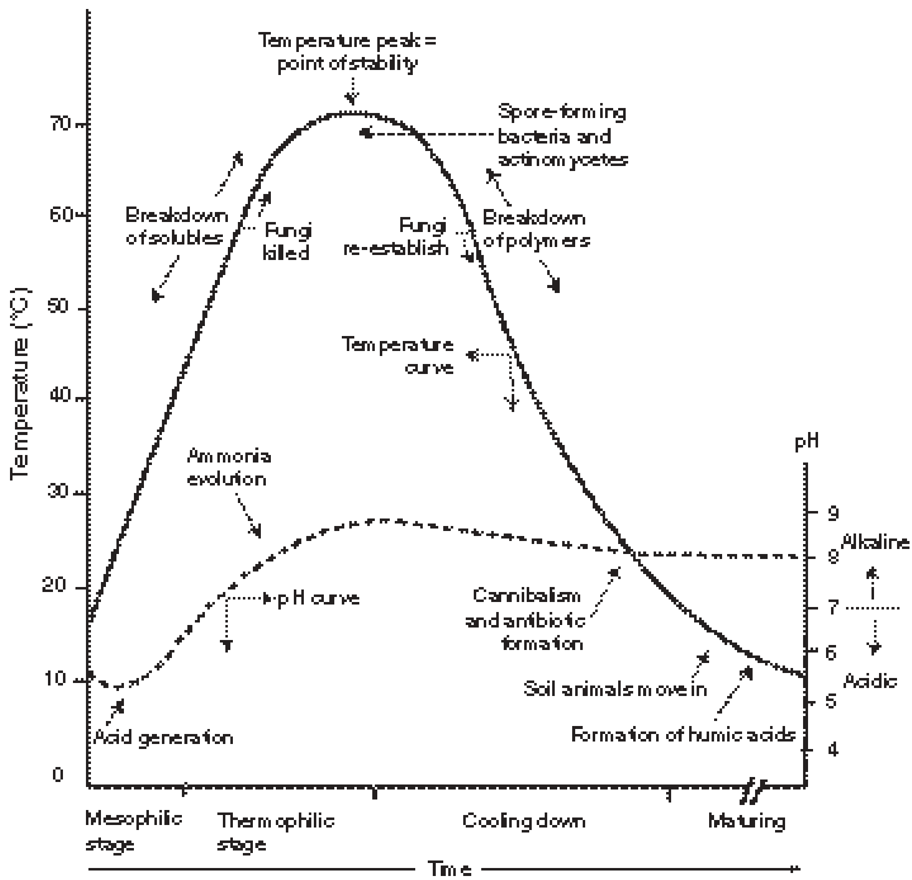
3.2.2 Composting

Composting is the process of breaking down organic materials of plant and animal origin to produce humus. The requirements for composting are the presence of soil micro-organisms and organic material such as animal manure, crop remains, municipal garbage, kitchen waste, hedge trimmings and non-seeding weeds (see Table 3.1). Additional requirements include moisture to hasten decomposition, temperature control to optimize micro-organism activity, and aeration to provide adequate oxygen for

the decomposition process and labour. Figure 3.1 shows some of the events (temperature and pH changes) that take place during composting. The figure is for a single pit without turning the compost.

The composting process takes place in four stages
, as follows (Lampkin 1990):

- Mesophilic stage
- Thermophilic stage
- Cooling-down stage
- Maturing stage.



Source: Lampkin 1990.

Figure 3.1 *Sequence of events during composting (temperature and pH variations)*

The mesophilic strains of micro-organisms present in the organic waste or in the atmosphere start to decompose the materials. Heat is produced and the temperature of the heap rises. The pH falls as organic acids are produced. Above 40°C, the thermophilic strains take over and the temperature rises to 60°C, at which fungi become deactivated.

Above this temperature, the reaction is kept going by the actinomycetes and spore-forming bacteria. In this high-temperature phase, the more readily degradable substances, such as sugars, starches, fats and proteins are rapidly consumed; the pH becomes alkaline as ammonia is liberated from the proteins. The reaction rate decreases as the more resistant materials are attacked; the heap then enters the cooling-down phase.

As the temperature falls, thermophilic fungi re-invade the heap inwards from the extremities and start to attack the cellulose. Later, the mesophilic strains of micro-organisms re-invade the heap.

The final stage, maturing, leads to the breakdown of the residual organic matter to produce the stable product of humus or humic acids. This stage may take several months (unless the process is hastened through frequent turning of the heap). During this period, there is intense competition for food among the micro-organisms. Antagonism and antibiotic formation occur, and the heap is invaded by macro-fauna (mites, ants, worms, etc.), which contribute to the further breakdown of the organic material by physical maceration of the particles.

Composting should be a continuous activity on the farm, depending on the availability of animal manure and the other constituent materials. It is advisable to prepare more compost when vegetative materials are plentiful, and to store it for use during the periods when materials are more difficult to find. If the compost is ready for use long before the planting season, remove and store it under shade, or cover with some impermeable material such as polythene. This clears the site for more compost to be made. Cover the stored compost well with a layer of soil and sufficient vegetative material and keep it moist until the time for use.

The recommended size for compost heaps is 1.5 m high and 1.5 m wide. Nevertheless, bigger heaps may be prepared with some modifications to ensure adequate air for their curing. To monitor the process of composting, a sharp stick should be driven into the heap at an angle. This is withdrawn periodically, and if it feels warm composting is proceeding actively. It the heap is too dry, the stick will show the growth of a white fungal mycelium. If the heap is too wet, the stick will feel cold as bacterial action is suppressed through lack of oxygen. Water should be added when necessary and the heap should be turned periodically to improve aeration. The frequency of turning depends on a number of factors, such as the availability of labour and how soon the manure will be required. The finished compost should be a dark, crumbly, earthy-smelling substance. In tropical conditions, compost breaks down rapidly and should be applied regularly.

The rate of compost applied depends on its quality, and the methods of application (broadcast, band placement, or per planting hill). A figure of 10 t ha^{-1} can be used as a general guide.

The compost should be mixed well with the soil to give an homogeneous mixture that will reduce nitrogen losses due to volatilization. Where livestock manure has been used in making compost, it is particularly important that the material is completely

broken down before use and there is no heat left. If used too soon it could burn seedlings or propagation material.

The carbon:nitrogen ratio (C:N) is a good indicator of how good composting material is. The C:N ratio means the amount of carbon present compared to one part of nitrogen (Table 3.2). A higher ratio means less nitrogen and the process of decomposition will take longer. For instance, sugar cane fibre has a ratio of 200 parts of carbon to one part of nitrogen, or 200:1, and is therefore difficult to compost. Sawdust (C:N ratio 400:1) is even more difficult to compost. Maize stover left in the field to rot takes a shorter time to decompose because it has a more favourable ratio (60:1). The best ratio is about 30 parts of carbon to one part of nitrogen, or 30:1. Note that excess nitrogen is converted into ammonia, which gives the compost heap a strong smell. The smell is an indicator that fibrous material rich in carbon should be added to bring the ratio back to a desirable level. The percentages of N, P, and K in the commonly used organic materials are given in Table 3.2. Note that most leguminous plant materials are rich in N. These can be used for green manuring.

Table 3.2 *C:N ratios of selected compostable materials*

Material	C:N ratio
Vegetable waste	12:1
Legume hay	12–24:1
Cow manure + bedding	15–25:1
Maize stalks	60:1
Straw	75:1
Grass hay	80:1
Sugar cane fibre	200:1
Sawdust	400:1

How to prepare compost from crop remains and non-seeding weeds

1. Loosen the topsoil and lay down a 30-cm layer of coarse material such as maize stalks. The maize stalks should be chopped into small pieces to accelerate decomposition. The coarse layer is to allow aeration and free drainage.
2. Add a 30-cm layer of green material (preferably legume cover crop materials, or municipal garbage or kitchen wastes, which are rich in N), and water thoroughly. This layer forms organic composting material.
3. Next, add a 5-cm layer of topsoil or old manure or compost to ensure the presence of micro-organisms to break down the compost.
4. Add a thin layer of wood ash and then water adequately.
5. Repeat steps (1) to (4) and continue until the compost heap is about 1.5 m high. The heap should also be about 1.5 m wide but can be any desired length.
6. Cover the heap with a thin layer of soil and then grass or banana leaves. This reduces the direct impact of rain, sun and wind, and reduces the internal loss of moisture and heat. It is an advantage to prepare compost in a shady place (Plate 30).

7. Take a sharp stick and drive it through the heap at an angle. The stick will be used periodically to measure the heat and moisture in the compost heap. If the heap is too dry, the stick will show the growth of a white fungal mycelium. If too wet, the stick will be cold as bacterial activity is suppressed through lack of oxygen.Water the heap when necessary.
8. Turn over the heap after 21 days and water it well.
9. Turn over the heap after another 21 days.
10. The compost should be ready three weeks after the second turning.

Note: Compost can also be prepared in a pit, a bin, a stack, a box, or other container.

Plate 30: Preparation of a compost heap under tree shade

How to prepare *boma* compost from fresh livestock droppings

(See Figure 3.2.)

1. Dig a pit 0.5 m deep behind the *boma*, putting the excavated soil beside the pit. The pit should be 1.5 m wide and any length, depending on the amount of material available. Loosen the soil at the bottom of the pit and place a layer of dry crop residues like maize stover or grass at the bottom.
2. Then place a layer of about 10 cm of fresh manure and bedding obtained from the *boma*.
3. Cover this with a thin layer of topsoil (1–2 cm).
4. Now add a 10-cm layer of manure and again cover with a thin layer of topsoil. Repeat the process until the compost heap is 1.5 m high.
5. When completed the whole pile is covered with soil, and finally with grass, maize stalks or banana leaves to prevent drying. In the dry season, the pile should be watered regularly.
6. Use a long pointed stick to monitor the temperature and moisture of the pile. Add water as soon as the stick feels dry. If there is no moisture, there is a whitish fungal mycelial layer showing on the stick.
7. After two or three weeks, the pile is turned into a second pit, and then into a

third pit after a further two weeks. All the time the pile must be covered with grass or crop residues to prevent drying up.

8. Three weeks after the second turning, use the stick to check the temperature. When the stick feels cool, the pile is ready for use. By now the compost should have a fresh earthy smell and no grass or animal droppings should be distinguishable. However, if the stick still feels warm to the touch, then the pile is still decomposing and requires more time.

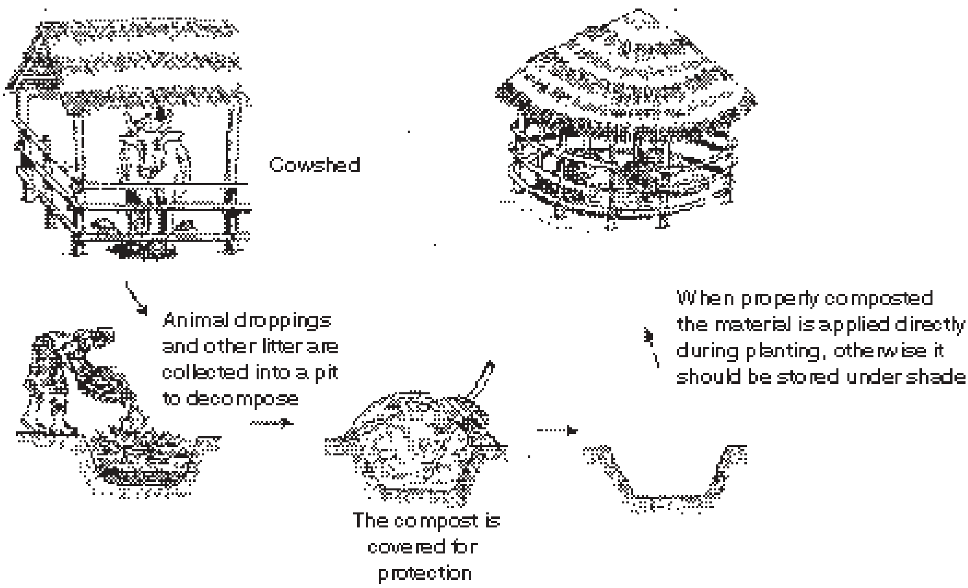


Figure 3.2 *Making* boma *compost*

How to prepare basket compost

Where the piece of land to be put under a crop is small, such as a kitchen garden, or where there is not enough FYM, then the 'basket' method can be used to make compost (see Plate 31). The following materials are needed:

- Banana fibres – long strips 15 cm wide
- Sticks – at least 60 cm long
- Kitchen garbage, farm and garden wastes and plant materials from leguminous crops.

There are several steps in making basket compost, as follows:

1. Prepare the garden. Keep leaves and plant materials of leguminous plants for use during composting. These are important as they contain useful plant nutrients.
2. Dig holes along the centre of the plots. The holes should be at least 12 cm deep with a diameter of 0.5 m, and should be spaced at 1 m apart along the centre of the plot.
3. Drive 5–9 sticks into the ground around each hole. An uneven number of sticks are good for weaving the basket.

4. Use the long strips of banana fibres to weave around the sticks to make a basket. If banana fibres are not available, use a larger number of sticks at closer spacing.
5. Place rotten garbage and animal manure into the basket first.
6. Add fresh materials like bean pods and leaves.
7. Fill to the brim with other organic waste and include some ash, and water the material.
8. Plant seedlings around the basket at a distance of 15–20 cm from the basket to prevent scorching by the organic matter concentrated in the basket.
9. Water the seedlings while they are young. Eventually, just water the basket. The plant roots will grow towards the source of moisture. The basket serves as a moisture and nutrient reservoir for the plants.
10. After harvesting, and when the compost is used up, remove the decomposed material and incorporate it into the soil during cultivation.
11. Put new composting material into the basket to start the process again.
12. Repair the basket as necessary.

Plate 31: Basket compost (photo: KIOF)

3.2.3 Liquid manure (using animal droppings)

Liquid manures are useful for top-dressing. Two methods of liquid manure preparation can be used, as outlined below.

Method I

Two wheelbarrows full of animal droppings, preferably poultry manure, are placed in a large drum. Water is added until it is three-quarters full, while stirring continuously until a thick 'porridge' is formed. The 'porridge' is covered and left to stand for 15 days while being stirred at 3-day intervals. On the sixteenth day the liquid manure is ready for application, after a dilution of 1 part liquid manure to 2 parts of water (1:2).

Before application, a shallow basin is prepared around the bases of the crop plants in the field into which the liquid manure is poured and then lightly covered with topsoil. The applications are repeated every two weeks until the crops are about to flower.

Method II

Fill a sack with 30–50 kg of animal manure (fresh manure from cattle, goats, sheep, chickens or pigs) and tie securely. Fill a drum with water, place a stick across the

diameter of the drum and use it to suspend the sack in the water. The water is stirred every 3 days for a period of 10–15 days. As the liquid manure matures it produces a strong smell as excess nitrogen turns into ammonia. It may be advisable to locate the drum some distance from the house to avoid the smell. Once this smell is gone, the liquid is ready for use. The product is diluted with water at a ratio of 1:2 before use (see Plate 32).

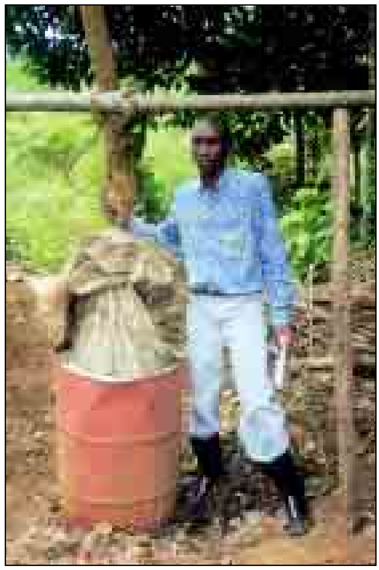


Plate 32: Preparation of liquid manure from cattle dung (photo: KIOF)

3.2.4 Making plant-tea solutions

Extra nitrogen for top-dressing can be made locally from a specially prepared liquid fertilizer termed 'plant tea'.

Procedure for making plant teas:

1. An amount of green leguminous plant material is chopped up and placed in a drum full of water at the ratio of 1:1.
2. The material is then left to decompose for 6–10 days. It is stirred occasionally.
3. Animal or human urine also contains useful levels of nutrients and can be added to the solution.
4. At the end of the tenth day, the mixture will have formed a green liquid (the 'plant tea'). The liquid may be diluted by adding fresh water.
5. This solution is then applied to the soil around the roots of the crop.

3.2.5 Mulching

Mulching is the covering of the soil with crop residues, dry grass and leaves. Once rotten and decomposed, mulch forms humus and adds to the organic matter in the soil. Mulching is important for the prevention of soil erosion, addition of organic matter to the soil, regulating the soil temperature, increasing soil micro-organism and biological activity, weed suppression, increasing water retention, and decreasing evaporation from the soil surface (Plate 33).

Plate 33: Mulching in a banana plantation, Mbarara, Uganda

It is important to ensure that sufficient mulch is maintained as soil cover to reduce evaporation of soil moisture and to discourage growth of weeds.

3.2.6 Green manures

Green manures are plants that are deliberately grown for the purpose of incorporation into the soil to improve soil fertility and organic matter content. Legumes are the most commonly grown green manures, but other plants that are not legumes, such as tithonia, may also be used. Most green manure crops also play a role in covering the ground and protecting it from solar radiation and soil erosion. Crops which serve these functions are often referred to as green manure cover crops.

Benefits of using green manures include:

- Nitrogen supplied by legumes
- Improved soil tilth and water infiltration
- Reduction in diseases and nematodes
- Weed control
- May trap nitrates and prevent leaching
- Control of erosion
- Source of feeds for livestock
- May also provide food for humans.

Species such as sunnhemp (*Crotalaria juncea*), Tanzania sunnhemp (*C. ochroleuca*), leucaena *(Leucaena leucocephala)*, velvet bean *(Mucuna pruriens)*, jackbean *(Canavalia ensiformis)*, lablab *(Lablab purpureus)* and *Tithonia diversifolia* have been used as green manures in the region.

An ideal green manure crop is one that meets most of the following criteria:

- It is fast growing (accumulates much biomass within a short period)
- It fixes nitrogen from the air
- It is deep rooting and thus improves soil structure and recycling of nutrients
- It covers the soil quickly, thus controlling erosion and suppressing weeds
- It produces many leaves and no hard, woody stems
- It is easy to establish and also to remove when necessary
- It does not compete much for moisture and nutrients with food crops
- It has multiple uses, e.g. food, fuel, fodder, control of pests.

Legume green manure crops can be intercropped with food crops, or planted after the food crop has been harvested or during the dry season if there is sufficient moisture. The legume is then incorporated into the soil during land preparation. In other situations the green manure crops are slashed and left as surface mulch. This also helps to check soil erosion at the beginning of the rains. To avoid competition for moisture and nutrients, some green manure crops, such as *Mucuna* spp., are interplanted two to three weeks after the food crop is planted. Legumes can also be planted as sole crops to improve soil fertility on degraded land. The green manure crops are later rotated with a cereal crop. The benefits in increased yields can sometimes be as high as those obtained from use of inorganic fertilizers. For example, Table 3.3 shows the benefits versus costs of using Tanzanian sunnhemp (*Crotalaria ochroleuca* or 'marejea') at Peramiho in Ruvuma Region of Tanzania.

Table 3.3. *Costs and benefits of using Tanzanian sunnhemp at Peramiho, Tanzania (TSh)*

Plot 1: Inorganic fertilizer, 1 acre		**Plot 2: Sunnhemp, 1 acre**	
Inputs/yields	Value	Inputs/yields	Value
Year 1 (1994/95)			
3 bags fertilizer @ 7,000	21,000	20 kg marejea @ 150 per kg	3,000
Yield 10 bags maize @ 3,500	35,000	Saleable yield	None
Profit margin	14,000	Margin	Loss of 3,000
Year 2 (1995/96)			
Fertilizer 3 bags @ 12,000	36,000	Fertilizer input	None
Yield 10 bags @ 5,000	50,000	Yield 14 bags @ 5,000	70,000
Profit margin	14,000	Profit margin	70,000
Total for two years	28,000	Total for two years	67,000

Source: Silenge and Bertram 1996.

In the Ruvuma Region of Tanzania, this crotalaria–maize cultivation system involves planting maize on the ridges and crotalaria ('marejea') in the furrows. The first season's ridges are planted with maize, while the furrows have marejea. During the second season, the ridges are broken and become furrows. The new ridges are formed over the last season's furrow, covering the legume or green manure and other vegetative trash. The legume crop is planted in the new furrow, while the food crop is planted on the new ridge, thus utilizing the nutrients released by the decomposing green manure residues (see Figure 3.3). In other areas, farmers can use legume cover crops that are suitable for the relevant ecological zones.

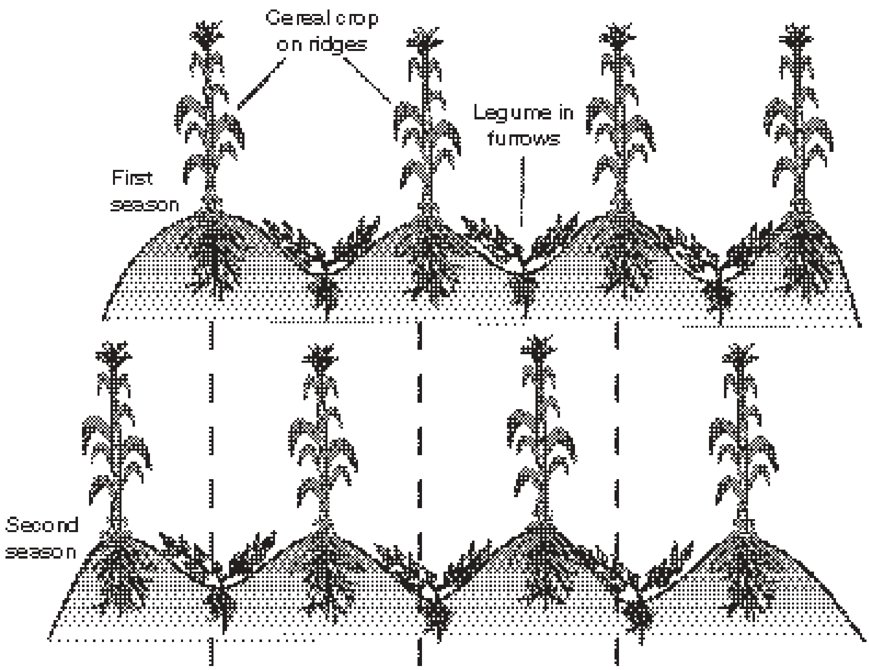


Figure 3.3 *Ridge-and-furrow system using a suitable legume cover crop*

Some recommended green manure cover crops for different situations

***Mucuna* spp.** (velvet bean) performs well at altitudes of 0–1,800 m above sea level (a.s.l.) and in medium-textured soils. It is used extensively as a legume cover crop for soil fertility improvement and erosion control and is one of the best N-fixers and weed suppressors (Plate 34). Within six months, mucuna can accumulate 7 t dry matter (DM) per hectare with a N content of 3.6%. It may require pruning to avoid twirling around maize.

Plate 34: Velvet bean *(Mucuna* spp.*)*: A dense cover crop interplanted with a maize crop

Velvet bean is not good for human consumption as it contains a potentially harmful chemical called 3,4-dihydroxylphenylalanine (commonly known as levodopa, or l-dopa), which is an amino acid that can cause involuntary muscle movements when consumed in high doses. The l-dopa can be removed by boiling the beans in several changes of water. Mucuna is an herbaceous legume with a potential for multiple uses.

Canavalia ensiformis (jackbean) does well at 0–1800 m a.s.l. Unlike mucuna, jackbean will grow in poor soils and in areas of low rainfall. However, jackbean produces less biomass than velvet bean and it is not a good weed suppressor (Plate 35). It can yield 5 t ha^{-1} DM in 6–12 months. It has 3.5% N content. Jackbean is toxic (it contains canavelin) and is used by some communities to control moles.

Plate 35: Jackbean *(Canavalia ensiformis)*

Crotalaria spp. takes 3–5 months to mature and grows best at 1,300–1,800 m a.s.l. It is known to suppress nematodes. Some species can be used as food or fodder (Plate 36). Crotalaria has excellent nodulation and high biomass accumulation (>8 t ha^{-1} DM in 3–5 months). Average N content is 4%. Growth may be slowed by wet weather, and seed production may be a problem because of pests. More labour is required during the first weeding (especially if broadcast) and during harvest. The species is good for short fallows to reclaim infertile land.

Plate 36: Tanzania sunnhemp *(Crotalaria ochroleuca)*

Lablab purpureus (*Dolichos lablab*) grows well at altitudes between 0 and 1,800 m a.s.l. It is mainly grown for food as it is palatable to both animals and humans and is drought tolerant. It produces as much biomass as mucuna (Plate 37). The beans are edible when green or dry. In the vegetative stages, lablab has 3.0–5.8% N in the fresh leaves. It produces 8 t ha^{-1} DM in 3–5 months. Its main disadvantage is its susceptibility to pests and diseases.

Plate 37: Lablab *(Lablab purpureus)*

***Desmodium* spp**. These are appropriate as a live mulch cover and thus effective in controlling weeds and erosion. Desmodium does well at 0–1,900 m a.s.l. It can accumulate 8 t ha^{-1} DM within 12 months and has good nodulation and a N content >3%. It is used to improve fodder quality but is slow to establish and requires more weeding.

***Vicia* spp**. (vetches). Vetches provide a fast-growing herbaceous cover crop producing large quantities of biomass (over 8 t ha^{-1} DM in 4–5 months) with good growth and 3.5–5.0% N content. Vetches are mainly used for green manuring and suppress weeds once they cover the ground (Plate 38). They perform well at higher altitudes (>1,800 m a.s.l.). However, low soil moisture, low soil fertility and poor soil structure affect their growth.

Plate 38: Vetch *(Vicia* sp.*)*

Tephrosia vogelii is a shrub which can grow well at altitudes of 0–2,000 m a.s.l. Biomass production ranges from 4 to 8 t ha^{-1} DM within 6 months. It is good for short and medium fallows as it is easy to establish and drought tolerant. It is also useful for fuelwood, but it is prone to nematodes.

Sesbania sesban is a shrub which grows well at 0–2,000 m a.s.l. The average N content of the leaf is 3%. It is good for intercropping with food crops where competition for soil moisture is likely to occur. It can also be used for fallows.

Establishing green manure cover crops

- Select the species best adapted to the area.
- Plant the green manure cover crop one to two weeks after the food crop in areas with high rainfall. In drier areas, the planting is done at the same time as the food crop.
- Plant mixtures of cover crops where possible.
- Weed when necessary.
- Leave the green manure cover crop as a mulch in the field after harvesting the food crop.
- Incorporate the mulch into the soil before planting the next crop. If the purpose is soil conservation, the mulch should be left on the surface.
- If the objective is to rehabilitate degraded land, then leave the green manure in the field. Most species re-seed themselves and this will ensure a continuous cover during the subsequent seasons.

There are various niches on the farm for which different species can be used, for example as hedges along boundaries; live cover for riverbank protection; contour buffer strips for terrace embankment stability and fodder supply; as a cereal/legume intercrop; sole forage crop; relay fallow crop for soil improvement; live mulch for ground cover on steep slopes; and in grass/legume mixtures in improved pastures.

How to use green manures

Green manures are incorporated into the soil during land preparation. When there is a high biomass turnover some of the biomass can be used for bedding, or as animal fodder. The rest is chopped up into small pieces before incorporation into the soil. Some farmers prefer leaving the green manure on the surface as mulch.

Weeds, used as green manure, are either uprooted before flowering and incorporated into the soil, or simply buried during weeding. If plant materials are infected, they may either be composted prior to application in the case of mild conditions or burnt completely if heavily diseased.

In poor soils, the soil is left under cover of the green manure sole crop for one or two seasons. This is referred to as 'improved fallow' and it helps enhance soil fertility. The green manure is incorporated into the soil at the end of the fallow period.

Farmers in Gatanga area of Thika District in Kenya have reported increased maize yields after using mucuna and crotalaria as green manures (Mureithi et al. 1998, 2000). When mucuna and crotalaria biomass was incorporated into the soil, the average maize yield was 2.0 and 2.5 t ha^{-1}, respectively. The average maize yield from plots without green manure was 0.7 t ha^{-1}.

Bio-fertilizers (inoculants)

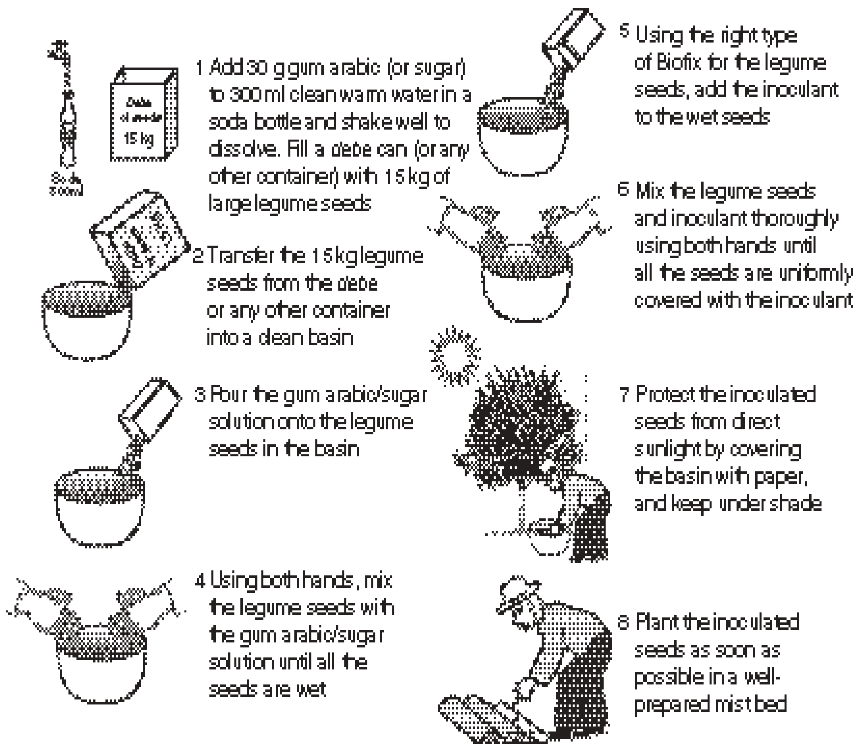
Legumes with nodules on the roots are able to fix nitrogen from the air. This is possible because of symbiotic relations with certain bacteria in the nodules. These *Rhizobium* bacteria have been cultured and packaged for distribution to farmers to inoculate a wide variety of leguminous crops grown in the region (Figure 3.4). These include beans, cowpea, pigeonpea, soybean, lucerne, leucaena and lablab.

The Department of Soil Science, University of Nairobi, uses *Rhizobium* bacteria to produce BIOFIX (available commercially) as a cheap alternative to nitrogenous fertilizer. It has shown promising results when used as a source of N-fixing bacteria for a wide range of legumes such as common bean (Plate 39), soybean, garden pea, cowpea, pigeonpea, lucerne, desmodium, stylosanthes, centrosema, and trees such as leucaena, gliricidia and sesbania. Other countries in the region producing inoculants are Uganda and Zambia.

Plate 39: Nitrogen-fixing nodules on bean roots

Some of the benefits of using inoculant are:

- Saving the use of chemical nitrogenous fertilizers by enhancing N fixation
- Low cost: one packet of inoculant can be used to plant a *debe* (or about 20 kg) of bean seeds. The cost in Kenya was about US$ 1.00 in 2001 (about KSh75)
- Easy to apply
- Gives increased yields of legumes
- Does not pollute the environment.



Source: MIRCEN Project, Department of Soil Science, University of Nairobi

***Figure 3.4** How to use BIOFIX*

An additional advantage of using the inoculant on leguminous crops is that more N is left in the soil for the subsequent crop. This technological option of substituting the biological fixation of atmospheric nitrogen for inorganic nitrogen fertilizer has great potential but is yet to reach most of the farmers in the region.

3.2.7 Livestock in soil fertility management

Livestock are important in replenishing soil nutrients in smallholder farming systems. In some farming systems such as the coffee–banana system in northern Tanzania, for example, for most farmers the primary function of stall-fed animals is the provision of manure for the banana crop. In the central highlands of Kenya, smallholder farmers are paying the equivalent of US$80 for enough manure to provide one tonne of nitrogen. This compares to only US$45 for the same weight of nitrogen from fertilizer urea. The higher cost of using manure is partly the result of transport charges for a bulky material, but note that there is also added value because of the organic matter it contains (ILRI 1998).

Livestock perform the prime function of recycling nitrogen and carbon from plants to animals and back to the soil. Livestock supply manure which improves soil microbial activities, augments minor elements such as boron, zinc and cobalt, and allows a balanced rotation based on legumes and arable cropping. Ruminants, whether open-grazed or zero-grazed (Plate 40), convert vegetative materials into manure, which is subsequently retained and distributed on the farm in suitable forms within the rotation consisting of cereals, legumes, root crops and N-fixing fodder plants.

Non-ruminant livestock (poultry, and pigs) can convert spoiled milk, vegetable and food wastes into marketable products. Manure from these animals is richer in nutrients than manure from ruminants. Four to five tonnes of poultry manure can be used in producing 2 t of maize crop, whereas more than 10 t of ruminant manure would be needed for similar production levels (see Table 3.1).

In addition to its role in fertility maintenance, livestock manure has the potential to produce energy in the form of biogas. A few farmers have installed biogas plants in which manure from their livestock pens is digested. The gas produced can be used for heating and lighting. The slurry which is recovered after the gas has been produced contains all the plant nutrients that were in the original manure as none are lost in the gas. However, biogas production requires some capital investment and discussion of the method is beyond the scope of this book.

Plate 40: A zero-grazing unit

3.2.8 Other methods for enhancing soil fertility

Earthworms

Humus is essential for a healthy soil. Under natural conditions humus is formed from organic matter through the activities of both soil micro-organisms and macro-organisms, influenced by appropriate soil moisture and temperature. Among the various soil macro-organisms, earthworms are particularly important as they feed on dead and decaying materials which they digest and then excrete as nutrient-rich 'worm casts'. In addition, earthworms can be used as feed for smallstock, e.g. poultry, fish and even pigs. Earthworms are promoted by an abundance of good compost. Soil organisms play a key role in the recycling of soil nutrients and greatly enhance their availability to plants.

Earthworm rearing by the Kenya Institute of Organic Farming (KIOF): Promoting living soil

Materials required

- A plastic open drum or a wooden box measuring approximately 60 cm deep, 180 cm long and 120 cm wide.
- Topsoil with some earthworms.
- Fresh dung or droppings (either from cattle, sheep, goats, rabbits or pigs)
- Dry materials, e.g. grass.
- A suitable cover, e.g. a sisal sack.
- Some water.

Procedure

Step 1. Mix all the topsoil, dung/droppings, grass and some water thoroughly in the open drum or box. Use moderate amounts of water to avoid making the growth medium too wet and therefore unsuitable for worm rearing.

Step 2. Cover the mixture of topsoil, dung, etc., with a sisal sack and place the drum or box in the shade. Ensure that moist conditions prevail in the growth medium all the time.

Step 3. Harvesting. In two weeks, the earthworms will have grown and multiplied. They can be harvested by sieving them with a wire mesh. The big worms will remain on the wire mesh. Thereafter, they can be removed and placed in a separate container for use according to the desired purpose.

Human waste

Some countries, such as China, have been using human wastes to maintain soil fertility for centuries. Where sanitation arrangements exist in eastern Africa, they are usually aimed at disposal of human wastes in a hygienic manner for health reasons. However, it is becoming necessary to look at human wastes as a potential resource and to see in what way they can be used to maintain soil fertility without creating health hazards. Urine can easily be added to a compost heap or diluted with water and applied directly as a nitrogenous fertilizer. Methods of handling faeces require much more care and discussion of them is beyond the scope of this book.

3.3 INORGANIC FERTILIZERS

3.3.1 The role of inorganic fertilizers

Inorganic fertilizers are a normal requirement for high crop yields. It is estimated that 30–50% of today's crop production in the world comes directly from the use of inorganic fertilizers. Use of the correct type, rate, time and method of application of fertilizers is important for raising production and avoiding damage to the environment. Inorganic fertilizers can quickly replenish lost plant nutrients. However, despite several years of agronomic research on the response of specific food crops to various types of fertilizers, over-generalized and rigid recommendations on their use continue to be made. Furthermore, continual use of inorganic fertilizers without inputs of organic matter can lead to declining yields because of other problems such as imbalance or deficiency of certain nutrients, acidification of the soil or deterioration in soil structure. Inorganic fertilizers should not be considered as an alternative to organic fertilizers or a substitute for organic inputs. They have complementary roles. The need for integrated soil fertility management where both are used is discussed in Section 3.5, below.

Precautions in fertilizer use

- Apply fertilizers on well-conserved land to avoid losses through erosion.
- Adequate soil moisture is critical for proper nutrient uptake: therefore use supplementary irrigation where possible if rainfall is below normal levels.
- Use land preparation practices that conserve or enhance soil moisture.
- Ensure correct application at planting time, usually just below the seed and along the planting row or into the planting holes (not broadcast widely).
- Cover with soil immediately after application so the seed is not in direct contact with the fertilizer.
- Consider the economics of fertilizer use: apply on high-value crops or in areas requiring rehabilitation.
- Best results are obtained when fertilizer is used in conjunction with organic manures. The organic manures supply additional nutrients, and therefore reduce the quantities of fertilizer needed.

3.3.2 Types of inorganic fertilizers

Fertilizers may be classified in several ways, depending on their sources, composition or grade, characteristics and applications. Inorganic fertilizers used in the region fall into two broad categories based either on the nutrient composition or the method of application.

Classification of inorganic fertilizers based on nutrient composition

The nutrient composition of a fertilizer is expressed as a sequence of three numbers that represent the percentage content of three major nutrients: nitrogen, phosphorus and potassium (NPK). The first number represents the total nitrogen (N), the second represents phosphorus (P_2O_5), and the third represents the water-soluble potassium

(K_2O). There are three types of fertilizers based on nutrient composition, namely single, incomplete and complete fertilizers.

Single fertilizers

These are fertilizers containing only one of the major nutrients (Table 3.4).

Table 3.4 *Common types of single inorganic fertilizers with their nutrient composition*

Nitrogenous fertilizers	Phosphatic fertilizers	Potassic fertilizers
Ammonium nitrate (34% N)	Single superphosphate, SSP (18% P_2O_5)	Potassium chloride or muriate of potash (60–62%, KCl)
Ammonium sulphate nitrate ASN (26% N)	Triple superphosphate, TSP (46% P_2O_5)	Potassium nitrate (44–46% KNO_3)
Calcium ammonium nitrate, CAN (26% N)		Potassium sulphate (50–53% K_2SO_4)
Calcium nitrate (16% N)		
Anhydrous ammonia (82% N)		
Sodium nitrate (16% N)		
Urea (46% N)		

Incomplete fertilizers

Incomplete fertilizers contain two nutrients, e.g. 18:46:0. The ones commonly used do not contain potassium. Examples are given in Table 3.5.

Table 3.5 *Incomplete fertilizers*

Nitrogenous and phosphatic fertilizers	Formulation (N:P:K content %)
Ammonium phosphate sulphate	13:39:0
Di-ammonium phosphate (DAP)	18:46:0
Mono-ammonium phosphate (MAP)	11:52:0
Ammonium phosphate nitrate	27:12:0
NPK	20:20:0
NPK	23:23:0

Complete fertilizers

The common types of complete fertilizers are NPK 20:10:10, NPK 15:15:15, NPK 17:17:17 and NPK 25:5:5 +5S. They contain all the three major elements, and in the fourth kind there is sulphur in addition.

Other forms of mineral fertilizers

Rock phosphate: Several types of rock phosphate have been used as a source of P. The most commonly used are rock phosphates from Mijingu, Sukulu, and Panda in Tanzania, and from Uganda. Usually the rock has a P content of 18–40% P_2O_5. The Mijingu rock phosphate (MRP) when finely ground has the following composition: P_2O_5 (31%), CaO (40%), Na_2O (1.3%), MgO (3.2%) and SiO_2 (9.4%). It may also contain some radioactive substances.

As with other conventional fertilizers, MRP is mixed thoroughly with the soil at planting. It can be used as a soil ameliorant for acid soils due to its high calcium con-

tent (CaO) of 40%. When added to compost manure, the quality of compost improves. However, compared to the other conventional P fertilizers, MRP releases its nutrients slowly over a long period of time, and the crop response to application of MRP is not as high as for the conventional (highly processed) fertilizers such as single or double superphosphates.

Classification of inorganic fertilizers based on application

Two categories are identified. These are:

- Planting (basal application) types
- Post-emergence types.

Planting fertilizers are used at the time of planting for most crops, depending on soils and agroclimatic zones. These include: DAP, MAP, TSP, SSP and NPK 23:23:0 and 20:20:0.

Top-dressing fertilizers are used mainly on food crops, but also occasionally on pastures. They include CAN, urea, ASN and sulphate of ammonia.

In addition, certain amendments can be applied to leaves as foliar feeds. Usually the formulation contains N as well as several micro-nutrients: Fe, Mo, Cu, Zn, Mn, Co, Bo, Cl and S. Potassium nitrate is also applied as a foliar feed to fruit trees, especially to induce flowering. It is usually formulated as NPK 13:0:46.

3.3.3 Fertilizer application

Since inorganic fertilizers are expensive, the method of application should be economical, accurate and efficient. The methods of application are both temporal (time) and spatial (space) based. These fall under three major categories.

Pre-plant applications

The method involves broadcasting (which entails spreading fertilizer over the entire surface of the soil to be fertilized), or applying the fertilizer to the planting rows, or to the actual planting hills. This is done immediately before planting.

The main objective in pre-plant applications is to distribute the fertilizer evenly, and usually to mix it with 5–10 cm of the soil surface by subsequent cultivation. Broadcasting is applicable either by hand or by tractor-drawn implements. At the small-scale level, the row or hill application is done by hand, confining the fertilizer to the planting points only. This reduces wastage of fertilizer.

At-plant applications

Here there are two common methods: placement with seed and band placement.

Placement with the seed

Applying the fertilizer at the same time as planting the seed is the most common practice for farmers who use hand or oxen-drawn equipment. Pangas or hand hoes are used to make a hole. The person preparing the holes according to the required crop spacing

would then apply fertilizer, while another person follows from behind to place the seed. Three fingers are used (i.e. thumb, index and middle finger) to simultaneously scoop out fertilizer which is applied where the seed grain will be placed. The second person will roughly stir the soil around the fertilizer and seed in a bid to mix and cover. This is to avoid direct contact of the seed with the fertilizer as too close association, especially with DAP fertilizer, can cause some burning of the seed, especially under insufficient soil moisture. Beans are particularly susceptible to damage in this way.

Band placement

Band placement entails placing the fertilizer to the side of and/or below the seed. It is more appropriate to use equipment mounted on a tool bar, which is either animal or tractor drawn.

Post-emergence application

Side dressing

Side dressing means placing the fertilizer beside the crop row. The kind of fertilizer being used determines its placement relative to the crop row. Side-dressed phosphatic and potassic fertilizers must be placed close enough to the row and sufficiently deep to be available to the plant roots. The placement of most nitrogen fertilizers is not as critical because of nitrogen mobility in the soil. However, plants are sensitive to high concentrations of ammonia, and nitrogenous fertilizers should, therefore, be placed a short distance from the crop row so that the concentration will be reduced as the fertilizer diffuses into the soil.

Top-dressing

Top-dressing entails applying fertilizers on top of the soil surface after crop emergence. Field crops and pastures can be top-dressed once or several times during the growing season.

Foliar application

This method is usually employed to supply N and micronutrients to a growing crop. Foliar sprays should be used to solve a temporary nutrient deficiency, or to obtain the required boost at a specific period, such as just before flowering. Long-term correction of nutrient deficiencies should be dealt with through proper soil and plant-tissue analysis followed by the indicated corrective action.

3.3.4 How much fertilizer to apply

Farmers have a tendency to buy what is in stock locally rather than what is appropriate for their needs. Neither are stockists in a position to advise farmers on the proper mix of fertilizers that would result in a ratio that is appropriate for a particular crop. The following are sample problems and calculations to give an insight into how to deal with this situation.

Sample problem 1

A farmer has 1.6 ha of land under maize. Two weeks after emergence, the crop shows signs of yellowing (chlorosis) affecting the lower leaves, and appears stunted. Advise the farmer on the fertilizer types to be used. Given that local traders have many types in stock, and the farmer needs your advice, how much of the fertilizer will be required?

Solution

Identify the missing nutrient, based on the symptoms, or soil data if available. In this case, it is suspected to be nitrogen. Note which fertilizers are available from stockists. Pick on nitrogenous fertilizers.

The recommended application rate for maize is 60 kg N ha^{-1}. Therefore, the farmer will require 96 kg N for the 1.6 ha (which is rounded off to 100 kg N). If the following are the available fertilizers in stock, KCl, DAP, SSP and urea, the choice will narrow down to either ammonia-oriented or nitrate-oriented fertilizers or both. In this case it is either DAP or urea.

Take DAP first. Table 3.5 shows the composition of DAP as NPK 18:46:0. The ratio for nitrogen is 18%. Use Table 3.6 (that is, the calculation or conversion table of nutrients to fertilizers) to decide how much fertilizer will be required.

From Table 3.6, 18% meets with 100 kg ha^{-1} at 556 kg. Since fertilizers are packed in 50 kg bags, the farmer will need approximately 11 bags of DAP. This costs approximately US$ 15 per 50-kg bag. Therefore, total cost is US$ 165 for the 1.6 ha.

Compare this with urea whose composition is 46-0-0. Using Table 3.6, 46% meets 100 kg at 217 kg. Therefore, 217 kg of urea are needed, which is a little over 4 bags of 50 kg each. This costs US$ 72. From the foregoing, it is more economical to buy urea than to buy DAP. There is also an added advantage from the lower cost of transport and application of the required amount of N using urea (fewer bags to handle). Also, P has not been indicated in the initial analysis, so why apply DAP? The farmer should note, however, that urea is a more acidifying fertilizer, it should not be used too frequently, and in any case not on soils that are already acidic.

Sample problem 2

From a stockist's shop, a farmer buys 4 bags of urea, 8 bags of triple superphosphate (TSP) and 2 bags of muriate of potash. If each bag is 50 kg, analyse the grade attained from mixing the fertilizers.

Urea: 4 x 50=	200 kg @	46:0:0
TSP: 8 x 50 =	400 kg @	0:46:0
KCl: 2 x 50 =	100 kg @	0:0:60

Solution

Get the total weight, given by 200 + 400 + 100 = 700 kg

Work out the individual nutrient from the mix.

Use the following formula.

Grade analysis/nutrient: $\frac{\text{Weight of fertilizer x \% element grade}}{\text{Total weight}}$

Therefore:

% N in urea: $\frac{200 \times 46}{700} = 13\%$

% P_2O_5 in TSP: $\frac{400 \times 46}{700} = 26\%$

% K_2O in the muriate of potash: $\frac{100 \times 60}{700} = 9\%$

Therefore, the fertilizer grade from the mix is NPK 13:26:9.

Note that nitrogen is listed as an element while the other two nutrients are listed in their oxide forms, i.e. N: P_2O_5: K_2O (or nitrogen, phosphoric acid and potash). Hence, to convert between amounts of phosphorus/phosphoric acid and potassium/potash, the following formulae are used:

P x 2.29 = P_2O_5
P_2O_5 x 0.44 = P
K x 1.20 = K_2O
K_2O x 0.830 = K
Mg x 1.66 = MgO
MgO x 0.602 = Mg
Ca x 1.39 = CaO
CaO x 0.715 = Ca

Example. Determine how much P is contained in one tonne (1,000 kg) of DAP 18:46:0.
Thus: P = $\frac{1{,}000 \times 46\%}{100} \times 0.44$ = 202 kg (or 10.12 kg in the 50-kg bag).

Sample problem 3

Determine the amount of nutrient in a fertilizer. To determine the amount of each nutrient in a fertilizer, the percentage of the nutrient is multiplied by the weight of the fertilizer, e.g. in a 50-kg bag of DAP (NPK 18:46:0):

Nitrogen: $\frac{50 \text{ kg} \times 18\%}{100}$ = 9 kg

Phosphate (P_2O_5): $\frac{50 \text{ kg} \times 46\%}{100}$ = 23 kg

Therefore P will be 23 x 0.437 = 10.0 kg.

Table 3.6 *Fertilizer calculation table*

Percentages (%) N, P_2O_5, K_2O in fertilizers (as shown on the bag) For example: 18:46:0, 26:0:0 or 17:17:17	Nutrient needed (kg/ha)																			
	5	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100
5	100	200	300	400	500	600	700	800	900	1,000	1,100	1,200	1,300	1,400	1,500	1,600	1,700	1,800	1,900	2,000
8	63	125	188	250	313	375	438	500	563	625	688	750	813	875	938	1,000	1,063	1,125	1,188	1, 250
10	50	100	150	200	250	300	350	400	450	500	550	600	650	700	750	800	850	900	950	1,000
11	45	91	136	182	250	273	318	364	409	455	500	545	591	636	682	727	773	818	864	909
12	42	83	125	167	208	250	292	333	375	417	458	500	542	583	625	667	708	750	792	833
14	36	71	107	143	208	214	250	286	321	357	393	429	464	500	536	571	607	643	679	714
15	33	67	100	133	179	200	233	267	300	333	367	400	433	467	500	533	567	600	633	667
17	29	59	88	118	167	176	206	235	265	294	324	353	282	412	441	471	500	529	559	588
18	28	56	83	111	139	167	194	222	250	278	306	333	361	389	414	444	472	500	528	556
20	25	50	75	100	125	150	175	200	225	250	275	300	325	350	375	400	425	450	475	500
21	24	48	71	95	119	143	167	190	214	238	262	286	310	333	357	381	405	429	452	476
22	23	45	68	91	114	136	159	182	205	227	250	273	295	318	341	364	386	409	432	455
23	22	43	65	87	109	130	152	174	196	217	239	261	283	304	326	348	370	391	413	435
24	21	42	63	83	104	125	146	167	188	208	229	250	271	292	313	333	354	375	396	417
25	20	40	60	80	100	120	140	160	180	200	220	240	260	280	300	320	340	360	380	400
26	19	38	58	77	96	115	135	154	173	192	212	231	250	269	288	308	327	346	365	385
28	18	36	54	71	89	107	125	143	161	179	196	214	232	250	268	286	304	321	339	357
32	16	31	47	63	78	94	109	125	141	156	172	188	203	219	234	250	266	281	297	313
33	15	30	45	61	76	91	106	121	136	152	167	182	197	212	227	242	258	273	288	303
35	14	29	43	57	71	86	100	114	129	143	157	171	186	200	214	229	243	257	271	286
38	13	26	39	53	66	79	92	105	118	132	118	158	171	184	197	211	224	237	250	263
40	13	25	38	50	63	75	88	100	113	125	138	150	163	175	188	200	213	225	238	250
45	11	22	33	44	56	67	78	89	100	111	122	133	144	156	167	178	189	200	211	222
46	11	22	33	40	54	65	76	87	98	109	120	130	141	152	163	174	185	196	207	217
50	10	20	30	40	50	60	70	80	90	100	110	120	130	140	150	160	170	180	190	200
60	11	17	25	33	43	50	58	67	75	83	92	100	108	117	125	133	142	150	158	167

Source: Government of Kenya 1998.

Use of the fertilizer calculation table

Table 3.6 can be used to find the right amount of individual fertilizers to use if the crop requirements and the percentage nutrients in the available fertilizers are known. The following is an example of how to use the table.

A farmer is advised to apply 60 kg N ha^{-1}, and has some urea at hand. How much urea does he need to apply? Urea is NPK 46:0:0. Locate the point where 46% meets 60 kg of the nutrient needed. This is 130 kg of urea needed.

How much DAP (18:46:0) and CAN (26:0:0) does he need if he wants to apply the nutrient rate of NPK 90:60:0 per ha? First, calculate the amount of DAP needed to supply 60 kg P_2O_5. Locate the point where the 46% and 60 kg meet. This is 130 kg. Next find the nearest figure to 130 in the 18% column. This is 139, which corresponds with 25 kg under the 'nutrients needed' column. Deduct this from 90 kg in the recommended rate. This is 65 kg N ha^{-1}, which should now come from CAN. To get the amount of CAN to supply 65 kg N, locate the point where 65 meets 26%. This is 250 kg N ha^{-1}. Therefore, the farmer needs to apply 130 kg DAP and 250 kg CAN per ha.

3.4 LIMING

Application of lime is carried out to manage soil acidity problems, improve availability of some plant nutrients, such as P, and promote microbial activity. For maximum contact, lime is mixed with the moist soil. For clay soils, best results are obtained by applying part of the lime before primary tillage and the rest thereafter. The laboratory will send the soil data, as well as information on the rate of lime application. The recommended rate of lime is 1.65 t ha^{-1} per milliequivalent of exchangeable Al.

For high pH-demanding legumes, e.g. common beans, apply lime 3–6 months before seeding so that the lime has time to react with the soil. The frequency of liming the same piece of land is best determined by soil testing, which should be done once every 3–4 years for annual crops but more often for sandy soils and soils under irrigation.

Demonstrations have shown increased yield when lime is used in acid soils (Plates 41a and b). Work in Embu, Kenya, showed that liming increased maize yields from 0.25 t ha^{-1} to 1.2 t ha^{-1}. The increases in yield resulted from the reduced soil acidity and the improved P, Ca and Mg availability.

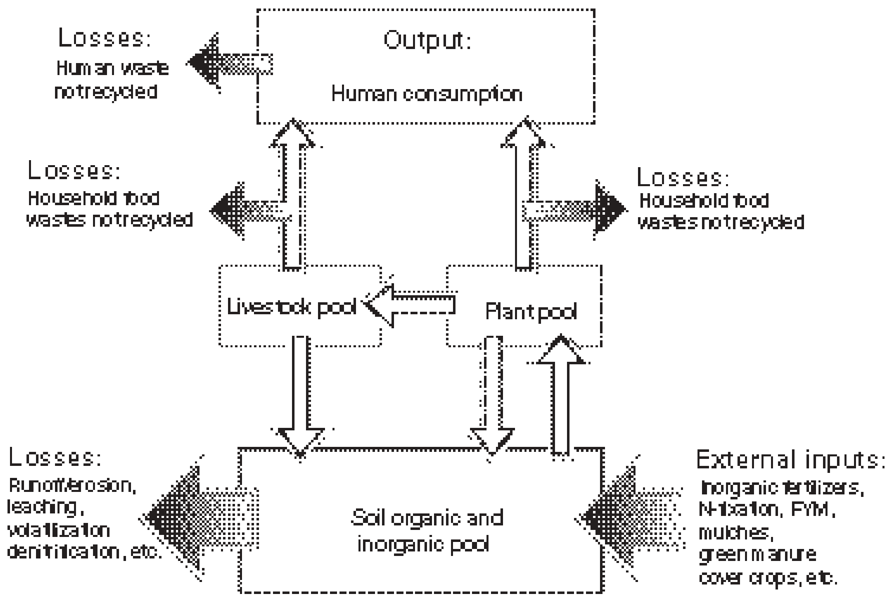
Plate 41a: Effects of lime on young maize crop grown in acid soils: Lime applied

Plate 41b: Effects of lime on young maize crop grown in acid soils: No lime

3.5 INTEGRATED SOIL FERTILITY MANAGEMENT

Integrated soil fertility management (ISFM) involves the use of carefully calculated combinations of mineral and organic fertilizers in association with complementary crop practices such as tillage, rotation, and moisture conservation.

The broad aim of ISFM is to utilize available organic and inorganic sources of nutrients in a judicious and efficient manner. Optimal nutrient cycling is essential, the aim being to create a tight system that synchronizes the release of nutrients by the soil with the demand by the crop. At the same time, the system seeks to minimize nutrient losses that would occur through leaching, soil erosion, runoff, volatilization and immobilization. Figure 3.5 shows how available organic and inorganic resources can be properly utilized in an integrated nutrient management strategy to improve soil fertility on a farm.



Source: Franzluebbers et al. 1998.

Figure 3.5 *Pools and fluxes in nutrient cycling*

Organic nutrient sources include FYM, plant residues, leguminous green manure cover crops, mulches, household and municipal garbage. An important aspect of ISFM is the maintenance of soil organic matter. With intensive cropping systems, recycling and re-using of nutrients from organic sources may not be sufficient to sustain high crop yields. Various amounts of nutrients removed from the soil, for example through harvested biomass, must be replenished from external sources. Thus the use of adequate amounts of inorganic fertilizers is essential to maintain soil fertility. ISFM is therefore an important strategy for enhancing soil nutrients through the combined use of both organic and inorganic fertilizers.

Some farmers address soil fertility problems by combining several organic and inorganic fertilizers. This kind of practice should give better yields and improve soil productivity. Inorganic and organic fertilizers are not mutually exclusive; their concurrent use is strongly recommended.

While chemical fertilizers are able to release nutrients immediately for plant uptake, organic fertilizers are important in providing organic matter to the soil, which is required for improving water retention and soil structure. In addition, organic fertilizers such as FYM release nutrients slowly during the growing stages of a crop. Well-managed organic manures are rich in N, but are deficient in P, hence the need to add mineral phosphatic fertilizers in appropriate amounts when using mainly organic manures on the farm.

3.5.1 Alternative strategies for combined use of organic and inorganic fertilizers

Some farmers use legume cover crops or FYM to provide basal N. Then N fertilizer is used for top-dressing if rainfall is favourable and the crop shows N deficiency. If rainfall is not promising, or if crops do not show N-deficiency symptoms, farmers will save the N fertilizer for the next crop. The following are some options in using both organic and inorganic fertilizers.

- Apply a handful of manure or compost in the planting hole, then add a moderate amount of the chosen chemical fertilizer (e.g. DAP, TSP, SSP or rock phosphate).
- Alternatively, apply a handful of organic fertilizer in the planting hole, and then cover with topsoil. Wait until the crop is ready for top-dressing and apply moderate amounts of CAN or liquid manure.
- Alternatively, where green manures have been used, apply moderate amounts of inorganic fertilizer in the planting hole.
- Alternatively, use rock phosphate where other inorganic fertilizers are not available, but only on soils with low pH. In western Kenya, tithonia green manure is reported to enhance solubility of rock phosphate.

Application of ISFM in a Rwandan case study

In Rubona, Rwanda, a combination of lime, organic manure and inorganic fertilizers (NPK) was found to be the most efficient way of enhancing the fertility of highly weathered infertile soils (Table 3.7).

Table 3.7 shows that Rubona soils are extremely acidic. Under low pH conditions, there is usually a high concentration of aluminium ions in the soil solution. Most horticultural and cereal crops do not tolerate acidity and grow best in soils with pH values between 6.0 and 6.5. With an average of 2.5 meq of exchangeable Al, the lime requirement for these soils will be approximately 4.0 t ha^{-1} (Kamprath 1984). All the exchangeable bases are low, resulting in low base saturation. Soils with a base saturation of >50% are generally considered to be fertile.

In the Rubona case study, continuous cropping of maize followed by beans for eight years gave no yield in control plots. A single application of 2 t ha^{-1} of lime significantly

increased the soil pH, Ca content and CEC, and decreased the level of exchangeable aluminium. Application of 8 t ha^{-1} of fresh FYM annually combined with 300 kg ha^{-1} of N:P:K 17:17:17 every six months significantly improved soil organic carbon and crop production.

Table 3.7 *Soil characteristics of Rubona site, Rwanda*

Characteristic	0–10 cm	10–60 cm
% carbon	1.4	0.2
pH (H_2O)	4.6	4.5
pH (KCl)	3.5	3.4
Exchangeable Ca per 100 g of soil	0.7 meq	<0.7 meq
Exchangeable Mg per 100 g of soil	0.1 meq	<0.1 meq
Exchangeable K per 100 g of soil	0.1 meq	<0.1 meq
Exchangeable Na per 100 g of soil	Trace	Trace
Exchangeable Al per 100 g of soil	2.6 meq	2.4 meq
CEC per 100 g of soil	4.8 meq	4.5 meq
Base saturation	13%	15%
P-Bray 1 per 100 g of soil	8 mg	6 mg
Clay %	36%	38

Source: Rutunga et al. 1998.

3.5.2 Nutrient budgets

Analyses of nutrient flows from most smallholder farms in the eastern Africa region indicate a negative balance, i.e. more nutrients are taken out of the farm than are being added to the soil. The following example is given to determine whether the current farming and management systems are resulting in negative or positive flows (net removal or net addition to current nutrient stocks). This also shows whether the current management system is sustainable or not.

Example of nutrient budget calculation

Nutrient flows into the farm (addition of nutrients)

(a) Inorganic fertilizer

A maize farmer applied 50 kg ha^{-1} DAP (18:46:0) at planting, followed by 30 kg ha^{-1} CAN (26% N) for top-dressing; 50 kg of DAP would provide 9 kg N (18% x 50), and 23 kg P_2O_5 (46% x 50), and zero K. To find out how much P (elemental) is in P_2O_5, multiply the P_2O_5 by a factor of 0.44 (see Section 3.3.4). Therefore, the amount of P applied is 23 kg x 0.44 = 10 kg. The 30 kg CAN provides 8 kg N (26% x 30).

(b) Organic fertilizer

The only available organic fertilizer is FYM, which the farmer applies to the maize crop at the rate of 1.5 t ha^{-1}. Analysis of a sample of the same FYM shows that the manure contains 0.8% N, 0.2% P and 0.6% K. Thus, 1.5 t FYM contains 12 kg N, 3 kg P and 9 kg K.

The total amount of nutrients (N, P and K) added to the soil is the sum of the organic and inorganic fertilizers applied during the crop season. Thus the amount of N applied (as shown above) is 9 + 8 + 12 = 29 kg ha^{-1}; the amount of P is 10 + 3 = 13 kg ha^{-1}; while the amount of K is 9 kg ha^{-1}.

It is known that some of the nutrients added to the soil are taken up by plants, some are lost through leaching or erosion, while some are retained in the soil. Therefore, not all the nutrients are recovered by the crop. The amount taken up by the crop is referred to as the 'recovery' or 'uptake' efficiency. This is expressed as a percentage of the amount of nutrients applied. Recovery efficiency is generally estimated at 30–50% for N, 40% for P, and 60% for K.

Nutrient losses from the farm through volatilization and leaching

In this example, the following assumptions are made with regard to nutrient losses from the total amounts indicated above:

- Out of the 8 kg added through the CAN, 25% was lost through volatilization, that is, 2 kg was lost
- Loss of P through erosion is considered negligible since the farm has well-maintained terraces
- About 10% of the K added was lost through leaching: thus 0.9 kg was lost
- After these losses, the remaining nutrient amounts are: 27 kg N per ha, 13 kg P per ha, and 8 kg K per ha.

Nutrient removal with the maize harvest

Maize grain harvest takes away nutrients from the farm. Farmers also often remove maize stover for feeding to livestock. One tonne of grain plus stover contains 24 kg N, 4 kg P and 23 kg K per ha. Assuming that 4.5 t ha^{-1} of maize grain and stover were harvested, this would remove 108 kg N, 18 kg P and 103.5 kg of K from the farm. Deducting the lost nutrients from the added amounts would leave negative balances.

Results

The results, summarized in Table 3.8, show that there is a net loss of N, P and K due to the grain and stover harvested and removed, and other losses. The system requires sufficient replenishment of the nutrients lost otherwise the farm's production will continue to decline.

Table 3.8 *Nutrient budget calculation (kg ha^{-1})*

Nutrient	Amount added	Estimated losses	Material removed: grain + stover	Net balance
N	29	2	108.0	–81.0
P	13	0	18.0	–5.0
K	9	1	103.5	–95.5

3.6 CONCLUSION

The material presented in this chapter emphasizes the importance of both organic and inorganic fertilizer for increased food production. The fertility of some soils can be maintained if good-quality organic fertilizers are available in sufficient quantities, but many soils need the addition of inorganic fertilizers, and sometimes lime, to maintain high yields. Farmers relying solely on organic fertilizers face the problem of scarcity of organic materials and variable quality depending on the source and the way the materials are handled. Inorganic fertilizers are not readily available to the small farmer, and are often not applied in the right amounts. Apart from the high costs of inorganic fertilizers, determining the right type to use has been, and continues to be, a major problem. The countries in the region are yet to come up with site-specific or ecozone-specific fertilizer recommendations. In addition, there are several other physical, socio-economic and policy issues that have contributed to the decline in soil fertility, but discussion of these is beyond the scope of this book.

Chapter 4

Case studies of soil fertility improvement

This chapter presents seven case studies based on farmers' experiences with green manure or cover crops. The examples are taken from Uganda, Rwanda, Tanzania, Kenya, Ethiopia and Zambia. They highlight the potential of green manure or cover crops for improving soil fertility and land productivity .

Case study I: On-farm evaluation of green manures in Ikulwe village, Iganga District, Uganda (adapted from Fischler and Wortmann 1999)

On-farm trials were conducted with active farmer involvement to integrate green manure into maize–bean cropping systems. Farmers observed less soil compaction after one season of a green manure crop compared to a weedy fallow or a maize crop. They also mentioned the efficient weed suppression by green manures. In most cases, no weeding was necessary for maize grown with mulches of the previously grown sole-cropped crotalaria, mucuna or lablab, while one weeding was sufficient for beans grown after a sole crop of crotalaria.

Farmers' preferences with regard to the effect of green manures on the subsequent maize grain yields were in the order: sole mucuna and lablab > sole crotalaria > intercropped crotalaria. Farmers preferred mucuna and sole lablab to crotalaria, particularly for erosion control. The farmers' evaluation of green manure indicated that, in addition to yield increases, other beneficial effects such as increases in soil fertility, weed suppression, soil moisture conservation, reduced soil compaction and erosion control, were important criteria, particularly in view of labour demand (Table 4.1).

In the Ikulwe case study, labour requirements for establishing a green manure crop varied according to species and cropping pattern. Crotalaria had higher weeding requirements, and therefore higher labour demand, for establishment as compared to mucuna and lablab. However, for production and mulching, sole-cropped mucuna and lablab required additional labour, but this was offset by the reduced labour for tillage and weeding in the seasons following establishment. The information obtained from on-station research, research conducted in collaboration with farmers, and farmers' own experimentation, led to the development of a decision guide on the use of green manure or cover crops (Table 4.2). The guide allowed the farmers to choose the right type of green manure or cover crop species.

The subsequent effects of green manure encouraged farmers, and their observations indicated an increased awareness of the long-term benefits such as improved soil physical and chemical properties and erosion control.

Table 4.1 *Farmers' evaluation of green manure cover crops on soil properties, labour demand, weed incidence and crop growth, Ikulwe Village, Iganga District, Uganda*

Observation	Crotalaria	Mucuna	Lablab	Maize
Observations of soils at planting of the first and subsequent crops	The soil after crotalaria was soft (friable) and thus easy to till	The soil was dark, soft and loose (porous). In most cases, there was a thick layer of leaves protecting the soil from erosion	The soil was moist, cool and soft at the end of the season. The top of the soil changed from brown to blackish. A thick layer of leaves covered the soil at the end of the season protecting it from erosion. The soil remained softer for a long time after uprooting the lablab	The soil was hard and dry at the planting of the subsequent maize crop
Labour demand for uprooting green manure crops and mulching of subsequent crops	It was easy to uproot and mulch crotalaria. Two elderly farmers said that uprooting and mulching was tiresome	Uprooting mucuna was rather difficult because it is deep rooted. It can be difficult to find the base of the twining plant. It was very easy to till.[1] No weeding was necessary at the planting of the subsequent maize crop	Uprooting lablab was difficult because it is deep rooted. Coarse material had to be cut to ease the planting of maize. There was no need to till the whole plot.[1] No weeding was necessary at the planting of the subsequent maize crop	Tillage and weeding were laborious, but subsequent planting was easy
Incidence of weeds in subsequent crops	In most cases, one weeding in beans but no weeding in maize was necessary because there were few weeds after crotalaria	There were no weeds at the time of planting the subsequent maize crop and only few volunteer mucuna plants grew during the season	There were no weeds during planting and only a few during the season	There were many weeds at planting and during the season
Growth of first subsequent crop	Maize germinated and grew well. The yields were high. Beans germinated well, and in most cases yields were high	Maize germinated and was greener and taller than maize grown after maize. The yields were high	Maize grew very well; it was greener, had thicker stems, and was less affected by drought compared to maize grown after maize. The yields were high	The maize crop did not look very good and the yields were much lower compared to maize grown after the green manure crop

Source: Fischler and Wortmann 1999.
[1] Farmers did not till the whole plot, only a narrow band where the maize was planted.

Table 4.2 *A farmer-designed decision guide on the use of four green manure species in central and eastern Uganda*

Farmer's objective	Suitable choice	Not suitable
Produce a sole crop	Mucuna or lablab	Canavalia
Intercrop with maize	Canavalia, or lablab at very low density	Mucuna
Intercrop with newly planted banana or coffee	Canavalia	Mucuna or lablab
Intercrop with established banana or coffee	Canavalia/mucuna at low density	Crotalaria
Intercrop between sweet potato mounds	Crotalaria or canavalia	Mucuna or lablab
Intercrop with newly planted cassava	Canavalia or crotalaria between rows of cassava	Mucuna or lablab
Intercrop with established cassava	Canavalia/mucuna at low density	Crotalaria
Produce fodder	Lablab or mucuna	Canavalia or crotalaria
Suppress weeds	Mucuna or lablab	Crotalaria or canavalia
Reduce nematodes	Crotalaria	Canavalia
Produce durable mulch	Crotalaria/canavalia (allow to mature)	Lablab or mucuna

Source: Fischler and Wortmann 1999.

Case study II: Farmers' experiences on intensive fallows in the central highlands of Rwanda (adapted from from Raquet 1990)

In the central highlands of Rwanda, farmers identified shortage of land and declining soil fertility on the cropped land as the main problems affecting crop yields. Furthermore, there was lack of sufficient manure and/or compost to apply to the farms, and whatever was available was applied exclusively to banana groves. Fallows had been reduced to less than two years, which is too short to restore soil fertility. Use of intensive improved fallows therefore became an alternative to the traditional grazed fallows.

The work included screening new leguminous plants (64 species), recording their biomass production and the effect this had on subsequent crops. In addition, trials were conducted to investigate the effect of incorporating *Sesbania macrantha* into the standard mixture for intensive fallow (the standard refers to a mixture of *Cajanus cajan*, *Crotalaria lachnophora*, *Tephrosia vogelii* and *Desmodium intortum* or *D. uncinatum*). In farmers' field trials (46 farmers) different fallow mixtures and periods (2, 3, and 4 growing seasons) were investigated with respect to growth performance and effect on subsequent crops. A majority of the 64 leguminous species screened were unsuitable for intensive fallow. Legumes identified for different forms of intensive fallow are listed in Table 4.3.

Table 4.3 *Farmers' experiences with legumes for different intensive fallows in the Central*

Highlands of Rwanda

Species	Potentially suitable for:
Mucuna utilis, Canavalia ensiformis, Crotalaria podocarpa, C. retusa, C. zanzibarica, Lupinus albus, L. angustifolius, Mimosa invisa, Dolichos lablab	Seasonal fallow
Crotalaria agatiflora, Crotalaria sp. (ex DRC), *Desmodium discolor, D. distortum, Lablab purpureus*	Integration into seasonal or multi-seasonal fallow (either to supply fodder, food, fuelwood or ground cover)
Mimosa invisa, Stylosanthes guianensis	Pasture
Mimosa invisa	Ground cover in newly established forests

Source: Adapted from Raquet 1990.

Initial observations of farmers' fields and experimental results indicated that the mixtures had great promise in improving crop yields. During the first season, after a one-year fallow, yields of maize were 970 kg ha^{-1} for the natural weed fallow, and 1,700 kg ha^{-1} for the standard mixture.

In managing the intensive fallows, the farmers often did not follow the recommendations of the extension service, preferring to follow their own ideas (Table 4 4).

Table 4.4 *Farmers' management of intensive fallows in the Central Highlands of Rwanda*

Criteria	Recommended by the extension service	Practised by the farmers
Quality of site	Medium	Marginal
Time of sowing	Short rains	End of short rains to long rainy season
Duration of fallow	1 year	2, sometimes even 3 years
Time of cutting	End of long dry season	End of long dry season; middle to end of short wet season
Incorporation technique	4 weeks after cutting, incorporation of hacked material without thick stems	After waiting several weeks till leaves fall, removal of stems and incorporation of leaves
Subsequent crops	Maize, beans	Sweet potato (bean, soybean)

Source: Raquet 1990.

Due to the scarcity of land, farmers selected the poorest sites, where the land was no longer productive, for the intensive fallows. Most farmers allowed the fallow to remain for two or more years, thus giving a longer period for the restoration of the soil and ensuring considerable quantities of fuelwood.

As far as methods of incorporating the green manure were concerned, the farmers preferred to leave the green material for several weeks after cutting until all the leaves had fallen off. Stems, branches and large roots were used as fuelwood. After the intensive fallow, farmers grew a variety of annual and perennial crops. First preference was given to sweet potato, which is traditionally the first post-fallow crop on their farms.

Unlike the on-station trial results, farmers observed strong growth and good tuber formation in sweet potatoes. They expressed satisfaction with the gain in fuelwood and crop yields on land that they had abandoned before green manuring.

Case study III: Multipurpose use of macro-contour lines, West Usambara Mountains, Tanzania (adapted from Pfeiffer 1990)

In the 1970s, farmers in the West Usambara Mountains, Tanzania, started shifting grazing to the mountain slopes as intensive cultivation of horticultural crops was expanding in the valley bottoms, formerly used for communal grazing. This resulted in considerable soil erosion on the slopes, leading to continuous decline in crop yields. To deal with this problem, the Soil Erosion Control and Agroforestry Project (SECAP) was established, with support from GTZ, in 1980 in Lushoto District. Initially, 0.7-m wide contour strips of Guatemala grass (*Trypsacum laxum*) were used to control erosion and at the same time provide animal feed. More than 1,200 km of strips were established in the project area, and grass planting material became a marketable item in several villages.

Later it became apparent that a single line of fodder grass was not effective in controlling erosion, and that there was also strong competition between Guatemala grass and the adjacent field crops. The strip was diversified by introducing creeping legumes (mainly *Desmodium uncinatum*), shrubs (*Leucaena leucocephala*) and trees (G*revillea robusta*). The contour strip was widened (to form a 'macro-contour line') to an average width of 2 m. Apart from effectively controlling soil erosion, this had the added advantages of improving forage quality, production of additional fodder (legumes, trees and shrubs), firewood and timber, and reduction of competitive effects on adjacent field crops as the trees, legumes and shrubs rooted more deeply than grasses. After screening and selection of fodder-plant species, the best macro-contour lines were tested on 45 farms under different ecological conditions. Trials were carried out by SECAP extension workers in cooperation with the farmers.

It was noted that in the fields with macro-contour lines soil erosion and accumulation between the strips were balanced, in contrast to the fields without contour strips.

In spite of a 25% reduction in cropping area under macro-contour lines, maize yields were higher than in the traditional cropping system which has no contour strips. This was attributed not only to the regular application of manure (resulting from additional feed) but also to better utilization of rainfall (resulting from reduced surface runoff). Other benefits included increased milk and fuelwood production. Because of these by-products, the improved systems with macro-contour lines were widely adopted by the farmers.

Case study IV: Development and transfer of forage production technologies for smallholder dairying in coastal lowland Kenya

(adapted from Njunie et al. 1994)

In the high-rainfall areas of coastal lowland Kenya, animal feed resources are inadequate, both in quantity and quality, to meet nutrient requirements of lactating dairy cows. In 1974, researchers from different organizations began collecting and screening forage germplasm to identify locally adapted, productive forages for these coastal lowlands. *Leucaena leucocephala*, *Clitoria ternatea* and *Macroptilium atropurpureum* were identified as being suitable for on-farm testing. In 1990 these species were planted on 13 smallholder farms in plots managed jointly by extension staff, researchers and farmers. The fodder-production systems tested were sole stand of Napier grass, Napier grass intercropped with *Clitoria ternatea* or *Macroptilium atropurpureum,* and *Leucaena leucocephala* alleys planted with maize or Napier grass. The clitoria and leucaena performed well and merited further testing under farmer management.

Field days were held to introduce the technologies, such as recommended planting arrangements. More than 288 farmers planted the legumes. Over 95% of farmers had recommended the legumes to their neighbours. About 60% of farmers adopted the agronomic and feeding practices recommended by research and extension staff. It was further noted that membership of a dairy self-help group influenced the adoption rate of specific practices. The result was that:

- Participating farmers adopted the forage legumes and recommended them to neighbours
- Research–extension–farmer linkages were strengthened through the testing of technologies that addressed jointly identified objectives
- The above linkages were facilitating the transfer of other forage technologies
- The major factor for the success of this programme was that the technologies being tested addressed a need (i.e. for protein-rich forage) that had been jointly identified by farmers and extensionists, with researchers being asked to provide potential solutions.

Case study V: Simon Mwaura, a successful legume green manure farmer in Gatanga, Kenya **(adapted from Mureithi et al. 1998)**

Simon Mwaura started working with green manure legumes in 1994 when several species – *Mucuna pruriens* (mucuna), *Crotalaria ochroleuca* (crotalaria), *Lablab purpureus* cv. Rongai (lablab) and *Canavalia ensiformis* (canavalia or jackbean) – were introduced in Gatanga Division by the Legume Screening Network (now the Legume Research Network Project – LRNP) of the Kenya Agricultural Research Institute, in collaboration with Environmental Action Team, a local NGO based in Kitale, Kenya.

Gatanga Division is a densely populated area about 45 km north of Nairobi. The predominant soils are Nitisols, which are slightly acidic (pH 5.6). The terrain is hilly with slopes ranging from 2% to 45%. The area receives a mean annual rainfall of 1,500 mm. Farm sizes are small, ranging from 0.1 to 2 ha, and are becoming even smaller as

a result of subdivision. The main cash crops are coffee, avocado, banana and arable crops (which include maize, beans and sweet potato), and horticultural crops such as tomato and French bean. A major constraint to improved yields is declining soil fertility as a result of continuous cultivation and soil erosion.

Green manure legumes were introduced to farmers in Gatanga to address this constraint, and Mwaura and his wife were among the first participating farmers. The soil of their small piece of land (0.4 ha) had become exhausted after long years of cultivation, and its productivity was low. Mwaura recalled that the maize yield from a plot of 55 x 13 m was only 90 kg, which is 1.3 t ha. Of the legumes that were introduced, they were particularly impressed by the performance of mucuna and crotalaria. This is because they were quick to establish and produced high biomass.

The farmer observed that because of the faster establishment, the legumes covered the ground quickly, reducing soil erosion and suppressing weed growth. Maize yields increased threefold from 1.3 to 4.5 t ha. The farmer observed that such yields are the same as those obtained by farmers using fertilizers, but the latter spend much more money buying the fertilizer than he spends on the legumes. Nowadays, Mwaura and his wife strongly believe that the green legumes restored 'life' to their soil! Because their plot of land is small and cannot support a dairy cow, they have bought dairy goats for provision of milk for home consumption. They are so impressed by the legumes that they have introduced leguminous fodder trees such as *Leucaena leucocephala, Calliandra calothyrsus* and *Sesbania sesban* for feeding the dairy goats. The trees will also provide firewood, which is scarce in the area.

Although Mwaura and his wife were not impressed by canavalia as a green manure legume, they are now growing it for controlling moles. During the initial efforts to introduce the legumes, they were taught that canavalia plants could repel moles, and they subsequently confirmed this on their farm. Previously, moles were causing serious damage to sweet potatoes, maize at the tasselling stage and banana stems. Nowadays, there are no moles and the crops are thriving.

Resulting from the successes that they have had with legumes, these farmers have become trainers on the value of green manure legumes, and how to establish them. Many farmers have visited them to learn about the benefits of the legumes. In 1997, they trained ten other farmers and supplied them with mucuna and crotalaria seeds free of charge. Their involvement with the trainees does not stop after training. They visit the trainees regularly to monitor their progress.

Another important task they undertake is that of seed bulking. Mwaura says that they decided to bulk seed because of the serious problem they had in acquiring seed when they wanted to expand their plot. Therefore, they decided to set land aside for bulking mucuna, canavalia and crotalaria seeds for their own use and for sharing with other farmers. In 1997, they produced about 50 kg of mucuna and 30 kg of crotalaria seeds. The LRNP bought 16 kg of mucuna seed from them for distribution to other farmers.

4.6 Case study VI: Approaches to restoring soil fertility using legume cover crops in Gununo (Gondar, Amhara), Ethiopia

(adapted from Amede et al. 2001)

Gununo is at an altitude of 1,920 m a.s.l. and has a mean annual rainfall of about 1,300 mm. The rainfall is bimodal, with a short rainy season (*belg*) from March to June and the main rainy season (*meher*) from July to the end of October. The dominant soils are eutric Nitisols. Farmers in the area identify and classify soil types primarily on the basis of crop yield, organic matter content, colour, workability, soil texture, land-use system or crops grown, location and distance from the homestead.

The farming system is characterized by small-scale production of mixed crops and livestock. Due to high population pressure (450 people per km^2), farmers have been forced to cultivate steep areas that used to be earmarked for grazing or for tree growing. This, coupled with continuous cultivation (the average landholding is about 0.25 ha per household), has resulted in decline in soil fertility.

To address the problem of low soil fertility, researchers set up Farmer Field Schools on legume cover crops aimed at introducing farmers to various legume cover crops and evaluating their performance under local conditions. The legume cover crop species tested were trifolium, stylosanthes, crotalaria, mucuna, tephrosia, vicia and canavalia. Participating farmers were asked to evaluate the performance of the legume cover crops and, after some discussion, they agreed on seven indicators: the root system, establishment of the crop, biomass production, resistance to drought, decomposition rate of the green manure, effects on soil moisture, and fodder value.

The importance attached to each indicator varied according to the socio-economic status of the farmers assessing it. For instance, livestock owners favoured legumes that can be used for feeding animals, like vetch and stylo. Farmers whose land was steep and affected by erosion found mucuna and canavalia best suited to their needs. Because of the acute shortage of land, farmers were unwilling to allocate a full growing season to legume cover crops. A likely niche identified for integrating legume cover crops was the outfield (*shoka*), where small-seeded cereals are grown in rotation with maize. The possibility of integrating the best bets (or options) as relay crops with short -term fallow to improve the degraded outfields was also being looked into.

Case study VII: Improved fallow systems developed through farmer-designed and farmer-managed trials in Kalichero, eastern Zambia **(adapted from ICRAF 1996)**

Most countries in the southern Africa region are faced with the problems of soil fertility depletion, food and fodder shortage, and decreasing supplies of fuelwood. Against this backdrop, the Southern Africa Agroforestry Research Network (SAARNET) was launched through ICRAF in 1987, with activities in Malawi, Zambia, Tanzania and Zimbabwe, and a mandate to generate agroforestry technologies to address the problems of declining food security and soil fertility, and shortage of fodder and fuelwood.

Work on improved fallows in Zambia is highlighted in this case study. In all improved-fallow research with sesbania *(Sesbania sesban)* in Zambia, both on-station and on-farm, the woody biomass is removed from the fallow area when the field is cleared and only the leaf and twig material is incorporated into the soil. The wood is used as fuel and as light construction material.

In 1993/94, farmers established trials which they themselves designed and managed using sesbania seed or seedlings obtained from researchers and extension staff. The farmers visited research trials to learn about the technology but were not given an experimental plan to follow; rather, they were encouraged to experiment with the technology as they wished. The objective of the trials was to assess farmers' experiences with the technology and how they modified it, and to provide feedback to researchers. In 1996, following their first post-fallow harvest, the farmers, three men and two women, were interviewed concerning their experiences. The experience of Ms Zeliana Mwanza, head of a household in Kalichero camp, near Chipata in the Eastern Province of Zambia, and results of the other farmers are given below.

Zeliana Mwanza learned about improved fallows through her camp officer in the 1993/94 season, shortly after the officer had attended a field day at Msekera Research Station. In January 1994, project staff planted a trial in Kalichero that they had designed and managed, and Zeliana was able to collect 620 sesbania seedlings. Her farm is 6 km from Kalichero. She used the seedlings to establish a trial she designed and managed herself, with an improved fallow of 528 m^2. Shortly thereafter, Zeliana herself attended a field day at Msekera and visited other farmers who had planted improved fallows. At the start of the 1994/95 season, she used naturally regenerated seedlings from her one-year fallow plot to fill gaps in her field and to establish a second, smaller improved fallow. She also tried to plant an improved fallow of pigeonpea (*Cajanus cajan*), but failed because of drought in the early part of the season.

In late 1995, Zeliana cut down her two-year-old sesbania trees and incorporated the leafy biomass into the soil. She used the firewood for cooking meals in the field – firewood that she said she would have collected from about 5 km away had she not had the sesbania firewood. She was very pleased with her maize yield after the fallow period – she harvested 232 kg from the plot (4.4 t ha). Her biggest problem associated with the fallows was the labour required for cutting the trees. She and her oldest child cut them with axes.

The five farmers in the trial planted a total of 17 improved fallows over the period 1993 to 1996. All used planting material from their own farms to plant new fallows, taking care to maintain a broad base by collecting seed from more than 30 trees. All were experimenting with the technology, testing such practices as:

- Intercropping with different crops (maize, sunflower, cowpeas or groundnuts) during the year of establishment
- Intercropping with maize during the second year after establishment
- Varying the time of planting of the intercrop with respect to that of the trees
- Weeding during the first year after establishment.

In 1996, the five farmers harvested their first crop of maize following a sesbania fallow: four had fallowed for two years and one for three years. The results were extremely promising, and on four of the farms maize yields increased by between 1 and 4 t ha^{-1} as compared with maize continuously cropped without fertilizer. Maize yields after the fallow exceeded those of fertilized maize on two of the farms. On the fifth farm, where the fallow had lasted three years, maize yields after the fallow period were only 77% higher than those of continuously cropped maize without fertilizer. Here, two problems were responsible for poor performance of the fallow: failure to weed and incidence of fire. Although fire is common in the area, it does not usually affect improved fallows. Nevertheless, protection against it is essential.

Three of the five farmers distributed seed to a total of 28 other farmers. All five planned to plant new improved fallows during the 1996/97 season. All the farmers indicated that there were beneficial effects of sesbania fallows on subsequent maize (or sorghum) yields compared with grass fallowing, continuous monocropping or rotational cropping.

4.8 CONCLUSION

The above case studies show clearly that farmers are very interested in the potential of legumes as green manure cover crops. Due to the wide range of ecological and socioeconomic conditions in the eastern Africa region, it has been necessary to try out many different legume species in order to find out which will be suitable in particular situations. Much of the investigative work has been done in close collaboration between farmers, researchers and extensionists. The results are exciting. Farmers have identified species which improve fertility, increase fodder for livestock, provide fuelwood and raise yields. Even in situations where holding sizes are small, some farmers are finding that land which has become exhausted can only be restored to productivity with the help of legume cover crops.

Chapter 5

Agroforestry for soil fertility improvement

5.1 INTRODUCTION

'Agroforestry is a dynamic, ecologically based, natural resource management practice that, through the integration of trees on farms and in the agricultural landscape, diversifies and sustains production for increased social, economic and environmental benefits' (ICRAF 2000).

Therefore agroforestry is promoted as a way of providing a variety of goods and services (including wood and non-wood products) to individual farmers and to the society as a whole.

5.2 ROLE OF AGROFORESTRY IN SOIL FERTILITY IMPROVEMENT

5.2.1 Nitrogen fixation

Micro-organisms (bacteria and fungi) in root nodules and mycorrhiza of certain trees and shrubs fix nitrogen from the atmosphere into a form crops can use in the soil. Some examples of nitrogen-fixing trees and the average amount of nitrogen fixed per hectare per year are shown in Table 5.1.

Table 5.1 *Nitrogen fixation by some trees and shrubs*

Species	kg N ha^{-1} yr^{-1}
Acacia albida	20
Acacia mearnsii	200
Allocasuarina littoralis	220
Casuarina equisetifolia	60–100
Coffee + *Inga* spp.	35
Erythrina poeppigiana	60
Gliricidia sepium	13
Inga jinicuil	35–40
Leucaena leucocephala	100–500
Prosopis grandulosa	40–50
Prosopis tamarugo	200

Source: Adapted from Young 1989.

5.2.2 Substitution of nitrogenous fertilizer by leguminous trees

In humid and sub-humid areas certain nitrogen-fixing trees have the capacity to yield 100–200 kg N ha^{-1} yr^{-1}. In the drier areas, nitrogen yield ranges from 50 to 100 kg. In nitrogen-deficient soils, it is common for each kilogram of added nitrogen to raise the cereal yield by 10 kg ha. Thus a cropping system using nitrogen-fixing trees has a potential either to raise cereal production by 1 tonne per hectare or to act as a substitute for purchasing five 20-kg bags of nitrogen fertilizer or 100 kg nitrogen. Using nitrogen-fixing trees in this way is popular with farmers who do not have access to fertilizer.

Sesbania sesban tree fallows grown in rotation with crops are known to improve soil fertility and increase yields. Studies conducted in Zambia and Kenya indicated that sesbania fallows increased maize yield, relative to unfertilized maize monoculture, for two or more cropping seasons after harvest of the fallows on the N-deficient soil. There was the additional advantage of sesbania providing fuelwood, which is in short supply for many households in the densely populated areas. Studies carried out in western Kenya (Rutunga et al. 1999) showed that *Tephrosia vogelii* and *Tithonia diversifolia* can accumulate sustantial amounts of biomass and nutrients (N, K and Ca) during a six-month fallow (Table 5.2), and indicated that a period of six months is appropriate for the production of high-quality biomass for green manuring.

***Table 5.2** Nutrient accumulation during a six-month fallow period*

Species	Total biomass* (t ha^{-1})	Nutrients (kg ha^{-1}) N	P	K	Ca	Mg
Tephrosia vogelii	9.5	154	5.7	100	75	17
Tithonia diversifolia	11.8	191	8.1	271	70	32
Natural fallow	3.8	5.4	2.6	52	10	7

* Above-ground, litter and root biomass.
Source: Rutunga et al. 1999.

Low levels of P in the two species indicate that improved fallows are unlikely to eliminate the need for P fertilizers on P-deficient soils, hence the need to use both organic and inorganic fertilizers for maximum crop production (see Chapter 3). *Casuarina equisetifolia* (Plate 42) has been used for rehabilitation of quarries and open mines in Kenya as it fixes nitrogen and can do well on N-deficient soils, such as those derived from coral, which have adequate supplies of other nutrients.

Plate 42: *Casuarina equisetifolia* – a tree for land rehabilitation

5.2.3 Humus from root and litter decomposition

Under normal conditions, new roots of trees develop while some of the older roots die back. As the old roots decompose, they add organic matter to the soil. Leaf litter from trees provides nutrients and organic matter to the soil. When the leaves fall or are cut and incorporated, they decompose and release humus and minerals to the soil. In a process called 'nutrient pumping', or nutrient cycling, roots of trees carry valuable minerals from below the soil surface, often from below the root zone of agricultural crops, to the leaves. When the leaves are cut or fall, the nutrients go to the food-crop rooting zone of the soil.

Plant litter of different quality contributes differently to the properties and maintenance of humus. High-quality residues are high in nitrogen, low in lignin and polyphenols, and decay rapidly, giving short-term release of nutrients to meet peaks of plant requirement. (See also Section 3.5.)

The leaves decay faster when applied fresh than when dry, and when buried (incorporated) in the soil as opposed to being placed on the surface of the soil.

Examples of soil-improving trees

Acacia albida (*Faidherbia albida*) is one of the best-known soil-improving trees. It is highly valued by farmers in the semi-arid areas. Increases of 50–100% in soil organic matter associated with a higher water-holding capacity and more nitrogen beneath the trees as compared to the surrounding areas have been noted. Yields of millet and groundnuts with no fertilizer can be up to 100% higher under these trees. Maize and sorghum yields in Ethiopia were over 50% higher under trees when compared with areas without the trees.

Acacia senegal (gum arabic) is used in a system of rotational intercropping in Sudan. After four years of intercropping with food crops, the trees are left as soil-restoring fallow for some 16 years before felling and replanting. Acacias, and notably *Acacia tortilis* in the dry areas, benefit the growth of pastures beneath them. The effect of trees is combined with the effect of animal droppings that accumulate when birds and animals rest under the trees.

Monocropping and continuous farming of the same parcel of land can seriously degrade the soil. Applying fertilizers helps replace lost nutrients, but appropriate nitrogen-fixing trees can supplement inorganic fertilizers. Analysis of economic returns from cereal cropping under *Acacia albida* in the eastern highlands of Ethiopia showed an income gain of 82% was possible where cropping was under 5 trees per ha compared to treeless fields (Poschen 1986).

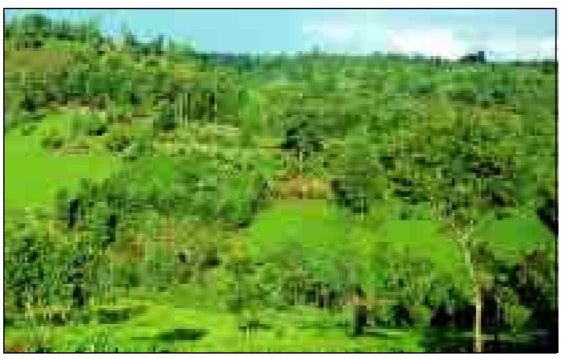


Plate 43: Agroforestry (general view)

5.2.4 Improving soil chemical conditions

Trees have the potential to improve acidic soils, or soils already rich in bases, through addition of bases in tree litter. Organic compounds combine with and bind aluminium ions, leading to a lowering in soil acidity.

Characteristics of a good soil-improving tree

The following are some of the characteristics of trees that are good for improving soil:

- A high rate of biomass production above the ground
- A high rate of nitrogen fixation
- A dense network of roots to promote good mycorrhizal associations. (Mycorrhiza is the association, usually symbiotic, of fungi with the roots of plants. The association is mutually beneficial. After mycorrhizal spores germinate, hyphae invade rootlets, growing both inside and outside the rootlets. Fungal hyphae on the exterior of the root serve as an extension of roots for water and nutrient absorption. These fungus roots are called mycorrhizae.)
- The existence of deep roots to bring up nutrients from lower soil layers and to ensure minimal competition with field crops
- An appreciable nutrient content in the root system and in the leaves
- A rapid rate of litter decay for nutrient release
- Production of sufficient litter for soil cover to protect against erosion
- Absence of toxic substances in the foliage or root exudates
- For soil reclamation or restoration, a capacity to grow on poor soils
- Not too invasive (i.e. not weedy).

5.3 OTHER BENEFITS OF TREES

5.3.1 Water conservation

Trees increase soil-water retention through organic matter, which acts like a sponge, thus increasing the soil's ability to absorb and retain water. However, care is needed when planting trees on cropland in dry areas because they also compete with crops for moisture.

5.3.2 Windbreaks

Trees act as windbreaks, reducing the rate of evaporation caused by high temperatures and dry winds, and hence helping improve crop performance. *Grevillea robusta* has proved particularly popular with farmers in Kenya for use as a windbreak because it causes little interference with the adjacent crops (Plate 44).

Plate 44*: A* Grevillea robusta *windbreak*

5.3.3 Shade

Tree crowns shade the soil, thus lowering surface temperatures and reducing evaporation losses.

5.3.4 Conserving soil

Trees help to control soil erosion in a number of ways. First, the roots hold the soil together. This is especially valuable when trees are planted along the contours. Leaf litter on the soil surface, as well as the protection by the tree crowns, lessens the force with which raindrops strike the soil. This means that more water can soak into the ground and less soil is carried away by runoff. Windbreaks provided by trees reduce the wind speed across the cropped field, thus lowering the amount of soil that is blown away. Trees and shrubs arranged as hedges along contours act as physical barriers that intercept runoff and cause soil to be deposited. *Calliandra calothyrsus* has proved particularly useful as a hedge plant because it fixes nitrogen and provides excellent fodder (Plate 45).

Plate 45: *Calliandra calothyrsus* and sweet potato for fodder

5.4 MANAGEMENT SYSTEMS FOR AGROFORESTRY

5.4.1 How trees benefit within an agroforestry system

Tree seedlings planted with crops have high survival and growth rates because they receive the same attention given to the crops. The tree seedlings are fenced and protected from animals; they are weeded with the crops; they make use of fertilizer applied to the crops; crops such as maize, sunflower, cassava and bananas act as windbreaks and nurse crops for the tree seedlings and young trees.

5.4.2 Contour vegetation strips

Contour vegetation strips are a combination of trees, shrubs, grasses and creeping vines planted on the contour to control storm runoff and soil erosion. This technology is also known as a barrier strip or hedge, a horizontal vegetation strip, a contour hedge or horizontal hedgerow, or a macro-contour line.

Example of useful species for contour vegetation strips in cropland

Some useful species are *Acacia* spp., *Leucaena* spp., *Sesbania* spp., *Calliandra calothyrsus, Grevillea robusta, Prosopis* spp., *Gliricidia sepium*, *Tephrosia vogelii*, *Crotalaria grahamiana* and *Croton* spp. A diverse mix of small dense shrubs and herbaceous plants in the understorey is important. They may include fodder plants such as *Dichrostachys cinerea* along the edge, *Stylosanthes, Crotalaria* and *Indigofera* species, and *Lablab purpureus*. All these contribute to soil fertility, ground cover and fodder production. Natural vegetation can be encouraged within these plantings (see Case Study III in Chapter 4).

Management of contour vegetation strips

Vegetation strips can be managed by pruning, lopping and applying mulches for soil improvement, or providing the materials for fodder and fuelwood. Grasses and vines can be cut and carried for fodder. Controlled grazing can be practised.

Benefits

The benefits of contour vegetation strips are increased organic matter, nitrogen fixation by leguminous trees, fodder, fruits, pods and potential for bee keeping.

5.4.3 Rotational wood fallow (improved fallows) for soil fertility

Natural fallows take a long time to restore soil fertility, and land shortage has resulted in the practise of shorter fallows. Hence, nitrogen-fixing trees or shrubs can be used to restore soil fertility more rapidly. These improved fallows should include such leguminous species as *Sesbania sesban, Leucaena* spp. and calliandra. These trees are grown for several years, after which they are cut and replaced with a food crop. The trees should be established at close spacing to encourage quick production of large amounts of biomass and to suppress weeds. The trees should be protected from animals.

Example of species for improved fallows

Some species that can be used for improving fallows are *Acacia* spp., *Leucaena leucocephala, Sesbania sesban, Calliandra calothyrsus, Mimosa scabrella, Gliricidia sepium, Prosopis* spp. and *Cajanus cajan*. These in turn can be mixed with valuable timber species such as *Markhamia lutea*.

Establishment

Improved fallows can be established in a variety of ways. These include direct seeding of clean-tilled, harvested plots (some trees and shrubs are easily established by direct sowing through broadcasting of seeds); selective cutting of bush fallow while retaining some naturally regenerating trees; and planting tree seedlings into closely spaced, deep planting holes or furrows within blocks of cleared cropland.

The fallow period ranges from one to ten years, the optimum duration depending on the perceived importance of soil fertility improvement, the value placed on the trees

with long maturation periods (e.g. timber trees, fruit trees), the immediate need for food or cash crops, and the availability of alternative land for annual (food) crops.

Management techniques

Once established, little management is required except for protection from livestock. The fallow periods should be 3–5 years. At the final harvest, the farmer can leave rows of trees which can be used as a seed source for the next fallow.

Benefits

Some woody legumes can add up to 200 kg ha^{-1} yr^{-1} of N to the soil and a sizeable amount of organic matter. This contributes significantly to soil enrichment. If the farmer uses multipurpose trees, additional benefits are seen. For example, *Sesbania sesban* provides fodder and pigeonpea, *Cajanus cajan,* provides legume grain. Where fodder is cut, the farmer should be careful not to remove too much or the fertility benefit will be lost.

5.4.4 Vegetation cut-and-carry

This is the system of biomass production and transfer where vegetative material is harvested and transported to another site for incorporation into the cropland. This material should have a high content of nutrients to enrich the soils.

Leguminous tree species, shrubs and local herbs are, for example, *Sesbania sesban,* and *Leucaena, Calliandra* and *Crotalaria* species. Work by ICRAF in western Kenya has shown that a local non-leguminous shrub, *Tithonia diversifolia,* can be used for soil improvement, especially when cut and applied together with rock phosphate as it improves the availability of phosphorus.

5.4.5 Trees in irrigation schemes

Irrigation schemes are usually established to grow a monocrop (e.g. rice, cotton or sugar cane). Farmers are then given small plots to grow food crops, which they have little time to cultivate. It is important to diversify production to provide both food and income through use of appropriate low-maintenance species like pawpaw, mango and *Moringa oleifera.*

Establishment

Trees are established by planting seedlings along canal banks (every 1–4 m) or in farmers' plots (2–10 m between trees, depending on area available and tree species). Rows of sesbania can be established by planting or direct sowing between every four rows of sugar cane (5 m between rows and 0.5–1 m within the row).

Management

Trees established outside irrigation areas (e.g. planted forests and windbreaks) require watering or water-harvesting structures during establishment stages.

Pollarding and coppicing (Plates 46 and 47) may be done to minimize shade and competition for light. Competition for nutrients and water is reduced by pruning of the roots. This is done by digging a ditch along the line of trees, ensuring that the roots entering the cropland are cut. The root pruning will also clear the canals and ditches.

Plate 46: Pollarding (managing *Acacia albida* in cropland in Oromiya, Ethiopia)

Plate 47: Coppicing (managing eucalyptus trees)

A disadvantage of trees in irrigation areas is that they harbour birds, especially *Quelea quelea,* which prefer trees with straight, vertical and thin branches. Such trees should be avoided; alternatively, branches can be pollarded every 1–3 years. Birds of prey will scare away seed-eating birds, and they can be encouraged by providing suitable vantage points like tall trees and poles from where they can scan for prey. In most cases, the value of the tree products provided will compensate for crop losses caused by birds.

Benefits of trees in irrigated areas include keeping the water cool, reducing evapotranspiration, improving crop yields by nitrogen fixation, providing firewood, and leaves which can be mixed with sugar cane tops and bagasse for livestock feed. Some species, such as *Tamarix* spp., are capable of taking up salts, thus reducing the risk of salinity.

5.5 AGROFORESTRY FOR IMPROVING SOILS IN ARID AND SEMI-ARID AREAS

Suitable technologies are required for increasing the productivity of arid and semi-arid areas through efficient rainwater and soil management in order to achieve increased food, fodder, poles, timber and fuel production. These areas receive an annual rainfall of between 400 and 700 mm. The soils are characterized by high exchangeable sodium, high pH, poor physical properties, and generally dense impermeable calcic horizons. Due to their poor infiltration and water-transmission characteristics, precious water is lost as runoff, causing erosion and downstream flooding.

Water management, using sunken planting, can increase the survival and early growth of trees. A circular pit some 50 cm deep is dug and only partly refilled with a mixture of topsoil and manure. The resulting depression serves to collect and concen-

trate water around the seedling, thus enhancing soil moisture. Farmers have used water-harvesting pits for banana production in the dry areas of Kitui District, Kenya (see Plate 48).

Micro-catchments can also be used and have proved valuable with pawpaw. Micro-catchments are shallow excavated channels, about 10 cm deep, facing down the slope in the shape of a V or U, and enclosing the tree or planting pit. Additional watering during dry spells can be done by means of an inverted bottle (Plate 49) that is filled with a urine/water solution (preferably ¼ urine and ¾ water) and pushed into the soil around the base of the plant.

Plate 48: Bananas grown in water-harvesting pits, semi-arid Kitui District, Kenya

Plate 49: Bottle-feeding a young mango seedling planted in a pit

Agroforestry is considered an appropriate land-use system for such areas to ease food, fuel, fodder and timber shortages and improve soil conditions. The positive effects on the soil are based on the penetration of strong roots to deeper layers to bring up plant nutrients, enrichment of the soil in humus and nutrient content, and on the improvement of the nitrogen status of the soil. The improvement of the water intake rate of soil that is under tree cover also helps in the conservation of rainwater.

5.5.1 Establishment and management of trees in saline and sodic soils

To establish trees in saline and sodic soils, holes are dug measuring 60 x 60 cm deep. Farmyard manure is placed in the holes at the rate of 20 kg per hole (one 20-litre *debe* per hole). Bigger holes, for example measuring 90 x 90 cm, can lead to better establishment of the trees. The trees should be watered frequently for a full year after planting. Lopping for fodder or fuel can be done 6–42 months after planting, depending on the species and the growing conditions. Tree planting in combination with other vegetation is regarded as an important weapon in combating dryland salinity. Planting trees

can significantly lower the water table, and therefore reverse the causal process of salinization. Organic matter can hold up to 20 times its own weight in water. This helps to prevent drying and shrinking of soils, thus improving the moisture-retaining properties in sandy areas.

A ridge trench system of tree planting is appropriate in alkaline soils for *in situ* rainwater conservation to help increase biomass. *Eucalyptus tereticornis, Populus deltoides* and *Tectona grandis* are good for reclamation of salt-affected land. *Acacia* species can produce 3,700 kg litter ha^{-1} yr^{-1} at a spacing of 5 m x 6 m. Experimental evidence shows that the acacia trees increase soil organic matter and reduce soil pH. Some fruit trees that are also relatively tolerant of salinity are listed in Table 5.3.

Table 5.3 *Some fruit trees that are tolerant to soil salinity*

Common name	Botanical name
Date palm	*Phoenix dactylifera*
Fig	*Ficus carica*
Pomegranate	*Punica granatum*
Grape	*Vitis* spp.

Trees are able to draw calcium and other bases from deeper soil layers to be concentrated in the leaves, and hence transferred to the topsoil, thus reducing acidity. Many of the trees commonly used in agroforestry have a moderate level of calcium in their tissue. *Gmelina arborea* has a high content of calcium.

5.6 CONCLUSION

This chapter shows that there are many different shrubs and trees that can play a role in restoring and maintaining soil fertility. In addition, most species contribute to the production of fodder and fuelwood, as well as helping to control erosion. Some species can be grown in association with crops, while others are more suited to being grown separately, either along contour lines or field boundaries or on fallow land which is being rested from cultivation. Care is needed to avoid competition with crops for moisture in dry areas. Selection of appropriate species, together with proper establishment and management, are needed to ensure that agroforestry plays an effective role in the farming system.

Chapter 6

Tillage in land productivity

6.1 INTRODUCTION

Soil tillage may be defined as those physical, chemical or biological actions carried out to prepare or improve soil conditions for seed germination, emergence, establishment, root development and crop growth.

As indicated in Chapter 1, there has been a notable decline in land productivity in eastern and southern Africa. Soil fertility is depleted through continuous cultivation without return of the plant nutrients exported from the fields with the harvest; organic matter is lost as a result of current tillage practices, and there is little or no return of crop residues to the soil. Soil compaction, associated with hardpans and plough soles, reduces rainfall infiltration into the soil.

Together, all these factors influence two determinants of water availability for crop growth, namely, soil moisture availability in the root zone (rain does not infiltrate and low water-holding capacity results in high runoff), and low plant water uptake capacity due to poor root growth and weak plants.

It is estimated that of the total area of cultivated land in the eastern Africa region, about 80% is worked using hand tools, 15% using animal-drawn implements, and about 5% by engine power (tractors). Thus, the bulk of crop production still depends on direct human energy. Even where draught animals are used, the dominant tillage operation is land preparation using the mouldboard plough, while the rest of the operations are carried out with hand tools. The use of other animal-drawn implements such as harrows, planters, cultivators, rippers, sub-soilers and ridgers is limited.

6.1.1 Tillage for improved land productivity

Tillage is necessary for successful farming, and can be applied at different stages: before the onset of the rains to assure maximum infiltration; before planting to establish a good seedbed; during the crop growing season to control weeds; and to direct water to the crop through ridging and other operations.

However, it should be noted that the tillage strategies for maximum crop yields and improved land productivity are very site specific. They depend on factors like rainfall, the crop being cultivated, soil depth, soil structure, the presence of hardpans, and the slope. In areas with serious weed problems, low risk of compaction, and sufficient organic matter content, conventional tillage using a mouldboard plough may be the best option. In areas with moisture-stress problems and a high risk of erosion, minimum tillage using a ripper would be more appropriate.

There is a need to improve the tillage systems and implements that are available to farmers. Currently the predominant implement is the ox-drawn mouldboard plough. This limits the kind of operation and the soil depth that the farmer can attain. Conventional mouldboard ploughs cannot be used to break the hardpans that are prevalent on many small-scale farms. Improved tillage techniques and implements should assist the farmer to increase soil moisture, prevent soil erosion, and enhance soil fertility. However, the labour requirement and implements needed for each tilling operation should be considered.

The use of hand tools (Plate 50) is associated with high labour requirements per unit of land. The amount of labour required for operations such as weeding can be an important factor limiting the total area of land a household can cultivate. There are seasonal labour shortages at peak times. Such labour shortages affect the timing of field operations such as ploughing, planting and weeding, often resulting in their being done too late and not to the required standard, thus leading to a decline in yields.

Plate 50: Hand hoeing

This chapter outlines the main tillage options practised at present in the region, and discusses the potential of some different alternative systems and their applicability. No single tillage system will give optimal results for all combinations of soil, climatic and socio-economic conditions. The choice of tillage method will affect all other operations within a production system. Success will only be achieved once the tillage operations fit within the whole system, including timing of operations, how soil fertility is replenished, how organic matter is maintained, how weeding is carried out, timing and method of harvesting, crop rotation, and choice of intercrops.

6.2 OBJECTIVES OF TILLAGE

The long-term objective of tillage is the maintenance of soil productivity. A good tillage system should improve soil and water conservation, maintain soil organic matter content, and preserve soil structure and pore stability. Important objectives of soil tillage are to open up the soil for seed germination and easy root development; to control weeds; to incorporate crop residues, manures and chemical fertilizers; to increase water infiltration, intake and storage (from rainfall or irrigation); to minimize soil erosion through runoff management; and to remove excess water from the soil surface and from the root zone.

These objectives can rarely be met by a single tillage operation. Furthermore, the appropriate solutions must be site specific. There are no blanket prescriptions. However, it is generally agreed that overworking the soil through excessive tillage often damages its structure, thus causing compaction, or leading to erosion by wind and water.

The following sections discuss the functions and limitations of tillage in greater detail.

6.3 TILLAGE FUNCTIONS AND IMPACT

6.3.1 Seedbed preparation

There are three main aspects to seedbed preparation for optimum germination of seeds and growth of plants.

Improvement of soil tilth

A desirable tilth is one that allows rapid infiltration of rainwater and storage of soil moisture in the root zone of the crop, provides optimum air availability and exchange within the soil, and minimizes resistance to root penetration.

Incorporation of materials to supply nutrients or improve the soil

Mechanical tillage (with tools) can be used to incorporate fertilizers, animal manure and green manures in order to ensure a thorough mix into the soil to the desired depths of the root bed. Minimum and no-till systems depend on biological tillage – by micro-organisms – to decompose and transfer organic materials to deeper soil layers. Tillage can also be used to incorporate other compounds like lime, which is used to improve the productivity of acidic soils.

Increasing the rooting depth

One of the reasons for low yields in this region is the limited amount of soil moisture available to crop roots at various stages of growth. Soil moisture can be increased if the rooting depth is increased through deep tillage. Deep-rooted crops such as pigeonpea (*Cajanus cajan*) can be incorporated into the rotation to loosen the soil below the normal root zone and to ensure a larger zone for extraction of water and nutrients.

The volume and quantity of the rich topsoil determines the capacity to store both water and plant nutrients. Farmers often maintain a shallow depth of ploughing because their implements cannot go deeper, and to avoid bringing up infertile soil layers from below. However, a deeper fertile root bed can be created through deeper tillage combined with the application of both organic and inorganic fertilizers over a number of seasons.

6.3.2 Reducing compaction and hardpans

Good tillage practices can improve soil structure, encourage root growth and facilitate the free movement of air and water in the soil. However, soil compaction can result from inappropriate tillage practices, such as continually ploughing and planting when soils are wet, combined with decreasing organic matter levels in the soil. It can also be caused by excessive tillage, which destroys the soil structure. Ploughing or cultivating with hand tools to the same depth year after year also leads to compaction. However, some soils are naturally compact, such as heavy clays (Vertisols), and others such as Luvisols often exhibit a compact cemented layer in the B horizon, having a very high clay content.

Soil horizons or layers which are highly compacted or indurated are known as hardpans, and are variously referred to as plough (or traffic) pans or soles, denoting the cause of the compaction. Plough pans are usually found just below the maximum depth of normal ploughing. The compaction restricts root development and water movement (Plate 51).


Plate 51: Effect of hardpans on root growth

Symptoms of soil compaction include excessive runoff or standing water, indicating reduced or impeded infiltration, increased power requirements for tillage and difficulty in performing tillage operations.

Effects of soil compaction on crops

Excessively compact soils have negative effects on crop growth and development. These effects include poor germination, including non-uniform emergence; shallow root systems that do not provide sufficient anchorage to the plant; wilting after short dry spells; poor taproots that bend horizontally at a shallow depth (Plate 51); and poor yields.

A simple field test to check the presence of hardpans is to observe the depth of roots by uprooting an established plant, or even a perennial weed. Plants growing in a deep root bed are more difficult to uproot, while plants growing in a soil with a hardpan are easily uprooted, and the roots are growing horizontally only a few centimetres below the surface.

The effect of hardpans is that crops suffer from water stress during short dry spells even in high-rainfall areas because the roots only have access to a very limited portion of the potential soil water storage. At other times the crop may suffer due to waterlogging as the water does not drain fast enough to maintain adequate aeration.

Prevention of soil compaction

Some actions to prevent development of compact layers include developing suitable crop rotations that include grasses and deep-rooted crops; carrying out all tillage and planting operations under good moisture conditions (avoiding ploughing or planting under wet conditions); reducing the number and intensity of soil-turning operations (promoting conservation tillage); varying tillage depth from year to year; breaking hardpans regularly to ensure proper drainage, better infiltration to lower layers and root penetration; and applying and maintaining adequate organic matter in the soil (see Figure 6.1).

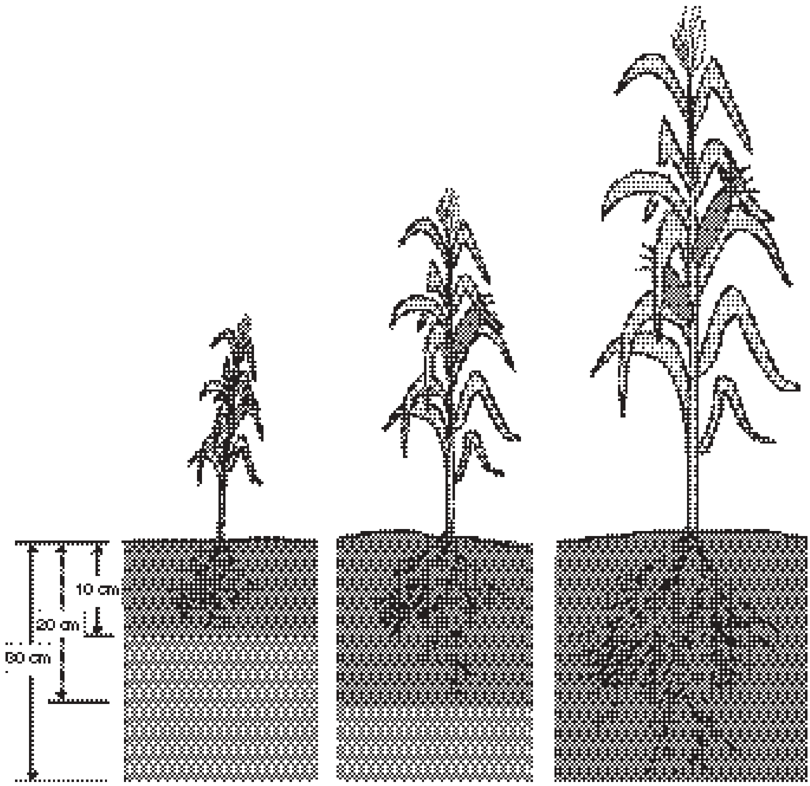


Figure 6.1 *Root system of a maize plant responding to different depths of till*

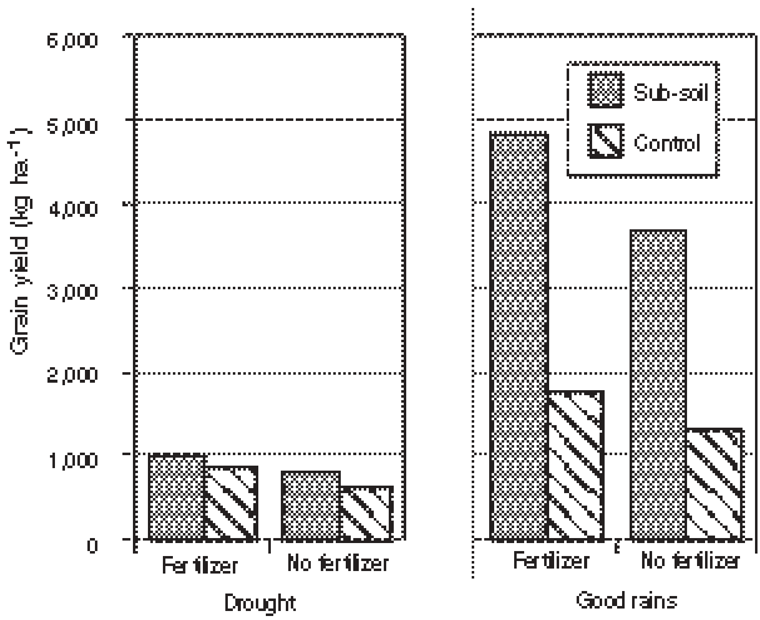
Breaking hardpans

Deep tillage is necessary to remove hardpans. In the eastern Africa region, animal-drawn ploughs reach a depth of about 15 cm, while hand hoes penetrate the soil to an

even shallower depth. With existing implements and power available, if the aim is to till to 30 cm, deep tillage can be achieved by progression from 15 cm to 20 cm to 30 cm in the first, second and third seasons, respectively. This will reduce the cost and the need for higher levels of power, although they could all be done in one season.

An alternative and more efficient way of breaking hardpans is to sub-soil using either animal-drawn sub-soilers or tractor-drawn implements such as a chisel plough. Tractor-drawn chisel ploughs have an average plough depth of 25–40 cm. These operations require a high energy input but can have a dramatic effect on crop growth. Efforts should be made to develop and introduce tillage systems and implements that require less energy.

Figure 6.2 shows the effects on maize yields from sub-soiling and fertilization (manure) demonstration trials in Babati, Tanzania, where tractor sub-soiling was carried out before the onset of the rains. Cattle manure was applied at a rate of 5 t ha^{-1}. Each column in Figure 6.2 represents the average from three plots cultivated with different varieties of maize (CG-4141, H-632 and Kilima). The results show that sub-soiling more than doubled maize grain yield during a year with good rainfall (1995/96). Even during a drought year (1996/97), the yield from the sub-soiled plots was higher, but the difference was less distinct, which is a result of the overall water deficit during that year. The trials were carried out by the Sida-assisted Land Management Programme (LAMP/Sida) through ORGUT-Consulting and the Ministry of Agriculture.



Source: Barron, Rockström and Gichuki 1999.

Figure 6.2 *Maize yields from conservation tillage demonstration trials in Babati, Tanzania, during a drought year and a good-rainfall year*

Where tractors are too expensive for individual farmers to hire for breaking hardpans, they can form groups to reduce individual costs. Generally, breaking hardpans can be done every few years to maintain improved infiltration capacity of the soil (Plate 52).

Plate 52: Ripping with oxen

6.3.3 Weed control

Manual weeding dominates in the region among smallholder farmers. In some areas, animal traction has been used for weeding in annual cropping systems. Larger or highly commercialized farms often use tractor-drawn implements or herbicides to control weeds. Weeding may be performed several times during the crop-growing season.

Tillage systems which lead to a well-prepared seedbed also facilitate the germination of weed seeds. Measures should therefore be taken to prevent weeds from seeding.

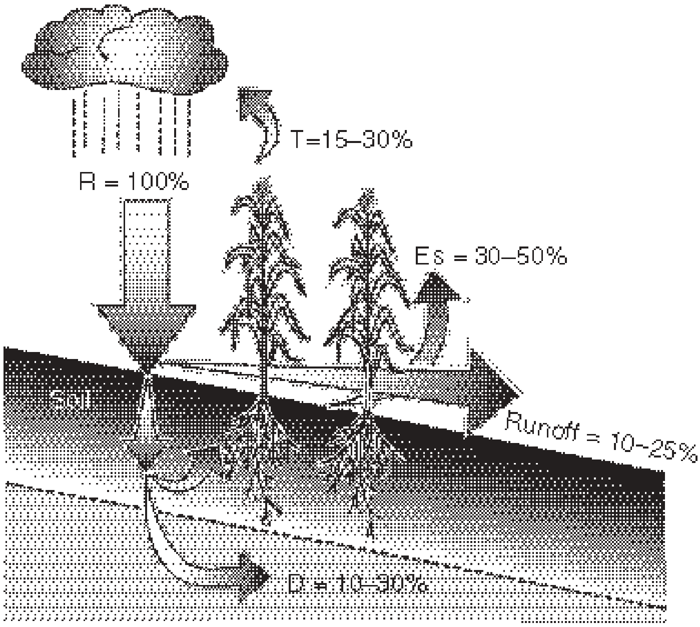
The control of rhizomatous grass weeds such as couch grass (*Digitaria scalarum*) and Kikuyu grass (*Pennisetum clandestinum*) is particularly difficult as they spread underground. Such weeds are generally not killed, and may even be spread, by inversion of the soil. Tillage methods that pull grass weeds onto the surface where they can dry out and be killed in the sunshine are much more effective than burying them. Conservation tillage systems which use tines rather than mouldboards are therefore more effective in controlling rhizomatous grasses than conventional tillage. Fast growing cover crops also help to suppress such weeds.

6.3.4 Water management

Water is often the major limiting factor for crop growth in many low-rainfall areas. This is not necessarily due to low rainfall totals. Other factors may include poor distribution of the rainfall over time (i.e. a high frequency of dry spells) despite high overall totals; high intensity rainfall events inducing high surface runoff (i.e. low infiltration of water into the root zone); high evaporation losses; and low nutrient content in the soil.

Tillage methods should aim to minimize the negative effects of these factors on crop growth. In general terms, for sub-Saharan semi-arid regions only an estimated 15–30% of the rainfall is actually used for crop growth, i.e. as transpiration. The rainfall partitioning from agricultural lands in sub-Saharan Africa is shown in Figure 6.3.

Good tillage aims at maximizing rain infiltration, minimizing evaporation losses and reducing drainage (by contributing to increased water-holding capacity). There are many ways of achieving this. Ploughing can be used to break the surface crust and increase infiltration, but at the same time excessive ploughing may result in compaction, reduced water-holding capacity (by accelerating the oxidation of organic matter), and increased evaporation (by increasing the soil surface area exposed to the air).



Note: R is rainfall, T is transpiration flow through crops, Es is soil evaporation and interception from soil and leaf surfaces, D is drainage
Source: Barron, Rockström and Gichuki 1999.

Figure 6.3 *Rainfall partitioning in the semi-arid tropics in sub-Saharan Africa*

This shows that tillage must be seen as a part of the production system as a whole, and each operation should be weighed against its advantages and disadvantages in relation to other farm measures. For example, if most crop residues are exported from the field after harvest (leaving the soil bare and minimizing the return of residue to maintain the humus layer) then ploughing should be done with great care, perhaps delayed in time or even abandoned in order to avoid further losses of organic matter.

6.3.5 Erosion control

All tillage operations should be carried out across the slope and along the contour (never up and down the slope). This discourages the flow of water down the slope, and checks the development of rills and gullies. Contour ditches (Plate 53) can be used to promote infiltration, but where drainage is necessary, graded contours are used to lead the excess water safely from the field.

Plate 53: Making contour ditches for water infiltration

Plate 54: Soil surface showing depositional crusts

Surface crusting (surface sealing or capping) of the soil is a major factor leading to high runoff (Plate 54). Tillage breaks soil crusts, and this opens up the soil for rainfall infiltration. At the same time, once broken, the crusts are often rapidly redeveloped when soils of poor structure are subjected to the impact of rainfall splash. Poor tillage can destroy the structure of the topsoil through increased oxidation of organic matter and breaking the soil into too fine a tilth.

Topsoil texture affects crusting, but it has been shown that most mineral soils in the region are prone to crusting, with clayey sands being the most susceptible. In general terms, soil crusting is most severe in the following circumstances:

- On soils with low organic matter content
- On soils that are often bare (with little crop residue or vegetation cover)
- In regions with high-intensity rainstorms
- On soils with high silt and very fine sand content.

Conversely, the highest infiltration is achieved in soils with good vegetation and crop-residue cover and high organic matter content. Turning the soil with a mouldboard plough can sometimes lead to reduced infiltration and increased soil erosion. However, severe and frequent crusting must be broken with a suitable implement to ensure good infiltration and adequate amounts of soil moisture. In these cases, farmers have to focus on a balanced package of careful tilling (to break crusts and increase infiltration) and long-term build-up of humus content in the soil.

Tillage practices for promoting infiltration and reducing soil erosion include contour tillage, contour planting, ridging and no-till planting. These techniques serve to enhance the roughness of the soil surface, thereby retaining excess runoff on the surface and allowing slow infiltration and storage.

6.4 CONVENTIONAL TILLAGE – THE TRADITIONAL APPROACH

A primary tillage operation is the initial, major, soil-working operation after harvesting of the previous crop. It is usually designed to leave the surface rough or cloddy. Secondary tillage then works the soil to a shallower depth, mainly to break up large clods and prepare a seedbed appropriate for the particular type and size of seed. Normally, conventional tillage refers to the physical soil manipulation in seedbed preparation using the hand hoe, mouldboard plough (ox-drawn or tractor operated), disc plough, rotavator and various harrows. Farmers generally attain a maximum depth of about 15 cm, leaving a fine seedbed that easily caps (i.e. the soil pores are sealed and a surface crust is formed), thereby leading to water and wind erosion. The many opera-

tions involved lead to higher costs of crop production, and water is not conserved effectively for use by the crop.

When a disc plough is used to plough grassland it creates a very rough surface, which requires a great deal of secondary tillage in order to prepare a seedbed. In this situation, the costs of preparing a seedbed are much higher when the primary tillage is done with a disc plough than when it is done with a mouldboard plough.

Many farming systems in the region have developed over the last century from extensive manually tilled slash-and-burn systems with long fallows to continuous cultivation systems based on conventional tillage using the mouldboard plough. This trend has resulted in progressive land degradation in many areas. The mouldboard plough is better suited for temperate climates with plenty of moisture and much less radiation than in the tropics. It was introduced, together with the disc plough, as part of European farming equipment and methods, and has remained without much change or adaptation to local conditions.

Conventional ploughing has some long-term negative side effects on soil productivity. The resultant compaction results in impermeable hardpans. There is also increased dissipation of organic matter resulting from increased exposure of the bare soil to solar radiation and excessive aeration as the soil is turned and inverted several times. Loosening the soil causes increased water and wind erosion, as well as loss of soil water due to an increase of evaporative surfaces.

The above physical factors directly affect soil productivity. In addition, conventional tillage has high labour and energy requirements and the difficulty of assuring good timing of farming operations. The latter two factors have a severe impact for resource-poor small-scale farmers.

Many smallholder farmers, especially female-headed households, do not have their own pair of oxen due to resource limitations and/or lack of grazing areas. The result is that these farmers depend on neighbours for ploughing operations, which obviously means that their seedbed preparation is carried out very late, often after the onset of the rains. This has serious consequences in semi-arid regions where the onset rainfall event may constitute some 10–15% of the total cumulative rainfall during a growing season, and where the length of the growing period is often very short (90–120 days). Planting that is late by only a few days may mean the difference between a successful harvest and crop failure.

6.5 CONSERVATION TILLAGE – THE NEW APPROACH

6.5.1 Defining conservation tillage

Conservation tillage includes any tillage sequence that reduces soil and water losses relative to conventional tillage by keeping the disturbance of the soil and loss of organic matter to a minimum. It often takes the form of non-inversion of the soil (soil is not turned using ploughs). Conservation tillage is, therefore, an attractive option in areas with land degradation problems and declining crop yields.

Recent recommendations, developed outside Africa, insist that a conservation tillage system must maintain at least 30% of the soil surface covered with mulch or stubble. This cover is eventually incorporated into the soil as humus. In tropical regions, however, especially in semi-arid and dry sub-humid areas, such conditions are difficult to fulfil given the low biomass yields, the high competition for crop residue (for fuel, fodder and construction) and the activity of termites. Conservation tillage often includes weed control by use of herbicides.

Mulch plays an important role in conservation tillage. Mulch plays the multipurpose role of reducing evaporation losses, increasing infiltration, and in assisting in the build-up of biological microflora and fauna that benefits long-term soil fertility and soil structure. Eventually, a mulch cover will also reduce weed development. A negative side-effect of mulching is often reported to be increased pest and disease infestation. It also causes difficulty with planting equipment unless the equipment has been specifically designed to cope with trash.

Principles and objectives of conservation tillage

The principles and objectives of conservation tillage are to:

- Build up surface cover by retaining crop residues (through no-tillage, minimum tillage or stubble-mulch tillage systems)
- Reduce soil disturbance by not inverting the topsoil
- Conserve moisture
- Reduce erosion
- Reduce tillage costs by minimizing mechanical energy and labour requirements
- Improve the timing of field operations.

Therefore, besides the purely land-related reasons for using conservation tillage, these systems also attempt to tackle three major bottlenecks often experienced among smallholder farmers in the region. These are poor timing of field operations (especially planting), lack of labour (by reducing the time needed to till), and the lack of draught-animal power.

6.6 CONSERVATION TILLAGE SYSTEMS

There are many different systems for conservation tillage depending on the primary objectives, the availability of farm power and equipment, and the crops grown. They include no-till or zero-tillage systems, reduced or minimum tillage, stubble-mulch tillage, ridge and furrow tillage, pitting systems, and double digging. Some are designed for mechanization with animal- or tractor-drawn equipment, whereas others are suited to hand labour. The following is a brief account of the systems which are already in use or being developed for the region.

6.6.1 No-till or zero-tillage systems

These systems involve opening a small slit or punching a hole in the soil for seed placement. The crop is planted directly into soil that has remained untilled since the harvest

of the previous crop. Weed control is often accomplished using herbicides, especially when shifting to the new system. When combined with cover crops and stubble or mulch application on the soil surface, weed growth is suppressed.

Some disadvantages of no-till are:

- An increase in soil compaction due to tractor or human traffic during planting over several consecutive seasons
- Soil crusting may develop in soils with unstable structure (low aggregate stability), thus increasing surface runoff and reducing water infiltration.

Generally, small-scale farmers cannot afford to use herbicides (or they prioritize in investing elsewhere). For soils that have not been chronically invaded by weeds, it is possible to progressively suppress weeds through a combination of additional weeding to reduce weed seeds and the use of cover crops.

6.6.2 Reduced or minimum tillage systems

Tillage increases the cost of crop production. It is therefore important for farmers to reduce the use of tillage equipment. Minimum tillage commonly refers to any tillage method in which the crop is grown with the fewest possible tillage operations.

A minimum tillage system differs from conventional tillage by having one or more of the following components:

- Fewer operations
- Less soil disturbance
- Lower power requirement
- Preparation of the seedbed only where the seeds are planted
- Residues are not buried.

The frequency of use of various types of equipment is minimized to perform only the necessary operations required to optimize soil conditions for seed germination, crop establishment and growth: to minimize human and vehicular traffic to avoid soil compaction and deterioration of soil structure; to conserve moisture; to reduce erosion; and to reduce mechanical energy and labour requirements.

Some of the practices to reduce tillage include the following.

Plough–plant

This involves ploughing and planting in one operation. When using oxen, the operation involves at least two people following the oxen as they plough, one dropping the fertilizer, one dropping the seed after several plough passes, depending on the desired crop spacing.

Disc–plant (stubble-harrowing)

A disc harrow is used to loosen the soil, chop up crop residues from the previous season and cut up weeds. Planting is then done without further soil disturbance, and the crop residues are left on the surface.

Strip and spot tillage

In strip tillage narrow 20-cm wide strips are cut along the planting row, while in spot tillage planting holes are made using hand hoes but leaving the rest of the land undisturbed.

Ripping

Advantages of ripping

Many conservation tillage systems use a ripper with a single chisel tine fixed to a plough or ridger frame. In ripping, only shallow parallel furrows are cut using a ripper without disturbing the soil between the planting rows. The ripper should cut regular lines to facilitate subsequent weeding with ox-drawn weeders. Planting is usually done at the same time. The distance between the furrows depends on the recommended spacing for the crop. Ripping can reduce or eliminate the need for ploughing.

The ripper is significantly faster than ploughing (tillage is limited to only a thin opening for planting). Because of this narrow working width, pulling a ripper requires about half the draught force of that needed for pulling a conventional single-furrow plough. The ripper is smaller and lighter than a plough, and is easier to operate; the farmer can also use smaller animals, or animals that may be weaker at the end of the dry season. The ripper is also cheaper to buy and cheaper to maintain. As a result of these advantages, the farmer can work larger acreages each season, and achieve timeliness in operations, thus taking advantage of the early rains. This is important, especially in seasons of lower-than-normal rains or, generally, for marginal-rainfall zones.

The weed problem can be serious in a rip tillage system. Therefore, action should be taken to lessen the problem over the longer term. The ripper (e.g. the Magoye ripper, Section 6.7.3) is a useful weeding tool. Points to note:

- If the Magoye ripper is to be used, the crop row spacing should be at least 50 cm. Using animal-drawn weeders hastens weed control and increases labour efficiency
- Some farmers are able to use herbicides to control weeds in the conservation tillage system
- Maintaining a ground cover of 30% suppresses weeds significantly
- Where hand weeding is the only option, timeliness should be observed by providing sufficient family labour or by working in communal or village groups
- Weeds should not be allowed to flower and produce seeds, as this makes future weeding more difficult.

A form of minimum tillage is practised under traditional slash-and-burn agriculture. Fire leaves the ground bare, covered with ash and free of weeds. Ploughing is not required (and might be difficult because of stumps). Seed, commonly finger millet, is planted directly in the soil.

6.6.3 Stubble- and residue-mulch tillage

This involves cutting the roots of weeds and other plants and leaving the crop residues on the surface or mixed into the top few centimetres of the soil. The cutting is usually done with a tined implement with blades or sweeps attached to the tines to uproot or

undercut the weeds. The result is to reduce erosion and to conserve water by reducing runoff, and also to regulate soil temperature and increase soil fertility and organic matter content. Equipment used for planting must have special furrow openers to avoid clogging with trash.

6.6.4 Ridge and furrow systems

Simple or tied ridging cultivation results in better soil and water management than conventional ploughing (Plate 55). The ridges and furrows help to regulate runoff flow, to increase water infiltration and storage and reduce soil and nutrient losses. The system is most suitable for gentle slopes, especially in marginal-rainfall areas. Row crops are planted either on the ridge top, in the furrow or along both sides of the ridge.

Plate 55: Tied ridges for water conservation

A ridger can be used for ridge and furrow cultivation. Sometimes a discontinuous furrow is made by making cross-ties that interrupt water flow in the furrow, thus creating a series of basins or pools to retain water for a while and to promote slow seepage. This is called tie-ridging. The ridges may be maintained for several seasons to reduce construction work. Usually seedbed preparation and planting are done in one combined operation.

A system of broad ridges (beds) and furrows has been found to be useful on Vertisols (black-cotton soils) because it allows drainage and facilitates cultivation. Modifications of the animal-drawn mouldboard plough have been used for making broad ridges for growing wheat and other crops on such soils in Ethiopia and Kenya (see Plate 20).

6.6.5 Pitting systems

There are several conservation tillage systems that use pits or holes. They aim to concentrate fertility where the crop is grown, to conserve water and organic matter and to minimize erosion. These systems are found in certain areas where farmers rely on hand labour rather than oxen for cultivation. The following should be noted.

Matengo pits

Structures called 'matengo' pits are used in the Southern Highlands of Tanzania. The pits can be up to 1 m x 1 m and 30 cm deep, but the actual size is determined by depth of the soil and ease of digging. The pits are laid out on sloping land forming a grid to cover the entire surface. Soil taken from the pits is used to form ridges around the pits. Crops are grown on the ridges and the weeds and crop residues are thrown into the pits. A rotational system is usually practised using crops such as maize, beans and

sweet potato, and the pits are regularly moved and new ridges built where the organic matter has accumulated. The pits also serve as structures to conserve water.

Zai basins

'Zai' basins are used in semi-arid areas to concentrate manure and runoff into basins or pits where the crops, e.g. sorghum, are planted. Zai pits have traditionally been used in the dry regions of Burkina Faso and Mali in West Africa. The pits are about 15–20 cm deep and 30 cm in diameter, with 1 m between the rows. Topsoil from the excavation is mixed with manure and put back in the pit where a few cereal seeds are then planted. The pits also concentrate rainfall runoff around the plants, thus improving moisture supply to the roots.

Planting holes

There are at least two systems being used in certain areas of Kenya and Tanzania. One of these is a system of planting five or nine maize plants in large holes of about 1.5 m diameter (four or eight plants along the edge and one in the middle, respectively). The soil is first dug out to sufficient depth to break through any hardpan, if present, and allow free drainage. The topsoil is returned, together with manure, and the remaining soil placed around the hole to catch rainfall and concentrate it where the plants are growing.

The second system, developed in Dodoma, is known as 'chololo' pits. The holes are similar to the above but only about 25 cm deep and 30 cm in diameter, being spaced at 60 cm within the rows and 90 cm from row to row. The rows are arranged roughly on the contour. The soil from the pits is put on the lower side of the pit, forming a half-moon shape that traps runoff into the pit. Planting is done in the pits.

6.6.6 Double digging

Double digging is practised by small-scale farmers. It involves removing the topsoil, mixing it with compost, then loosening and digging the sub-soil to break the hardpan, if present, and facilitate root access. The topsoil is then put back on top of the loosened sub-soil. The purpose of double digging is, therefore, to create a deep layer of well-manured topsoil for easier root penetration, water retention and aeration. Double digging allows close spacing of crops as the beds are well fertilized.

Procedure for double digging:

- Select the site – near the homestead if to be for a kitchen garden
- Measure and peg out the selected area: 1.5 m x 7 m (about 10 m^2)
- Loosen the topsoil to a depth of about 30 cm, remove it and keep it aside. Mix it with good compost at the rate of 7 wheelbarrows for each 10 m^2 plot
- Dig into and loosen the sub-soil but do not remove it
- Return the topsoil back on top of the subsoil.

Several such beds can be prepared parallel to each other but leaving a 30–60 cm space between the beds. Once dug, do not step on or compact the soil. Always weed and harvest while standing on the path (Plate 56). A double-dug bed should be planted

more closely than normal because the plant roots spread downwards much more easily. In addition, the leaves of the plants give protection to the soil from the sun, wind and rain. Close spacing also keeps down the growth of weeds. The bed is dug again after 3–4 planting seasons.

Plate 56: Double-dug beds with vegetables

6.7 CONSERVATION TILLAGE EQUIPMENT

A tillage implement consists of a simple tool or a group of tools together with the associated frame. Apart from the wide variability of farming systems, the selection of tillage equipment will also be influenced by the availability of implements, power, labour and capital. Tillage implements may be grouped in accordance with their intended functions, which are: breaking–cutting; semi-turning; and cutting and turning.

In ploughing, draught requirements are dependent on the depth, width of furrow, adjustments and maintenance of implements. It is estimated that 25% of the draught is required for cutting the soil, 25% for turning the furrow, and 50% to overcome friction. The smaller the surface area of the implement that is in contact with the soil, the lower the friction and the lower the draught requirement. Draught requirements can be reduced through use of more efficient tools. Otherwise, the farmer must use stronger draught animals, or engine power, which may not be available.

The draught-power requirements for tine rippers and sub-soilers are less than those of a plough. This makes the breaking of hardpans and the achievement of deeper tillage possible under existing ox-cultivation technologies. Eliminating soil inversion can also reduce power requirements. Some of the major implements used for soil tillage are discussed below.

6.7.1 Hand tools

Plain hand hoe (*jembe*)

Hand hoes are probably the most widely used tillage implements among farmers throughout the region. The hoe usually has a steel blade, with an 'eye' for a wooden handle (Figure 6.4). The hand hoe is a universal implement because it is used for digging before planting, and then weeding, ridging, planting and harvesting.

The ability of the hand hoe to penetrate the soil during tillage increases with the weight and with the thinness of the blade (or the tines in the case of the forked *jembe*). Hoes are usually designed for specific tasks or functions. It would therefore be useful for farmers to invest in a number of different types of hoes to handle different tasks.

Normally, however, farmers have only one hoe, which they employ on all the different tasks. However, special hoes for breaking hard ground are made from car springs by local artisans.

Hand hoeing works the seedbed to a depth of about 15 cm. The surface is left rough with large clods. This technique, however, has the following drawbacks. For ease of digging, the land is usually cleared of surface trash, thus leaving it bare and vulnerable to erosion, and hand hoeing is slow and tedious. Therefore, seedbed preparation, planting and weeding tend to be done poorly, leading to low yields; and the repeated shallow digging leads to formation of hardpans that reduce water infiltration.

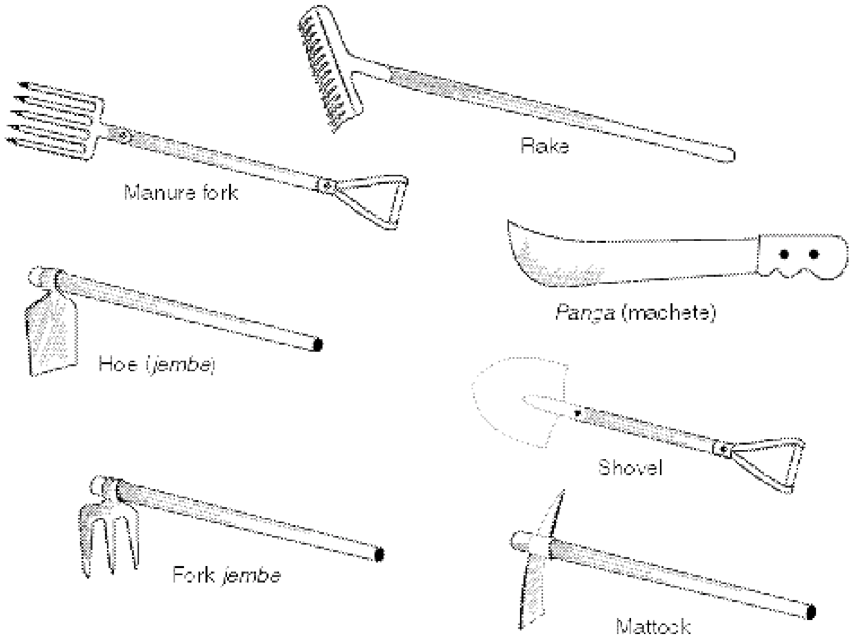


Figure 6.4 *Various hand tools*

Forked hand hoe (forked *jembe*)

This tool has been used extensively in the region. It is used in weeding, especially in couch-grass infested areas. A forked hoe is a very effective tool to be used by small-scale farmers in shattering hardpans created from continual use of blunt and worn out ordinary hoes.

6.7.2 Tined cultivators

On light soils, tined cultivators can be used as primary tillage implements to loosen the soil with little turning and incorporation of crop residues. This tillage practice is appropriate in dry areas with sandy clay loam or sandy clay soils that are susceptible to crusting. Tine tillage is then used to break the crust and enhance rainwater infiltration. A spring tine cultivator is ideal for this tillage operation.

6.7.3 Rippers, sub-soilers and chisel ploughs

Rippers

A ripper is a single metal shank narrower than a ploughshare. It takes the place of a plough body and is used to create narrow furrows on unploughed land. Shallow furrows with loose soil appear only where the implement has passed. Ripping requires less draught power than conventional ploughing and can, therefore, be 3–5 times faster than ploughing so farmers can work and plant a larger area.

Ripping breaks soil crusts, thus enhancing rainwater infiltration. The only limitation with ripping is the difficulty of maintaining straight-line operations. There are several types of ox-drawn rippers, such as the Magoye ripper developed in Zambia (Figure 6.5).

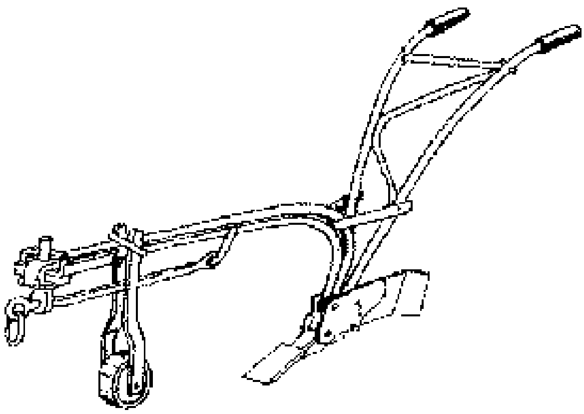


Figure 6.5 *The Magoye ripper*

The ripper is used for making planting furrows (followed by manual planting) in unploughed fields. The attachment works well in dry soil and can therefore be used to prepare the land for planting before the rains start. Using the ripper also allows the opportunity to introduce row planting. This necessitates the use of broader yokes that are adapted to the row width used in the field. Oxen or donkeys must be trained to walk in straight lines. The ripper can be adjusted to cut as deep as 25 cm in not too heavy soils, and thus can also be used to break shallow hardpans.

Sub-soilers

Many annual crops can have a rooting depth of 80 cm or more. However, their ability to reach such a depth is often limited by a hardpan. Plough pans, caused by years of conventional ploughing, with either tractor or animal traction, can completely stop infiltration. This may lead to severe drought for the crop, even when there is enough rain. A sub-soiler is used to break the hardpans. It consists of a rigid bar point made of very hard steel, such as that found on car or lorry suspension springs, and is fixed on a normal plough beam (Figure 6.6). The sub-soiler can penetrate the soil up to 40 cm if the soil is not too heavy or clayey, and breaks the hardpan at point of entry. As it moves

along in the soil, it lifts the hardpan and shatters it. For effective shattering of the hardpan, it is recommended that the operation be done when soils are fairly dry. When the soils are damp, only a groove will be formed.

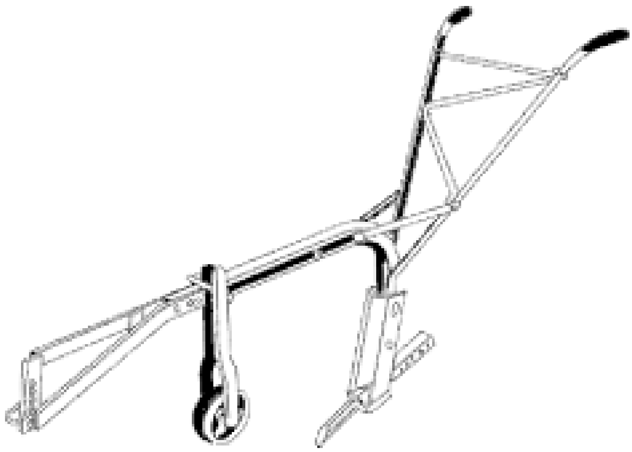


Figure 6.6 A sub-soiler on a plough beam

However, when plough pans are caused by tractors, the breaking often has to be done by tractor also (the pan is simply too thick and hard to be broken by an ox-pulled sub-soiler). Tractor-drawn chisel ploughs can be used for this purpose. The animal-drawn Magoye sub-soiler needs a beam extension in order to assure that the plough beam is adjusted for maximum depth penetration.

Chisel ploughs

Chisel ploughs are rippers that are designed for use with tractors. They have two or three rows of spring-loaded tines with ripping points attached to a frame (Figure 6.7). Chisel ploughing can be used to loosen the sub-soil hardpans without inversion of the topsoil layer. Chisel ploughing requires less draught power per unit area than mouldboard ploughing.

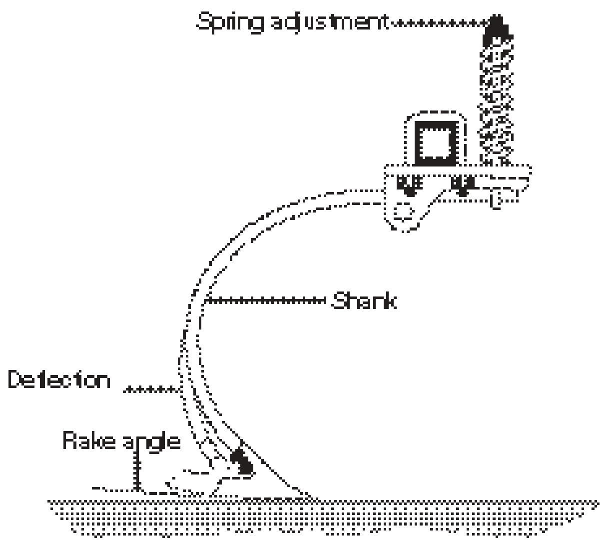


Figure 6.7 A chisel plough

6.7.4 The maresha plough

The traditional Ethiopian 'maresha' plough (Figure 6.8) is a wooden plough that has a sharply pointed metal tip and a metal hook hinged to the handle of the plough. Two flat wooden wings are fitted by the hook to the handle and by a steel pin to the beam on the other side of the implement. The plough scratches, lifts and slightly turns the soil leaving a furrow and two small ridges. The plough is often used for primary and secondary tillage operations (Plate 56).

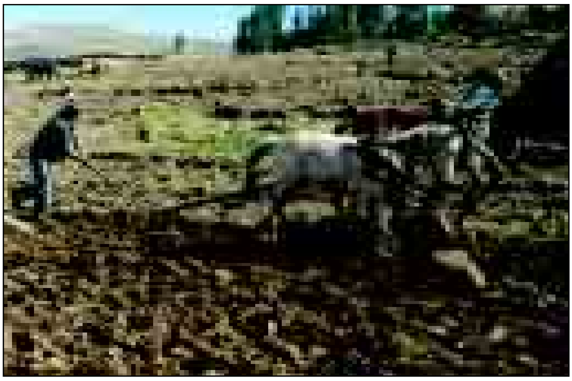


Plate 56: *Ploughing with a maresha plough*

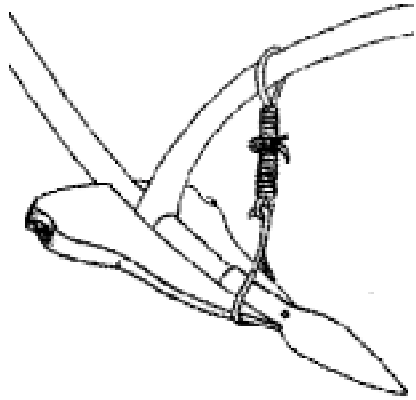


Figure 6.8 *A maresha plough*

6.7.6 Ridgers

Ridging can be carried out with an ox-drawn implement such as the Magoye ripper. This ripper has small wings which create small ridges, but extensions can be added when larger ridges are required. It then becomes a ripper–ridger (Figure 6.9). Ripping at the same time as ridging improves infiltration in the furrows and reduces water loss from evaporation.

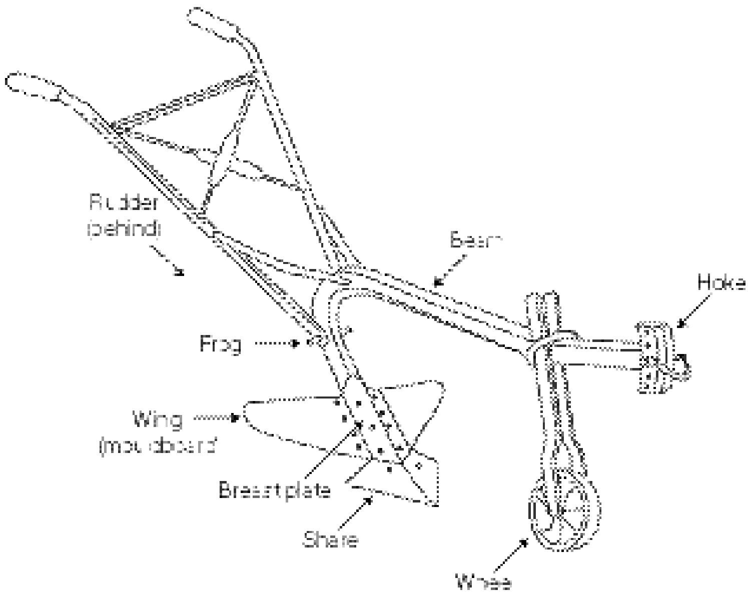


Figure 6.9 *An animal-drawn ripper–ridger*

6.8 TRANSITION TO CONSERVATION TILLAGE

The transition from conventional tillage to conservation tillage involves a complete change in the crop-production system, which includes all inputs, technologies and field operations carried out within a given agroclimatic setting. Changing the technology used will also change most of the field operations.

For example, the transition to planting in permanent planting lines using an animal-drawn ripping tine (such as the Magoye ripper) without prior ploughing is a conservation-tillage option that has produced much interest among farmers in eastern and southern Africa. This change from one implement (from the mouldboard plough) to another (the ripper tine), will affect most other operations including:

- Timing of land preparation
- Precision in planting (row and inter-row spacing)
- Training of oxen
- Number and type of weeding operations
- Fertilizer use (both fertilizer and manures)
- Intercropping and cover cropping
- Crop rotations
- Mulching
- Pest management
- Soil and water conservation
- Post-harvest management of crop residues (burning versus conserving).

Timing of planting is crucial. With a ripper, the time needed for land preparation is drastically reduced as only the planting lines are actually tilled. This increases the chances of completing tilling before the onset of the rains, or just after. Seeds are placed in the rip-lines, together with the manure/fertilizer. This ensures that no nutrients are wasted in the space between the planting lines (nutrients that often are used by weeds).

The change to the use of rippers also requires that oxen be properly trained to walk straight in order to obtain the required plant population. Correct planting arrangement also makes weeding with animal-drawn equipment possible, following the straight lines. Correct spacing is important to reduce competition for light, water and nutrients. A string can be used to guide the ripper (in order to ensure the right row spacing). The farmer can also choose to use the same planting lines season after season, rather than opening new lines. Eventually, the lines will have an accumulation of nutrients. These lines will therefore concentrate the nutrients and water close to the plant roots and away from the weeds.

Abandoning the conventional plough often leads to a weed problem. One solution is to use herbicides, but weeds can be reasonably suppressed by maintaining a mulch layer on the surface throughout the rainy season. In situations where most crop stover is taken away for feeding livestock, a possible alternative is to intercrop with a cover crop. This cover crop should be a quick-growing and nitrogen-fixing legume (see section below on legume cover crops). In addition, one final weeding can be done just before the main crop harvest but before the weeds set seed. This ensures that the weed seeds in the soil are progressively reduced.

It is possible to introduce conservation tillage through a gradual modification of the traditional or conventional practices. Transition from conventional tillage to conservation tillage can proceed in three steps, stopping at the second stage if preferred:

1. Conventional tillage (i.e. mouldboard plough)
2. Minimum tillage (e.g. ripper + cultivator)
3. Zero-tillage.

The time taken to achieve a full positive impact will depend on how poor the soil structure is, but generally at least four years are needed. A test of when successful introduction of conservation tillage has been achieved is to submerge soil aggregates in water. If the soil does not collapse then the structure is good. (This does not apply on black-cotton soils which can maintain aggregates even after long heavy compaction as a result of their shrinking and swelling character.)

Summary points for extension workers and farmers on transition to conservation tillage

- Carefully discuss with farmers each farm operation within the current production system, in line with Table 6.1, below. The goal is to marry the current operations with a new plough-free system. There is no absolute blueprint, i.e. every farmer or group of farmers will want to design their own systems for conservation tillage in management of weeds, planting, tilling, fertilizer application and post-harvest management.
- Start by breaking hardpans if necessary. Check hardpans using the uprooting test described earlier to check how the roots develop. If they are easily uprooted and are bent, then the farmer has a pan. Prevent the formation of new hardpans. Abandon the plough (disc plough or mouldboard plough) in favour of a ripper or chisel plough.
- Give preference to crop rotations with deep-rooted plants like pigeonpea (*Cajanus cajan*) and crotalaria. Boost organic matter content and nitrogen in the soil by maximizing the use of legumes as intercrops. Maintain a permanent cover of mulch or cover crop if possible. Improve weed control – weed not only during the growing season, but also introduce a late weeding at harvest or post-harvest in order to minimize seeding of weeds. The weeding can be done both mechanically (manually or with implements), or chemically (by herbicides). Reduce tillage: practise ripping into rows, direct seeding (see Table 6.1).

Table 6.1 is a guide that can be used when planning a conservation-tillage production system with farmers. Basically, it gives a menu of options for the different operations involved. Added to the operations shown in Table 6.1, a choice of crop rotations must be made. It is crucial to abandon monocropping and instead introduce a diversified rotation.

6.8.1 Rotations, intercropping and legume cover crops in conservation tillage

Rotations

Crop rotation is the growing of different crops in a predetermined cycle on the same piece of land. During their growth, different crops need different minerals, have different root depths and attract different diseases and pests. The crops used usually include row crops, small grains, legumes and grasses. Legumes enhance plant nutrient levels, while grasses improve soil structure. Rotation of crops prevents pest build-up and ensures balanced crop nutrient uptake according to the different plants' nutritive requirements and rooting depths.

Table 6.1 A conservation tillage system (farm operation options)

Operation	Options: Implements/ traction	Options: Methods	Options: Timing	Comments
Sub-soiling (30–50 cm depth)	Chisel plough Tractor		Dry season. Once every 2–3 years	Possibility of hiring tractor among several farmers.
	Sub-soiler Animal	Rows, ca. 0.8 m apart	Dry season. Once every few years	Can be done at any row spacing. If ripper–planting is done, it is recommended to sub-soil at an angle of 90° from planting rows (except when slope is >10%)
Weed control, dry season	Sweep: Animal, tractor, hand hoe		Any time after harvest	
Tillage and planting	Chisel plough – Tractor	Tillage of entire surface (20-cm depth). Seeding by seed drill/ planter or by hand	One month to a couple of weeks before the onset of the rains	Dry planting can be considered
	Ripper – Animal	Ripping at row-to-row distance (15–20 cm depth). Seeding by seed drill/ planter or by hand	One month to two weeks before the onset of the rains	Dry planting can be considered
Fertilization – Basal dressing	Manual	Full recommended P and 1/3–1/2 N in ripping line, beside the seed	P at dry planting; N after onset of rains	
– Top-dressing	Manual	As recommended		
Planting cover crop	As planting of main crop			Choose rapidly covering crop
Water management	Ridger – animal	Ripper can be fitted with wings for ridging	As soon as crop is established	
	Tie maker – animal		As soon as crop is established	
Weed control in standing crop	Ridger/cultivator – animal	Ripper can be fitted with wings for ridging		This operation is possible with animal traction because of the row planting
	Hand hoe – manual	Herbicide		
Post-harvest treatment				
– Mulching	Manual			Return of realistic amounts of mulch
– Weeding	See above on weed control			

Intercropping

Intercropping involves growing two or more crops in the same field at the same time, with at least one of the crops providing quick ground cover. Intercropping can help improve soil fertility when legumes are used. Intercropping also allows for intensive land use where landholdings are small. Using several plant strains results in conservation of agricultural diversity when compared with pure strains.

Legume cover crops

In the eastern Africa region, legumes are well recognized as sources of cheap proteins in human nutrition, and to a lesser extent in livestock feeding. Legumes also play important roles in soil conservation and soil fertility improvement (see Chapter 3).

In no-till systems, legumes are grown and then slashed down, or are killed with a herbicide to form a protective mulch cover. This cover later decomposes to form useful humus. Legumes for the no-till systems should have the following characteristics:

- Be low-growing or creeping herbs or small shrubs
- Be aggressive, competitive and able to outgrow weeds (that is, the legume should have rapid early growth)
- Planting material (seed or cuttings) should be readily available
- Able to improve soils (therefore able to grow well on poor soils)
- Possible to establish in a no-till system
- Able to stand severe moisture stress and other difficult conditions normally encountered in the relevant area
- Have low establishment and management costs
- Be easy to kill using a relatively safe herbicide in order to form a protective mulch which does not interfere with the operation of no-till equipment
- Able to retain the protective ability for the required period (slow decomposition)
- Should not act as alternative hosts for pests and diseases that attack the cultivated crops
- The cover crop itself should not become a weed that affects the main crop
- Should preferably produce some useful grain.

In a mulch tillage (no-till) system, it is important to drill the seeds to ensure effective contact with the soil and to create a narrow mulch-free band for good germination. Inoculation with the appropriate *Rhizobium* bacteria may be necessary. To ensure proper establishment and growth, inorganic fertilizer should be used to supply phosphorus and other nutrients that may be deficient in the soil. As indicated in Chapters 3 and 4, the identification of suitable cover crops is continuing at various research establishments.

6.8.2 Residue management in conservation tillage

Although the recommendation is to keep a cover of 30% on the ground, residues such as maize stover interfere with cultivation. The problem can be overcome if a tractor-drawn disc harrow is available to chop the residues. If ox-drawn equipment is used, strip tillage may be the best approach. Hand labour can be used to move the residues into lines on the contour where they will help to suppress weeds. Cultivation (preferably

with a ripper) and planting can then be done in the intervening strips. Alternatively, planting is done through the residue without moving it into lines.

6.8.3 Timing of tillage operations

Delayed tilling of the land and planting after the first showers of rain reduces the growing period of the crop, and hence subsequent yields. Therefore, tillage should be done immediately after harvesting. Less draught is then required to pull implements through the soils. In Kisii District, Kenya, for example, ploughing is done round the stooks while the maize is drying. Soils should not be cultivated when they are wet as the implements will cause smearing and compaction.

6.8.4 Improving the performance of the ox-drawn plough

Although this chapter has stressed the importance of conservation tillage and the advantages of using a ripper instead of a mouldboard plough, it is likely that the plough will continue to be the main tillage implement for many farmers for some time to come. However, much ploughing is done badly because the plough is worn or not functioning properly.

It is important that farmers and extension workers fully appreciate the functions of all the parts of a plough. Parts that are commonly found missing include the draw bar, adjusting bar, regulator and hake (see Figure 6.10). The removal of these parts makes it very difficult for farmers to get good-quality work output from their ploughs. Much can be achieved with the use of the existing plough if it has all its parts functioning as required (Table 6.2)

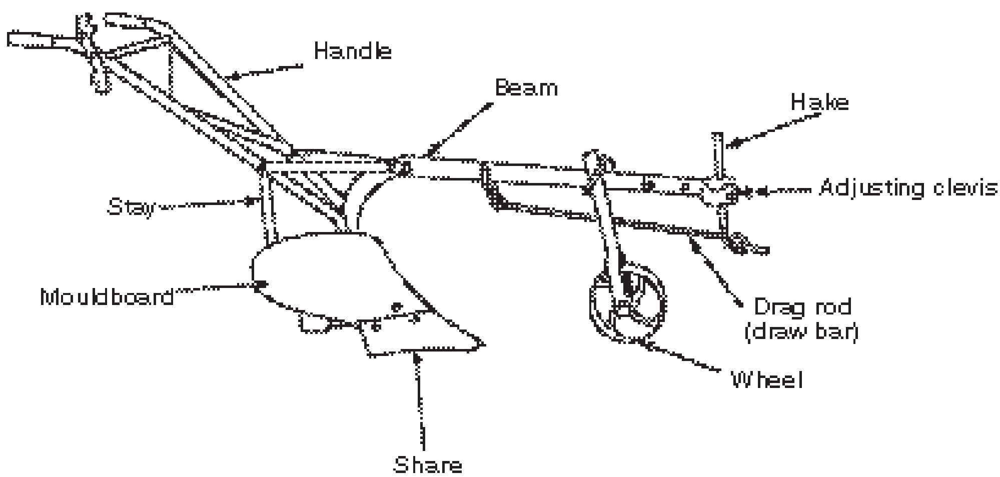


Figure 6.10 *Parts of the ox-drawn plough*

Table 6.2 *Plough parts that control tillage depth*

Plough part	Functions
Vertical regulator	Controls the depth of cultivation
Hake	Used to regulate the depth and width of cultivation. The hitching point and chain point can be changed vertically and horizontally
Share	Cuts soil slices and lifts them slightly. It must be sharp since a blunt share smears the soil
Draw chain	Transmits the required draught force from the animals to the soil-engaging implement. The standard chain is 2.5 m, but it can be increased to 3.5 m for deeper tillage
Depth wheel	Steadies the plough as it moves through the soil and maintains the required depth

A badly adjusted plough has a high draught requirement. It fails to uproot or bury weeds and can lead to shallow hardpan formation because the field is ploughed at a shallow depth season after season. The end result is poor crop establishment and subsequent low yields. Common problems and ways of solving them are given in Table 6.3.

Table 6.3 *Common problems in using a mouldboard plough*

Faults	Possible causes	Remedies
Poor penetration	Blunt share Draw chain short Depth wheel high Adjusting bar high	Replace share Increase the draw chain Raise the depth wheel Raise the adjusting bar
Shallow depth	Share point worn out Draw chain short Depth wheel high Adjusting bar high	Replace share Increase the draw chain Raise the depth wheel Raise the adjusting bar
Wide furrow slice	Wrong plough yoke Wrong placement of the hitching point	Use 80–90 cm yoke Move the hitching point towards the unploughed land
High draught power requirement	Badly adjusted plough	Check direction of pull follows a straight line

The following recommendations should also be noted:

- The vertical regulator should be used all the time for control of depth of tillage
- Counter-sunk bolts should be used for the parts which are in contact with the soil to reduce draught on the plough
- Ox-drawn equipment should never be used on fields that still have tree stumps in them.

Modifications of the ox-drawn plough

The animal-drawn Victory plough has been condemned for its lack of versatility. In its original form, it could only perform one function: to plough. In Zimbabwe and Zambia, however, some development work has gone into making a multipurpose frame with different attachments that can be used as and when necessary. This is an advantage to farmers who already have their own ploughs. They can now add other units.

6.9 CONCLUSIONS

This chapter has shown the weaknesses of conventional tillage and the benefits that can be obtained from conservation tillage. It has also shown that changing from conventional to conservation tillage is not a simple process. There are different approaches and different needs depending on the climate, soil, cropping system and available resources. Recent advances in other parts of the world, notably North and South America, Europe and Australia, now have conservation tillage as part of a broader integrated system of ‘conservation agriculture’ that is guided by three key principles: no or minimal soil inversion, permanent soil cover (mulch or cover crops), and well-designed crop rotations. Each farmer must find the method which works best for him, and time is needed before the benefits are realized.

Appendices

Appendix 1: Soil texture by 'feel'

It is possible to tell the soil texture class of a soil by 'feel', that is, by examining the dry sample, and then feeling a wetted sample between the fingers (see Figure A1). The following are the points to note.

Sand
Loose and single grained. Individual grains can readily be seen and felt. If squeezed in the hand when dry, it will fall apart when the pressure is released. If squeezed when moist, it will form a cast, but will crumble when touched.

Sandy loam
Contains enough sand, silt and clay to make it somewhat coherent. When squeezed, it will form a cast that readily falls apart. But if squeezed when moist, a cast forms, which requires careful handling to avoid any breakage.

Loam
Has a moderate amount of sand, silt and clay. It is very smooth and slightly plastic. If squeezed when dry, it will form a cast that requires careful handling. The cast formed by squeezing the moist soil can be handled quite freely without breaking.

Silt loam
A soil having a moderate amount of fine sand and only a small amount of clay. Over 50% of this soil is silt. When dry it appears cloddy. Under wet or dry conditions, it forms casts that can be handled without breaking.

Clay loam
This is a fine-textured soil that breaks into clods and hard lumps when dry. Under moist conditions, it is fairly plastic and sticky. It is possible to form long ribbons between the thumb and finger when moist. When squeezed, it does not crumble but readily forms a compact mass.

Silt clay loam
Is a fine-textured soil that forms readily broken and hard lumps or clods when dry. When moist, it can be kneaded in the hand to form an unbreakable cast. It has better drainage properties than clays because of the presence of silt.

Clay
A fine-textured soil, which forms comparatively hard lumps or clods when dry. When moist, it is very plastic and sticky and forms long ribbons between the fingers and thumb.

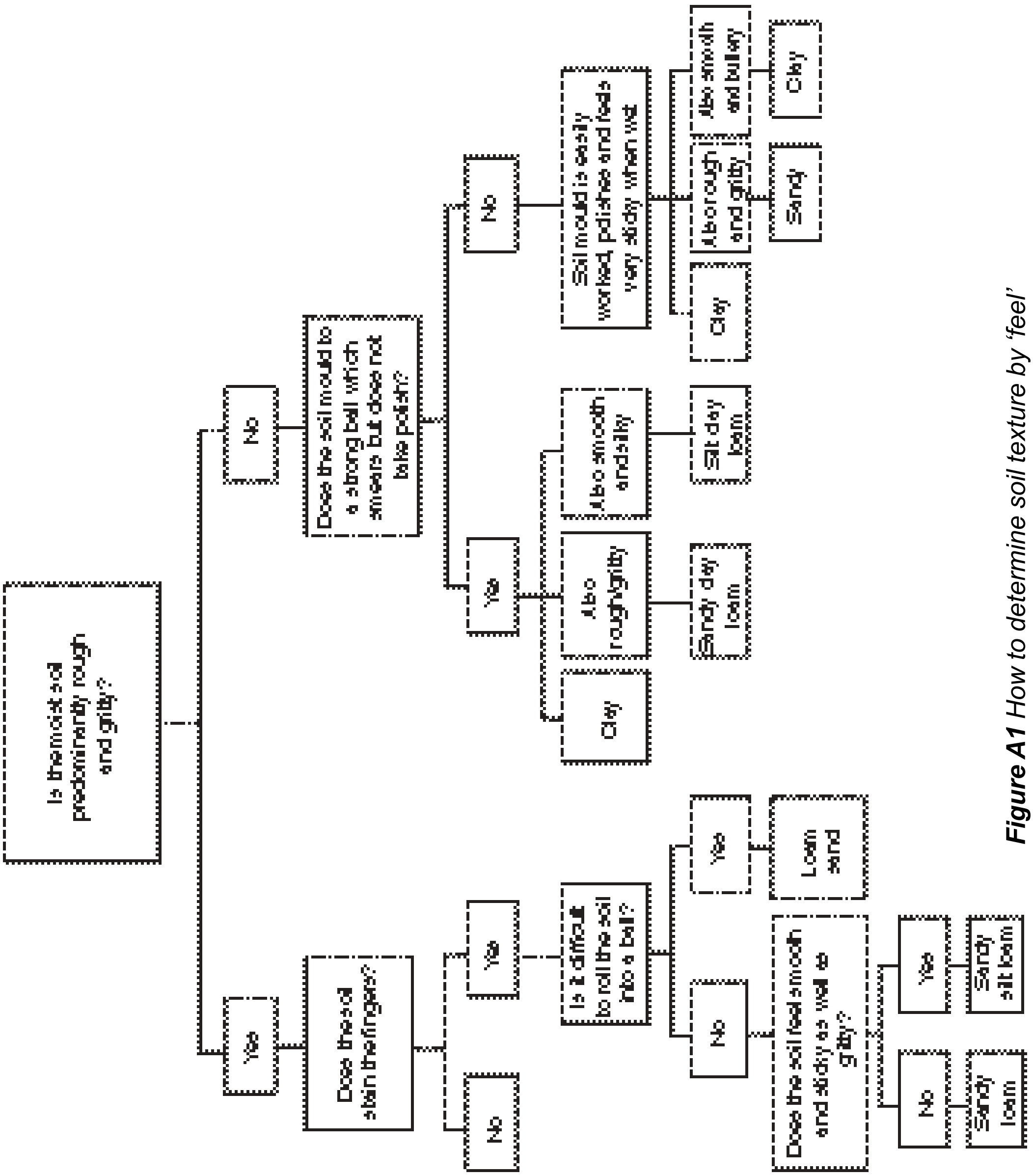


Figure A1 *How to determine soil texture by 'feel'*

Appendix 2: Notes on soil properties

Base saturation percentage

This is the extent to which a soil material is saturated with exchangeable cations (Na, K, Ca, Mg) other than hydrogen and aluminium expressed as a percentage of CEC.

Cation exchange (cation adsorption) capacity

Negative charges on the very large external surfaces of clay and humus attract positively charged ions. The exchange of ions occurs in the soil and the most numerous cations are calcium (Ca^{2+}), magnesium (Mg^{2+}), hydrogen (H^+), sodium (Na^+), potassium (K^+), iron (Fe^{2+} or Fe^{3+}), and aluminium (Al^{3+}). Ion exchange occurs between the solid and liquid phases of soil, resulting in either adsorption or release of cations.

Cation means an ion with a positive charge (missing one or more electrons). *Exchange* refers to a reaction in which an ion attached to a soil particle (colloid) exchanges places with an equivalent amount of cations in the soil solution. *Capacity* refers to the quantity of cations that the soil can hold (milliequivalents charge per gram of soil).

Hence, *cation exchange capacity* (CEC) is a measure of the ability of an insoluble material to undergo displacement of ions previously attached and loosely incorporated into its structure by oppositely charged ions present in the surrounding solution. It is the total amount of cations that can be adsorbed by the soil, expressed in milliequivalents per 100 g of oven dry soil. Zeolite minerals used in water softening, for example, have a large capacity to exchange sodium ions (Na^+) for calcium ions (Ca^{2+}) of hard water. High cation exchange capacities are characteristic of clay minerals and numerous other natural and synthetic substances possessing ion-exchanging properties.

Cation concentration on colloidal surfaces may change due to leaching or adsorption by plants roots (losses in cations); and the application of lime, gypsum and fertilizers and loss of soil moisture by evaporation (gains in cations).

Cation exchange is an important reaction in soil fertility, correcting soil acidity and alkalinity and changing soil physical properties. Organic colloids have much higher CEC than inorganic colloids.

Plant nutrients like calcium, potassium and magnesium are supplied to plants in large measure from exchangeable forms. The amount of soil moisture significantly influences this exchange of ions. Where the proportion of H^+ is large, the base saturation will be low and the soil highly acid. Hence the Ca, Mg, and K cations will be in low supply and thus less available to plants.

FAO has established CEC values of 8–10 me per 100 g of soil as minimum values (within the top 30 cm of soil) for satisfactory crop production under irrigation. Any CEC values of <4 me per 100 g soil (measured at the pH of the soil) indicate a degree of infertility unsuitable for irrigated agriculture.

Exchangeable sodium percentage (ESP)

This is a measure of the concentration of sodium in a soil. It is the extent to which the adsorption complex of a soil is occupied by sodium. The amount of exchangeable sodium is influenced by organic matter content, texture, type of clay mineral, and potassium content. High ESP is known to lower infiltration rates, hydraulic conductivity and moisture-holding capacity of the soil. The reclamation of sodic soils requires application of appreciable amounts of gypsum as amendment to neutralize the excessive alkalinity.

Land productivity

Land productivity is the ability of land to produce specified outputs under given management conditions, but also being subject to factors such as climate, topography and drainage. Productivity is usually expressed in terms of crop yield(s) per unit area (e.g. kg ha^{-1}). Specific production potential is influenced by the chemical, physical and biological properties of soils.

Soil aggregation

Soil aggregate stability is an expression of the resistance of soil aggregates to breakdown when subjected to potentially disruptive processes. Mechanical stability of aggregates is determined by the dry-sieving and wet-sieving techniques. The latter is an effective method for testing the water stability of soil aggregates. The nature of soil aggregates and the amount of water dispersible aggregates contribute to the formation of surface sealing and crusting (due to soil splash). The rate of dispersion or breakdown of aggregates determines the time taken to develop surface sealing and ponding of rainwater.

Soil alkalinity (sodicity)

Soil sodicity is a measure of the exchangeable salts (held by clay particles) such as sodium. Sodic soils have a soil pH greater than 8.5 and an ESP of greater than 15%. The presence of sodium carbonate in soil raises the soil pH thus rendering nutrients like phosphorus, manganese and zinc unavailable for plant growth. High concentrations of exchangeable sodium despite raising the soil pH also have marked effects on soil structure – they reduce aeration, infiltration, soil workability and permeability of the soil. Soil sodicity is common in arid and semi-arid areas.

Soil colloids

The most chemically active and also smallest particles in the soil matrix are the soil colloids. Soil colloids are inorganic (clay) and organic (humus) in origin. Generally, soil colloids significantly influence the availability of nutrients to plants, microbial population activity, levels of toxicities of soil elements to plants and the physical condition of soils.

Organic colloids – humus

During decomposition of organic matter in the soil, some of the carbon, hydrogen, oxygen, and nitrogen are converted to water, carbon dioxide, methane and ammonia, while other components decompose more slowly into stable forms that are stored in the soil and are usable by plants as food. These stable forms are known collectively as humus. The end products of the decomposition of humus are mineral salts, carbon dioxide and ammonia. Humus is also an important source of phosphorus and sulphur. The C:N:P:S ratio in humus is about 100–120:10:1:1.

Humus has a very high CEC range of 100–300 me per 100 g of soil. Due to this property, humus acts similarly to clay in retaining available nutrients against leaching and maintaining the nutrients in a form available to plants and micro-organisms (Foth 1984).

Humus absorbs large quantities of water and exhibits the properties of swelling and shrinking. Soil humus, though less stable (due to microbial decomposition), significantly contributes to soil aggregation (structure formation). The incorporation of crop residue mulch into the soil is very important in maintaining a favourable amount of humus in the soil.

Soil consistence

Soil consistence is the resistance of soil to deformation, mechanical disintegration and rupture, and includes soil properties such as plasticity, stickiness, friability and resistance to compression and shear.

Consistence depends on soil texture, especially clay, and the moisture content of the soil. Other factors that influence soil consistence include organic matter content, structure and type of clay mineral. Soil consistence affects tillage operations, particularly the draught of most farm implements.

The friability of soil refers to the ease with which it can be crumbled into smaller soil fractions. A friable soil often has the optimum conditions for tillage operations, which result in better seedbed preparation with good drainage, gaseous exchange and heat conductance. Soil friability is more common with medium-textured soils, e.g. loams and some silt loams, than with fine-textured soils.

Soil crusting

A soil crust is a thin brittle layer of hard soil formed on the surface of soil when dry. A soil crust does crack, peels off and may be moderately thick (0.5–3 cm). Soil crusts are of two types: *depositional crusts* (due to deposition of silt-laden sediment) and *structural crusts* (due to physical forces and inherent soil properties). Soil crusts mechanically impede seedling emergence, retard root development and soil aeration, and necessitate the use of excessive force in tillage operations. Where soil compaction has occurred over time and very thick soil crusts of 20–30 cm have formed, the phenomenon is referred to as *hard setting.*

Soil fertility

Soil fertility is the capacity of a soil to provide adequate and balanced amounts of nutrients for the growth of plants. Other necessary factors must be favourable for adequate nutrient uptake. Some of these are soil moisture and temperature, aeration, water-holding capacity, a pH that should be near neutral, without hard pans that would inhibit root growth, and also have adequate organic matter as well as conditions that promote the growth of soil micro-organisms.

Soil reaction (soil pH)

This is the degree of acidity or alkalinity of a moist soil. Acidity refers to the amount of the total CEC occupied by the acidic cations (H^+ and Al^{3+}). Soil reaction is measured and expressed as pH, which is the negative logarithm of the hydrogen ion concentration. The more acidic a soil is, the lower the soil pH value. Soil acidity is caused by the presence of excessive exchangeable hydrogen (H^+) and aluminium (Al^{3+}) ions.

Most plant nutrients are readily available at pH range of 6–6.5. Soil reaction affects the solubility of plant nutrients, therefore the availability of the nutrients to plants.

Table A2.1 *Effects of soil reaction on soil properties*

Soil property	Soil reaction
Chemical	Macronutrients (N, P, K, Ca, Mg and S) have a decreased availability at pH <6. Most micronutrients (Fe, Mn, Zn, Cu, B) have low availability at pH >7.5.
Biological	Bacteria and actinomycetes dominate at pH >6. Fungi dominate at pH <6.
Physical	Ca and/or Mg dominance favours flocculation. Na dominance causes deflocculation.

Soil salinity

This is a measure of the concentration of soluble salts within and on the surface of a given soil. Saline soils contain large quantities of salts. Sodic soils have excessive amounts of sodium, and have a pH range of 7–8.5 and an electric conductivity of greater than 4 millimhos per cm at 25˚C. Salinity is common in arid and semi-arid areas where low levels of annual rainfall and high daily temperatures have led to high water evaporation rates and consequently contributed to high concentrations of soluble salts. During rainy periods, these salts are leached and therefore form some highly saline water tables. Saline water tables contribute to the upward movement of salt by capillarity action to the upper soil layers. These high concentrations of soluble salts in the topsoil can be toxic and often reduce the availability of soil water to plants (by causing reverse osmosis).

Soil salinity significantly affects crop performance and yields. Crops have different tolerance levels to salinity and hence it is important to consider this when determining the type of crops to grow in an area.

Soil sealing

Soil sealing is caused by the dispersion of soil particles in the immediate surface layer of the soil. It is associated with the formation of a thin layer (1–5 mm) at the surface of the soil that is very dense and hard when dry, without any porosity, and which does not crack. As a result of the sealing, the infiltration of rainwater into the soil is impeded and therefore runs off even on very gentle slopes.

It has been observed that more than a month of rain may be required before a sealed soil layer is sufficiently softened and broken up to allow rainwater to enter the soil. The process of soil-surface sealing is often attributed to compaction by physical forces (through rain splash, trampling and flooding), slaking by chemical dispersion of aggregates, and deposition of silt-laden sediment which subsequently clogs all pores or may wash in to form sub-surface sealing. Soil sealing is a prerequisite to crusting.

Soils with a fair percentage of silt (5–10%) and clay (<20%) are prone to sealing. Sealing occurs in topsoils of the more acidic crystalline rocks like granites and gneisses, or of sedimentary rocks like quartzitic sandstones.

Soil slaking

Slaking of soil is the phenomenon where structural instability of the topsoil layer occurs due to the dispersion of individual soil particles in times of excessive wetness, leading to the formation of a hard surface crust upon drying. Slaking is associated with clogging of pores and lowers the infiltration capacity and surface water storage capacity of soil. Slaking is associated with fine sandy soils that are low in organic matter and calcium. Slaking is increased through excessive tillage operations, which enhance the destruction and breakdown of soil aggregates and organic matter content.

A slaked soil will have undergone advanced structural degradation, tending to be hard when dry but rapidly moistening to form very loose, highly erodible soil.

Soil structure

Soil structure refers to the size of soil particles and type of aggregation. Soil structure ranges from small crumbs to large lumps or clods. The following types of soil structure are recognized: single grain, granular, crumb, blocky, columnar, prismatic, platy and massive. A greater proportion of clay in a soil produces a more stable structure, particularly in sandy soils. Good drainage, high organic matter content and presence of cementing agents (e.g. iron oxides) produces very stable structures.

Generally, soil structure affects the water-holding capacity, aeration, drainage and erosional properties of soil.

Soil texture

Coarse-textured soils (e.g. sandy soils)

These soils are loose, friable, well aerated and drained and easily tilled. They have poor moisture- and nutrient-holding capacity, which can be improved by adding organic matter (as a binding agent and also to increase the water-holding capacity).

Fine-textured soils (e.g. clay)

These soils have large amounts of colloidal clay, which makes them plastic, and they puddle under saturated soil moisture conditions. The structure of clay soils can be improved by planting crops with fibrous root systems, e.g. legumes and grasses.

Appendix 3: Glossary of soil terms

eluviation—The removal of soil material in suspension (or in solution) from a layer or layers of a soil. An eluvial horizon is therefore a horizon that has been formed by the process of eluviation. Usually, the loss of material in solution is described by the term *leaching*.

erodible—Susceptible to erosion. (Expressed by terms such as 'highly erodible', 'slightly erodible', etc.).

exchangeable sodium percentage—The percentage of the cation exchange capacity of a soil occupied by sodium.

gley soil—Soil developed under conditions of poor drainage resulting in reduction of iron and other elements and characterized by grey colours and mottles.

hardpan—A hardened soil layer, in the lower A or in the B horizon, caused by cementation of soil particles with organic matter, or with materials such as silica, sesquioxides or calcium carbonate. The hardness does not change appreciably with changes in moisture content, and pieces of the hard layer do not slake in water.

illuvial horizon—A soil layer or horizon in which material from an overlying layer has been precipitated from solution or deposited from suspension.

indicator plants—Plants characteristic of specific soil or site conditions such as soil fertility or drainage.

infiltration rate—A soil characteristic determining or describing the maximum rate at which water can enter the soil under specified conditions, including the presence of an excess of water.

leaching—The removal of materials in solution from the soil. See *eluviation*.

mesophilic bacteria—Bacteria whose optimum temperature for growth falls in an intermediate range of approximately 15˚C to 45˚C.

mineralization—The conversion of an element from an organic form to an inorganic state as a result of microbial decomposition.

mineral soil—A soil consisting predominantly of, and having its properties determined predominantly by, mineral matter. Usually contains <20% organic matter. Based on the percentage organic matter, one can clearly see that most soils in the tropics are mineral soils, i.e. most of the properties are inherited from the parent material. Thus a mineral soil can have organic horizons if the latter is enriched with organic compounds.

mulch—Any material such as straw, sawdust, leaves, plastic film, loose soil, etc., that is spread upon the surface of the soil to protect the soil and plant roots from the effects of raindrops, soil crusting, evaporation, etc.

mulch farming—A system of farming in which the organic residues are not ploughed into or otherwise mixed with the soil but are left on the surface as a mulch.

mycorrhiza—Literally 'fungus root'. The association, usually symbiotic, of specific fungi with the roots of higher plants.

nitrogen fixation—Biological conversion of molecular di-nitrogen (N_2) to organic combinations or to forms utilizable in biological processes.

organic phosphorus—Phosphorus present as a constituent of an organic compound, or a group of organic compounds such as glycerophosphoric acid, inositol phosphoric acid, cytidylic acid, etc.

parent material—The unconsolidated and more or less chemically weathered mineral or organic matter from which the solum of soils is developed by soil-forming processes.

ped—A unit of soil structure such as an aggregate, crumb, prism, block or granule, formed by natural processes.

permeability—The ease with which gases, liquids or plant roots penetrate or pass through a bulk mass of soil or a layer of soil. Since different soil horizons vary in permeability, the particular horizon under question should be designated.

physical properties—Those characteristics, processes or reactions of a soil which are caused by physical forces and which can be described by, or expressed in, physical terms or equations. Examples of physical properties are bulk density, water-holding capacity, hydraulic conductivity, porosity, pore-size distribution, etc.

porosity—The volume percentage of the total bulk not occupied by solid particles.

potassium fixation—The process of converting exchangeable or water soluble potassium into a form not readily available to plants.

profile—A vertical section of the soil through all its horizons and extending into the parent material.

rhizobia—Bacteria capable of living symbiotically in roots of legumes, from which they receive energy and often utilize molecular nitrogen. Collective common name for the genus *Rhizobium*.

soil—The unconsolidated mineral material on the immediate surface of the earth that serves as a natural medium for the growth of land plants. It has normally been subjected to and influenced by genetic and environmental factors of parent material, climate (including moisture and temperature effects), macro- and micro-organisms, and topography, all acting over a period of time.

soil conservation—(i) Protection of the soil against physical loss by erosion or against chemical deterioration, that is, excessive loss of fertility by either natural or artificial means; (ii) A combination of all management and land-use methods that safeguard the soil against depletion or deterioration by natural or man-induced factors.

soil horizon—A layer of soil or soil material approximately parallel to the land surface and differing from adjacent genetically related layers in physical, chemical and biological properties or characteristics such as colour, structure, texture, consistency, kinds and numbers of organisms present, degree of acidity or alkalinity, etc. Very few if any soils have all of the horizons well developed, but every soil has some of them.

soil organic matter—The organic fraction of the soil; includes plant and animal residues at various stages of decomposition, cells and tissues of soil organisms, and substances synthesized by the soil population. Usually determined on soils which have been sieved through a 2.0-mm sieve.

soil piping or tunnelling—Accelerated erosion which results in subterranean voids and tunnels.

soil structure— The combination or arrangement of primary soil particles into secondary particles, units, or peds. These secondary units may be, but usually are not, arranged

in the profile in such a manner as to give a distinctive characteristic pattern. The secondary units are characterized and classified on the basis of size, shape and degree of distinctness into classes, types, and grades, respectively.

stubble mulch—The stubble of crops or crop residues left essentially in place on the land as a surface cover before and during the preparation of the seedbed and at least partly during the growing of a succeeding crop.

surface sealing—The orientation and packing of dispersed soil particles in the immediate surface layer of the soil, rendering it relatively impermeable to water.

terrace—A more or less level piece of ground on a slope, having a ridge or embankment of earth or stone, often, but not always, with a ditch on the lower side. The ditch would normally be constructed on the contour or a slight grade to allow controlled flow of excess water where necessary. The term terrace may refer to the level ground or to the embankment or to both.

thermophilic organisms—Organisms which grow readily at temperatures above 45°C.

water-stable aggregate—A soil aggregate that is stable to the action of water such as falling drops or agitation, as in wet-sieving analysis.

water table—The upper surface of groundwater or that level below which the soil is saturated with water; locus of points in soil water at which the hydraulic pressure is equal to atmospheric pressure.

Appendix 4: Glossary of fertilizer terms

available nutrients—Nutrient ions or compounds in forms which plants can absorb and utilize in growth.

biodegradable—A material capable of degradation by biochemical processes.

carbon-nitrogen ratio (C:N ratio)—The ratio of the weight of organic carbon to the weight of total nitrogen (mineral plus organic forms) in the soil or organic material. It is often used for the carbon–organic nitrogen ratio when the mineral nitrogen levels are low.

fertilizer—Any organic or inorganic material of natural or synthetic origin which is added to a soil to supply one or more elements essential to the growth of plants.

fertilizer carrier—Major NPK fertilizer or liming components with which micronutrients or pesticides are incorporated for purposes of dilution and more uniform distribution.

fertilizer, complete—Used formerly to denote a fertilizer containing appreciable contents of N, P and K, but now also to include secondary and micronutrients essential for plant growth.

fertilizer, compound—A fertilizer formulated with two or more fertilizer compounds or ingredients.

fertilizer grade—The guaranteed minimum analysis, in per cent, of the major plant nutrient elements contained in a fertilizer material or in a mixed fertilizer. (Usually refers to the percentage of $N:P_2O_5:K_2O$, but proposals are pending to change the designation to the percentage of N:P:K.)

fertilizer, granular—Fertilizer materials processed to achieve uniform size, stability and shape.

fertilizer, starter—A relatively small application of fertilizer applied with or near the seed for accelerating early growth of the crop.

fixed phosphorus— That phosphorus which has been changed to a less soluble form as a result of reaction with the soil; soluble phosphorus that has become attached to the solid phase of the soil in forms highly unavailable to crops.

foliar diagnosis—An estimation of mineral nutrient deficiencies (or excesses) of plants based on examination of the chemical composition of selected plant parts, and the colour and growth characteristics of the foliage of the plants.

lime, agricultural—A soil amendment consisting principally of calcium carbonate but including magnesium carbonate and perhaps other materials used to neutralize soil acidity and furnish calcium and magnesium for the growth of plants.

luxury uptake—The absorption by plants of nutrients in excess of their need for growth. Luxury concentrations during early growth may be utilized in later growth.

macronutrient—A chemical element necessary in relatively large amounts for the growth of plants. These elements are C, H, O_2, Ca, Mg, K, P, S and N.
micronutrient—A chemical element necessary only in extremely small amounts for the growth of plants. These elements consist of B, Cl, Cu, Fe, Mn, Mo and Zn.
nutrient antagonism—A reciprocal relationship among concentrations of two or more nutrients in plants (examples are K and Mg, Fe and Mn).
nutrient stress—A condition of plant growth when inadequate nutrient supply restricts growth.
plant nutrient—An element which is absorbed by plants and is necessary for completion of the life cycle.
slow release—A fertilizer term used interchangeably with delayed release, controlled release, controlled availability, slow acting and metered release to designate a rate of dissolution (usually in water) much less than is obtained for completely water-soluble compounds. Slow release may involve either compounds which dissolve slowly or soluble compounds coated with substances impermeable to water.

Appendix 5: Glossary of tillage terms

conservation tillage—Any tillage sequence which reduces loss of soil or water relative to conventional tillage, often leaving crop remains on the soil surface as mulch cover, and minimizing the extent of inversion of the soil during tillage.

conventional tillage—The combined primary and secondary tillage operations normally performed in preparing a seedbed for a given crop.

contour tillage—Performing the tillage operations and planting on the contour within a given tolerance.

crop-residue management—Handling, placement and utilization of stubble, stalks and other crop residues by tillage operations: (i) to remove residues from the soil surface (burying); (ii) to anchor residues partially in the surface soil while leaving the residues partially exposed at the surface (mulch tillage); (iii) to leave residues entirely at the soil surface intact or cut into smaller pieces. (Residues may be removed by non-tillage methods, i.e. harvesting, burning, grazing, etc.)

strip cropping (strip farming)—The practice of growing two or more crops which require different tillage sequences, or the same sequences in different seasons, in alternating strips along contours or perpendicular to the prevailing direction of wind.

listing (ridging)—A tillage and land-forming operation using a tool which turns two furrows laterally in opposite directions, thereby producing beds or ridges.

minimum tillage—The minimum soil manipulation necessary for crop production, or meeting tillage requirements under existing soil and climatic conditions.

mulch tillage—Tillage or preparation of the soil in such a way that plant residues or other materials are left to cover the surface; also, mulch farming, trash farming, stubble mulch tillage, ploughless farming.

no-tillage system—A procedure whereby a crop is planted directly into a seedbed, not tilled since harvest of the previous crop; also zero-tillage.

optimum tillage—That combination of tillage operations which maximizes growth of crop plants.

ploughless farming —Tilling soil without ploughing so that the crop residue will be left on the surface; also, trash farming, stubble mulch and subsurface tillage. See also *mulch tillage*.

plough sole (traffic sole, plough pan, tillage pan, traffic pan, compacted layer)—An induced sub-surface soil horizon or layer having a higher bulk density and lower total porosity than the soil material directly above and below, but similar in particle size analysis and chemical properties. The pan is usually found just below the maximum depth of normal ploughing and frequently restricts root development and water movement.

plough–planting—The ploughing and planting of land in a single trip over the field by drawing both ploughing and planting tools with the same power sources.

reduced tillage—A tillage sequence in which the primary operation is performed in conjunction with planting procedures in order to reduce or eliminate secondary tillage operations. See also *minimum tillage*.

ridge planting—A method of planting crops on ridges formed through tillage operations. This practice is used in areas where a large proportion of the rainfall comes in intense storms of short duration. Usually only one seed row is planted on each ridge.

strip tillage—Tillage operations performed in isolated bands separated by bands of soil essentially undisturbed by the particular tillage equipment.

sub-soiling—Breaking of compact sub-soils, without inverting them, with a special knife-like instrument (chisel) which is pulled through the soil at depths usually of 30–60 cm and at spacings usually of 60 cm to 1.5 m.

surface tillage—Cultivating or mixing the soil to a shallow depth or barely below the surface.

slit planting—A method of mulch tillage. Two to four weeks prior to seeding time an area 30–50 cm wide is thoroughly tilled by ploughing, middle busting, or disk tilling to form a conventional seedbed for each row. At planting time, or at first cultivation, the remaining living mulch material in the middle of the row is cut loose and killed or retarded.

sod planting—A method of planting in sod with little or no tillage.

tillage—The mechanical manipulation of soil for any purpose; but in agriculture it is usually restricted to the modifying of soil conditions for crop production.

tilth—The physical condition of soil as related to its ease of tillage, fitness as a seedbed, and its resistance to seedling emergence and root penetration.

Appendix 6: Critical leaf nutrient concentrations in some selected crops

	N (% DM)			P (% DM)			K (% DM)		
Crop	L	M	H	L	M	H	L	M	H
Cereals									
Maize	<2.9	3–5	>5	<0.25	0.3–0.6	>0.6	<1.5	1.8–2.6	>3
Rice	<2.5	3–4	>4.5	<0.2	0.2–0.4	>0.4	<2	3–4.5	>4.5
Root crops									
Cassava	<4.5	4.5–5.5	>5.5	<0.3	0.3–0.5	>0.5	<1	1.5–2.0	>2.0
Potato	<1.5	3–5	>6.5	<0.2	0.4–0.6	>0.6	<2	3–5	>7
Sweet potato	<2.5	3–4	>5	<0.12	0.2	>0.3	<0.8	1.0–1.5	>2
Yam	<1.5	1.5–2.0	>2.5	<0.15	0.2	>0.3	<1.5	1.5–2.5	>2.5
Food legumes									
Beans	<2	3–5	>5	<0.2	0.2–0.5	>0.5	<2	2–3	>3
Cowpea	<2	3–4	>5	<0.2	0.2–0.5	>0.5	<2	2–3	>3
Groundnut	<2	3–4	>5	<0.2	0.2–0.5	>0.5	<2	2–3	>3.5
Soybean	<2	3–5	>5	<0.2	0.3–0.5	>0.6	<2	2–3	>3.5
Vegetables									
Carrot	<2	2–3	>3.5	<0.2	0.3–0.4	>0.5	<2	2–3	>4
Cucumber	<2	2.5–4.0	>5	<0.2	0.3–0.5	>0.6	<2	2.5–4.5	>5.5
Eggplant	<2	2.5–3.0	>4	<0.2	0.3–0.5	>0.6	<2	2–4	>4
Onion	<2	2–3	>3	0.2	0.2–0.4	>0.4	<2	2–3	>3.5
Sweet pepper	<3	3–4	>4.5	<0.2	0.3–0.5	>0.6	<3	4–5	>5
Sweet corn	<2.5	2.5–3.5	>3.5	<0.2	0.3–0.6	>0.6	<2	2.5–3.5	>4
Tomato	<3.0	3.5–4.5	>5.0	<0.3	0.3–0.8	>0.9	<2	2.5–4.5	>5
Fruit crops									
Avocado	<1.5	1.6–2.0	>2.5	<0.1	0.1–0.3	>0.3	<0.3	0.5–2.0	>3
Banana	<3.0	3.0–3.5	>3.5	<0.1	0.1–0.2	>0.3	<3	4–5	>5
Mango	<1.5	2–3	>3	<0.2	0.2–0.3	>0.4	<3	3–4	>5
Orange	<2.0	2–3	>3.5	<0.15	0.2–0.3	>0.3	<1	1–2	>2
Papaya	<1.5	1.5–2.0	>2.5	<0.1	0.1–0.3	>0.3	<0.8	1–2	>2
Pineapple	<1.5	1.5–2.0	>2	<0.15	0.2	>0.25	<0.18	2–3	>3.5
Watermelon	<1.8	2–3	>3	<0.2	0.2–0.4	>0.5	<2	2–3	>3.5
Tree crops									
Cocoa	<2	2.0–2.5	>2.5	<0.1	0.1–0.2	>0.2	<1	1–3	>3
Clove	<2	2.0–3.0	>3.0	<0.1	0.1–0.2	>0.2	<1	1–2	>2
Coconut	<1.8	2.0–2.5	>2.5	<0.1	0.12–0.15	>0.17	<0.8	1.0–1.5	>2
Coffee	3–9	2.5–3.5	>3.5	<0.1	0.1–0.2	>0.2	<1.5	2.0–2.5	>2.5
Tea	<3.5	4–5	>5	<0.3	0.3–0.5	>0.6	<1.5	1.5–2.5	>2.5
Cash crops									
Sugar cane	<2	2–3	>3	<0.2	0.2–0.3	>0.3	<1	1–2	>2
Tobacco	<2	2.0–2.5	>3	<0.2	0.2–0.4	>0.5	<2	2–4	>4
Spices									
Chillie	<2.5	3–4	>4.5	<0.2	0.3–0.4	>0.5	<2.5	3–4	>4.5
Pepper	<2.5	3.0–3.5	>3.5	<0.15	0.2	>0.2	<2.5	3–4	>4.5
Fodder crops									
Grass	<1.5	2–3	>3	<0.2	0.2–0.4	>0.4	<2	2.0–3.5	>3.5
Legumes	<3	3–5	>5	<0.2	0.3–0.5	>0.6	<2.0	2.5–4	>4

DM = dry matter; L = low; M = medium; H = high.
Source: Dierolf et al. 2001.

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RELMA, the successor of the Regional Soil Conservation Unit (RSCU), is based in Nairobi and operates mainly in six eastern and southern African countries: Eritrea, Ethiopia, Kenya, Tanzania, Uganda and Zambia. RELMA's goal in the region is to improve livelihoods of small-scale land users and enhance food security for all households. In pursuit of this goal, RELMA promotes environmentally sustainable, socially and economically viable farming and marketing systems, and supports policies that favour small-scale land users.

RELMA organizes, on a regional level, training courses, workshops and study tours. It also gives technical advice, facilitates exchange of expertise and produces information materials for the dissemination of new knowledge, techniques and approaches. A variety of reports, handbooks, posters and other information materials are published and distributed in the region on a non-profit basis.

About this book

This book addresses the subject of soil fertility and land productivity in the eastern Africa region. It is now generally agreed that the high levels of poverty prevailing in these countries, especially among small-scale farmers, result partly from very low and declining soil fertility. The immediate purpose of this handbook is to provide reference material for middle- and senior-level extension workers, to highlight some of the factors that lead to poor land productivity, and to provide simple methods of correcting the situation. It is expected that the book will be used by these senior staff to train the extension agents who are in direct contact with farmers.

The book focuses mainly on soil properties, plant nutrients, organic and inorganic fertilizers, the maintenance and improvement of soil fertility, and the role of agroforestry and tillage practices in land productivity. The ultimate purpose is to help farmers raise land productivity to levels that would contribute significantly to food supplies and improved nutrition, income growth, and thus to poverty reduction in the region.

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