CHERISH THE EARTH

Soil Management for
Sustainable Agriculture and
Environmental Protection
in the Tropics

Land and Water Development Division
Food and Agriculture Organization of the United Nations
Viale delle Terme di Caracalla
Rome 00100
Italy

Tel: (39-6) 5225 3964
Fax: (39-6) 5225 6275

Based on a text by Professor Dennis J. Greenland
Design, editing and production by Words and Publications, Oxford, United Kingdom

CONTENTS

INTRODUCTION **2**

THE PROBLEM: **3**
Increasing production while enhancing the quality of the resource base

A BRIEF HISTORY: **6**
The development of sustainable farming systems

An historical perspective 6

The sustainability and non-sustainability of current soil management systems 8

THE SOLUTION: **11**
Establishing sound principles of good soil management

Maintaining and improving soil productivity 11
- *Managing soil nutrients* 12
- *Managing soil physical conditions* 13
- *Managing soil organic matter and soil biological conditions* 16

Avoiding and rectifying soil degradation 17
- *Avoiding erosion* 18
- *Rectifying chemical degradation* 19
- *Avoiding and rectifying physical degradation* 21

Avoiding environmental damage 21
- *Off-site damage due to soil erosion* 22
- *Damage due to misuse of fertilizers* 23

APPLYING THE PRINCIPLES: **24**
The practice of good soil management

Sustainable systems in the humid tropics 24

Sustainable systems in the sub-humid tropics 25

Sustainable systems in the semi-arid tropics 26

Sustainable systems in the wetlands 26

THE NEED FOR ACTION: **29**
Building on today's knowledge for a sustainable future

INTRODUCTION

In the course of the present century, the world population has increased from less than two thousand million to over five and a half thousand million. Until one hundred years ago, the expanding population's increasing needs for food, fuel, fibre and construction materials were met from the land by cultivating progressively larger areas. The much greater increase in population during this century has been supported mainly by greatly intensifying the use of much of the land that is already cultivated. In the course of the next twenty-five years a further two thousand million people will be added to the global population. Most of these people will live in the tropics. As a result, the demands which will be placed on the soil and water resources of the tropics will far exceed those of the past.

There have been some outstanding successes in the development and implementation of methods to increase food production in the tropics, most notably with rice from the wetlands, and wheat and maize from the better soils where irrigation is available. Improvements in less advantaged areas, and with subsistence crops such as sorghum, millets and cassava, have been slow. In Africa and in some other areas, the rate of increase in food production has actually been slower than the rate of population growth. Where increases in production have been achieved in Africa, they have mostly been through the cultivation of areas not previously considered suitable for development, or through the intensification of production on a non-sustainable basis.

The aim of this brochure is to summarize past and present soil management practices in the semi-arid, sub-humid and humid tropics, taking account of the importance of sustainability and the problems of environmental degradation which may accompany intensified use of the soil. It is intended to assist all those concerned with agricultural development and the environment to recognize the problems of soil degradation, and the compatibilities and incompatibilities of increased agricultural production with protection of the environment.

This brochure describes how, under lower demographic pressure in the past, soil management practices have evolved to provide sustainable soil management systems, adapting both to the environment and to existing social and economic circumstances. An understanding of the factors that determine the sustainability of these systems—and of their breakdown under increasing demographic pressure—has made it possible to establish sound principles of sustainable soil management. Such management aims not only to maintain or improve soil productivity, but to avoid (and where necessary, to rectify) all forms of soil degradation so that damage to the environment is prevented. The ways in which these principles may be applied to the development and implementation of more productive and sustainable management systems are also discussed in this brochure.

THE PROBLEM

Increasing production while enhancing the quality of the resource base

More than one million years were needed for the world's population to grow to the level of one thousand million. This figure was reached in the middle of the last century. It is now increasing by approximately one thousand million every ten years (see Figure 1). Perhaps surprisingly, in view of Thomas Malthus' prediction in 1798 that the world would shortly outgrow its ability to feed itself, the world continues to support its rapidly increasing population.

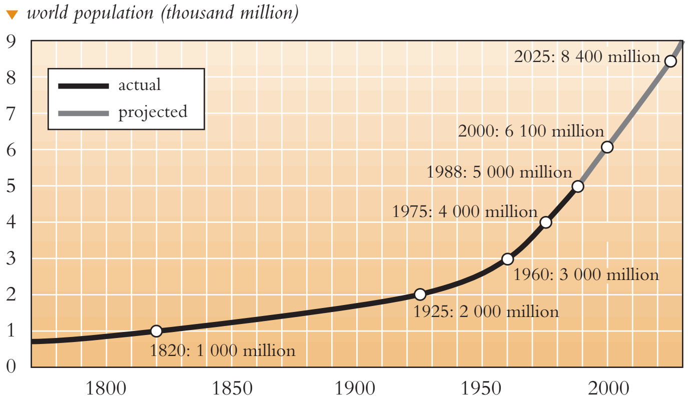
Two factors underlie the ability of the earth to support the enormous increase in the number of people now living:

- the resilience of soils in response to increasing demands made on them; and
- the increasing knowledge of farmers and scientists about how to manage soils productively and sustainably.

Probably the most important advance in knowledge which has helped to sustain the huge growth in population was the discovery of how to manufacture inorganic fertilizers. As a result of collaboration between a farmer (John Lawes) and a scientist (Henry Gilbert) at Rothamsted in England, this discovery was further exploited. Their experiments in soil management began a century and a half ago, and still continue today on exactly the same plots of land. These experiments show that, under the soil and climate conditions where they have been conducted, a sustainable system can be achieved, at least in terms of the local environment, and yields are generally far higher now than ever before (see Figure 2). Other advances in crop improvement and pest management, including the use of pesticides, have of course made a significant contribution.

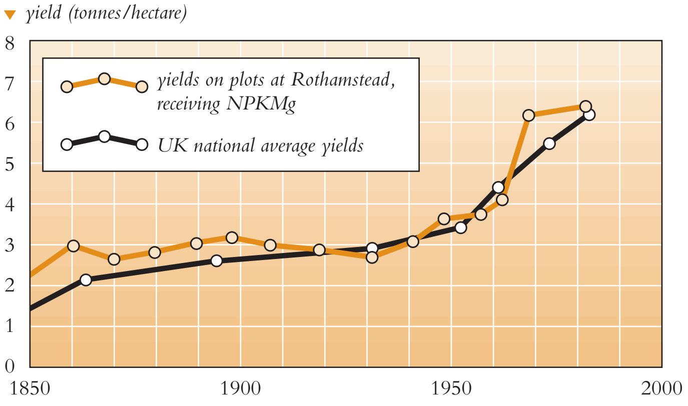
Much of the debate about the sustainability of systems requiring high inputs of synthetic chemicals has focused on the possible damage to the health of those living on the produce of those systems. The health of the population

Figure 1 Growth of world population



World population has increased rapidly since the middle of the nineteenth century, and is now increasing by approximately one thousand million every ten years.

Figure 2 Wheat yields on the Broadbalk Field plots, Rothamsted



Crop yields on the continuous wheat plots of Broadbalk Field, Rothamsted, UK (receiving NPKMg inorganic fertilizers on an annual basis) are comparable with UK national average wheat yields.

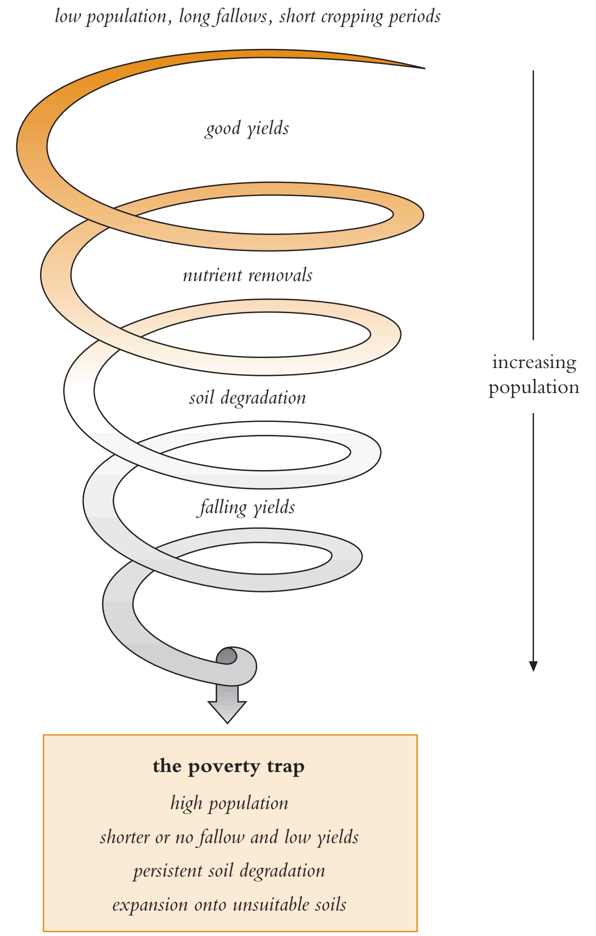
supported by food grown under intensive management systems is, in fact, better than ever before achieved.

A soil management system that depends on large inputs of inorganic fertilizers may be sustainable when considered in isolation, but the sustainability of mineral and energy resources from which the fertilizers are made must also be taken into account. In addition, the environmental effects of the movement of chemicals (from fertilizers and pesticides) out of the soil and into the groundwater, and of by-products released into the atmosphere, should also be considered. Particular attention should be paid to the effects of these chemicals on the plant and animal populations, and the biodiversity of those populations.

Several thousand years before the work of Lawes and Gilbert, a different sustainable agricultural system was developed, aiming to support a burgeoning population in southern and eastern Asia. This was the rice cultivation system of the great river basins, where the entrapment of water and silt from the annual flooding of the rivers has enabled crops of rice to be grown continuously ever since. Again, the burden of population pressure became too heavy for the traditional system to support, and only the interaction between scientist and farmer—eventually leading to the green revolution—enabled rice yields to be raised to levels that have continued to support the growing population. Here also, questions have been raised about the sustainability of the system. The traditional system depended on the erosion of silt from higher land, thus resulting in the degradation of the upland areas. Green revolution technology depends on external energy inputs and has led to higher levels of methane and nitrous oxide emissions, making a substantial contribution to the greenhouse effect and creating changes in the atmosphere which could affect all of the earth.

In much of the rest of the world the pressure of population growth has, until recently, been much less than in Europe and the great river basins of Asia. Soil management methods have therefore had less reason to intensify, and have evolved more slowly. These regions are also those of generally poorer soils and more difficult climates. Population growth here has been slower, partly for that reason. However, in recent years, health improvements and other changes have led to more swiftly growing populations. This has accelerated the demand for food, as well as other agricultural products. Increases in food production have been achieved, but mostly by expanding the area cultivated. In Africa the method of increasing production has often been to intensify production in areas of shifting

Figure 3 The downward spiral to the poverty trap



After McCown and Jones, 1992

Intensified land use in the areas of shifting cultivation leads to shorter rest times for fallow fields and, ultimately, to soil degradation and reduced crop yields. This will inevitably give rise to a non-sustainable system, incapable of supporting a growing community.

cultivation—by extending the cultivation period and decreasing the length of time the soil is allowed to rest under naturally regenerating vegetation. This type of change produces a non-sustainable system (see Figure 3).

Perhaps the biggest challenge facing farmers, economists and soil scientists today is to develop sustainable farming systems together with the political and socio-economic conditions in which they can be practised, so that a much larger population may be supported by the soils of these less fertile areas.

Many attempts to introduce continuous arable cropping systems into the semi-arid, sub-humid and humid tropics have failed. Often, the maintenance of the nutritional status of the soil has not been adequate. Other causes of failure include soil degradation in one or more of the following ways:

- physical degradation due to erosion, compaction and crusting;
- chemical degradation associated with nutrient mining and acidification;
- biological degradation associated with loss of organic matter; and
- deterioration of drainage conditions causing waterlogging or salinization.

While arable cropping has often been found to be non-sustainable, production of tree crops in the humid and sub-humid tropics has presented relatively few problems with respect to sustainability. In the semi-arid areas, animal production has sometimes been possible on a sustainable basis. Problems of sustainability in animal production systems have arisen as stock numbers have increased with no improvement in the carrying capacity of the land. In periods of drought or water shortage, overgrazing can lead to denudation of vegetation and, as a result, exposure of the soil to wind erosion. Thus, for arable cropping and pasture production, there is a great need to establish economically viable and socially acceptable methods of soil management which are both productive and sustainable.

Although much remains to be done, the basic principles of good soil management are now well established. *They should now be widely known and understood, evaluated and adapted to suit the specific soils and environmental, social and economic conditions of different regions*. The necessary policies must then be implemented so that good soil management may be practised in such a way that it provides a satisfactory livelihood for the farmer and his or her family.

A BRIEF HISTORY

The development of sustainable farming systems

An historical perspective

Probably the earliest form of soil management originated when nomads—people who moved between grazing areas with their animals—discovered that they could grow crops readily on new land but that if they endeavoured to grow crops on the same piece of land for more than one season, they would obtain less food from the crops they planted. Once this lesson had been learnt, the process of 'shifting cultivation' gradually became more sophisticated. As building skills improved, communities were able to provide themselves with more sophisticated shelters. Thus they became less ready to abandon their settlements and more interested in producing crops within easy reach of their homes. The home became fixed for several years and crops were grown for one, two or three seasons before yields became poor and new land had to be cultivated. The more observant soon recognized that certain plants were indicators of relatively high fertility soils, and would therefore show them where they could expect to obtain good crops. They would also have learnt that crops would flourish where animals had been housed, and that the sites of abandoned homes were also good places to grow crops.

Thus the system of shifting cultivation evolved from the stage where homes and fields were abandoned after one or two years, to the stage where the home was settled for perhaps a decade or more. In addition, most of the food on which the family depended was now grown on fields where crops were rotated, at intervals of a few seasons, onto land that had not been cultivated for decades. When dwellings were fixed in place, a permanent 'home garden' was often established near the house, on sites where animals had been housed and on land where household refuse had been added to the soil.

This form of soil management by shifting cultivation has been widely practised throughout the world. It is an essential response to the problem of obtaining food where the soil itself is incapable of sustaining the continuous production of crops for an unlimited period. The system is sustainable as long as there is sufficient land for the soil to be allowed to recover until its productivity returns to the former level. It is also dependent on the knowledge and experience acquired by the farmers themselves.

Figure 4 The phases of land cultivation

Phase I	Phase II	Phase III	Phase IV
Simple shifting cultivation	Recurrent cultivation	Recurrent cultivation with continuously cultivated plots	Continuous cultivation
Dwellings and cultivated area shift together	Cultivated area shifts more frequently than dwellings	Always complex with several field types	May involve alternate husbandry with planted and cultivated pastures or fallow crops
	May be complex with more field types		

Greenland, 1974

The stability of shifting cultivation systems practised by generations of farmers who have lived in the same area for many years may be contrasted with the non-sustainability of superficially similar, slash-and-burn methods used by displaced people. Such communities are often forced to settle in unsuitable areas of poor land with which they have no experience. Unsuitable cultivation methods on fragile soils may then lead to irreversible soil degradation after only one or two seasons of cultivation. The fact that the community has no right of long-term tenure to the land means that there is little incentive to seek a more sustainable land management system.

There were exceptions to the common experience of rapid yield decline, and a few soils were found to allow good crops to be grown indefinitely. These soils were highly valued, and wherever they occurred great care was taken to preserve them. To protect the soils against severe rainstorms, particularly in mountainous areas where any cultivable land is scarce, farmers learnt how to build terraces. These controlled the flow of water and prevented the soil from being washed away. In Asia, terraces were often built which retained the water so that paddy rice could be grown. Some terrace systems were built so well that they have remained in place for thousands of years and are still performing a valuable role today (Figure 5). While relatively common in Asia, stone terraces are occasionally found in Africa in the small number of areas where the soils are of a high inherent fertility.

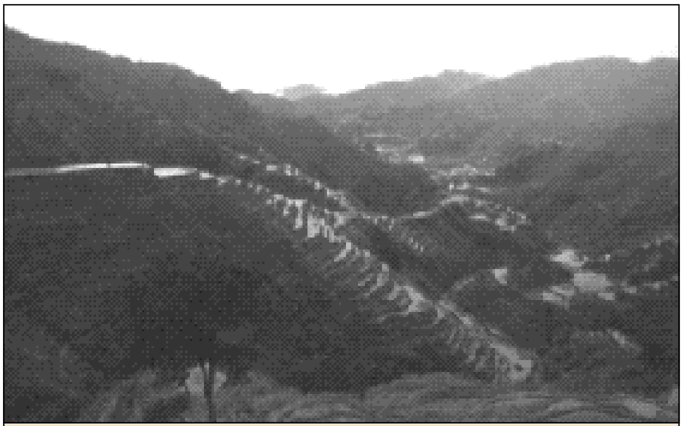
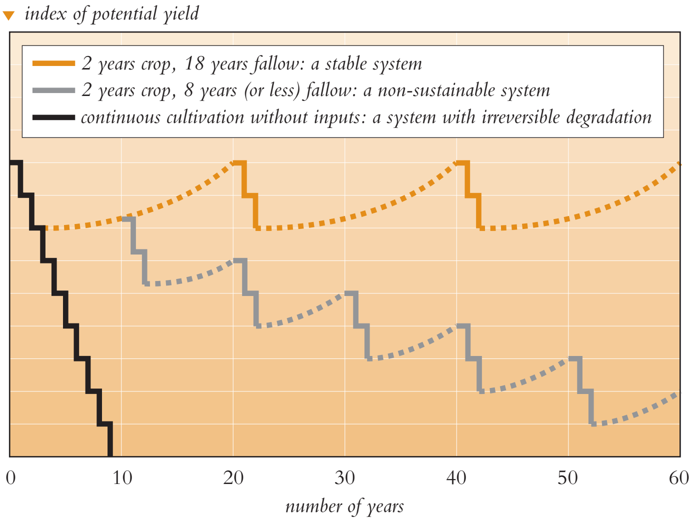


Figure 5 *Ancient stone wall terraces of the Ifugao, Banaue, Philippines*

Professor D.J. Greenland, F.R.S.

Figure 6 Agricultural systems compared



A diagrammatic representation of changes in potential soil productivity under a stable system of shifting cultivation, a non-sustainable system (where the fallow period is too short to restore fertility) and a system of continuous cultivation without inputs.

The system of shifting cultivation found on the more widespread areas of lower fertility, with 'far fields' cultivated for a few years and then rested, and home gardens manured and continuously cultivated, remains widely practised today. However, it can only be considered sustainable if there is sufficient land available for the far fields to be rested long enough for their productivity to be restored—perhaps for ten years or more (Figure 6). This is now the exception rather than the rule.

In some areas, other methods evolved to improve soil fertility. One example is the 'chitimene' system found in Zambia. On sandy soils of exceptionally low inherent fertility, branches of trees are carried from adjacent woodland and piled on the area to be cultivated. They are then burnt so that the ash adds to the nutrients in the cultivated plot. In the high hills of Nepal, soil fertility has been maintained by collecting and composting leaves and litter from nearby forest areas. The compost is then spread on the soil as a mulch to protect the soil against erosion, and add to the soil nutrients. Both systems involve a transfer of nutrients from woodland or forest to the cultivated land. The sustainability again breaks down when there are too many people to support. The trees in proximity to the cultivated land are gradually destroyed, and the woody material has to be carried from further afield. The forest and woodland themselves become less productive as their nutrients are mined and transferred to the cultivated land and, eventually, exported in produce.

A similar transfer of nutrients takes place in pastoral systems where animal manure is used to supplement soil fertility. Where there is ample grazing land, such a system may be sustainable, but as the concentration of people and animals increases, the depletion of nutrients in the grazing areas causes their productivity to decline. The situation is usually exacerbated by the losses of nitrogen and sulphur, which occur when the grasslands are burnt.

Thus, although these systems of nutrient cycling and transfer may be sustainable under low population densities, the sustainability breaks down as the pressure on the land increases.

A different system developed some seven to eight thousand years ago in the wetlands of Asia. In China and northern India, it was discovered that rice would grow for many years in the flooded areas adjacent to rivers. It grew best where the water was not too deep and flowed slowly around the plants, draining away shortly before the grain was ready to harvest. As the population increased, all of the land near the river was taken. It was then found that the alluvial soils were deep and easy to work, so that low mud banks could be built to retain the water, which could then be diverted in channels to flood the soil. This enabled rice to be grown on the flood plain of the river at considerable distances away from the river itself.

Unlike crops growing on the upland areas, the rice would continue to yield well. We know now that this is due to the nutrients carried in the floodwaters, and deposited with the silt brought into the fields with the annual floods. The nitrogen added by various nitrogen fixing organisms such as blue-green algae, and the effective suppression of most weeds by the flooding also make an important contribution to yield maintenance under these conditions.

The natural productivity of most wetland rice areas appears to have been sufficient to maintain yields of rice between one and two tonnes per hectare for centuries. However, as demand has grown and areas suitable for development as rice paddies have become scarce, it has been necessary to find alternative techniques to increase rice yields. These have included the increased use of all forms of organic manures and, in recent years, the gradual supplementation and replacement of manures by inorganic fertilizers. These techniques, used in combination with the spread of rice varieties able to respond to the higher fertility conditions, have proved successful. Equally important has been the extension of irrigation as a result of dam construction, and the distribution of assured water supplies to a much larger area.

The sustainability and non-sustainability of current soil management systems

All forms of production systems exist today, from nomadic herding to continuous, intensive monocrop systems. Their distribution is determined by soil and climate conditions, and by social and economic factors. In very general terms, as one moves from drier to wetter areas, pastures and animals become less important, and trees more so. Population density is greatest where soils are most fertile, and management systems the most intense.

Most production systems have evolved so that they are sustainable in terms of the environmental conditions prevailing at the time—including the level of demographic pressure. Given that demographic pressure has increased dramatically over the past century, and will continue to do so for the next half century, sustainability in relation to agriculture and soil management must be defined to include the need for increases in demand to be met. FAO (1991) has given the following definition:

> *'A sustainable agricultural system is one which involves the management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development conserves land, water, plant and animal genetic resources, and is economically viable and socially acceptable'.*

There are many other definitions of sustainable agriculture and land use, some simpler, and some more comprehensive (see box). Inherent in these definitions is the point that sustainable soil management must not degrade the soil or contaminate the environment, while providing the desired support to the production of food, fuel, fibre and construction materials.

Definitions of agricultural sustainability

'It means survival'

A subsistence farmer

•

'Low input, no input, organic farming'

An environmentalist

•

'Living on interest and not capital'

An economist

•

'The successful management of resources for agriculture to satisfy changing human needs, while maintaining or enhancing the quality of the environment and conserving natural resources.'

FAO Research and Technology Paper No.4: *Sustainable Agricultural Production: Implications for International Agricultural Research*. TAC/CGIAR, 1989

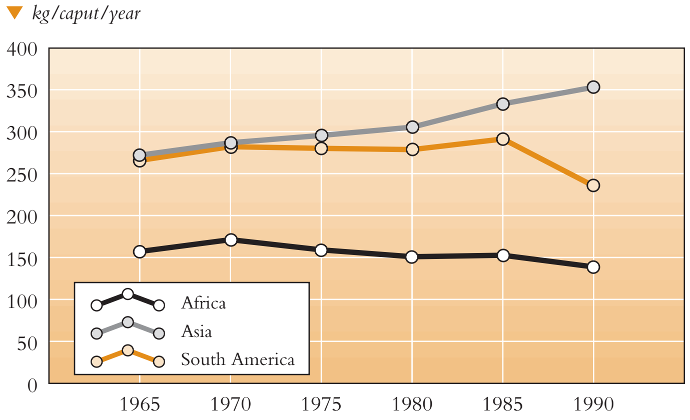
•

'A sustainable agricultural system is one which involves the management and conservation of the natural resource base, and the orientation of technological and institutional change in such a manner as to ensure the attainment and continued satisfaction of human needs for present and future generations. Such sustainable development conserves land, water, plant and animal genetic resources, and is economically viable and socially acceptable'

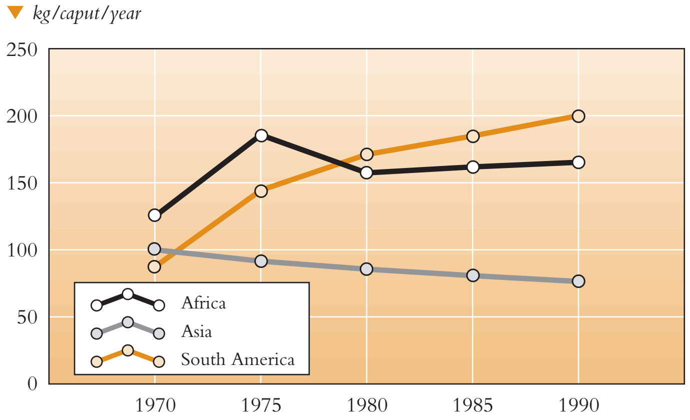
FAO, 1991

Figure 7 Per caput production of a) cereal, and b) root and tuber crops in Africa, Asia and South America (1965–1990)

a) cereal production



b) root and tuber production

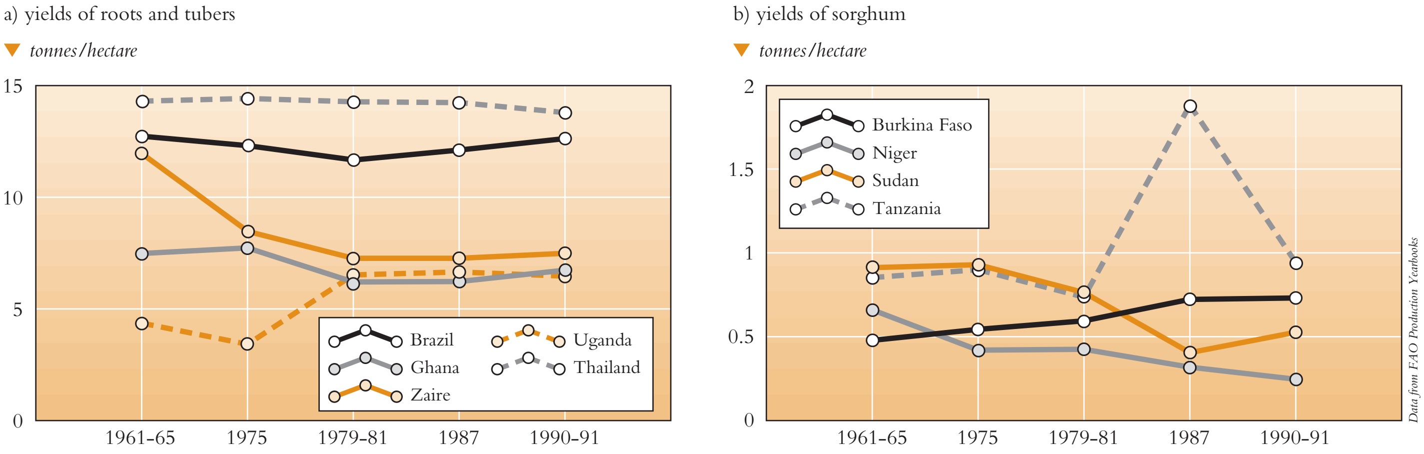


Data from FAO Production Yearbooks

Agriculture has evolved through various stages of shifting cultivation into semi-permanent systems, and to systems of continuous cultivation. All of these systems are being practised in different parts of the world at the present time. All of them can be sustainable, and all can fail, depending on the biophysical and socio-economic conditions in which they are practised. Indications of success or failure are given by changes in per caput food crop production in different regions (Figure 7).

Perhaps most significant among the data are the declining yields of major staples in some African countries—cassava in Zaire, and sorghum in Sudan and Niger—testifying to the

Figure 8 National average yields of a) roots and tubers, and b) sorghum, in selected countries (1961–1991)



a) yields of roots and tubers

b) yields of sorghum

Data from FAO Production Yearbooks

declining productivity of soils in those countries, and the expansion of cultivation onto marginal soils (Figure 8).

Within a stable political and social environment, farmers will always strive to evolve a system that is sufficiently productive to support their immediate social group, for the present and foreseeable future. Where markets exist, they will also strive to increase production to provide economic benefits for themselves and their families. Difficulties arise, however, as a result of changing social, economic and political circumstances. Of greatest significance among these has been the increasing demands on the land as populations have grown, leading to conflicts over both land and water supplies. Productivity will only rise in favourable social and economic circumstances, and it is the role of governments to establish such circumstances. In the following sections, the principles on which sustainable land management practices must be based are described, and the successful practice of those principles in different agro-ecological zones is discussed.

THE SOLUTION

Establishing sound principles of good soil management

Good soil management has always required that the soil be used in such a way that its productivity is maintained—or preferably, enhanced. This requires that the chemical and physical condition of the soil does not become less suitable for plant growth than when cultivation commences. Cultivation normally means that the soil will, in fact, deteriorate due both to nutrient removal when harvesting crops, and to physical damage to the soil structure. What is essential is that the deterioration is reversible, by chemical additions to the soil, mechanical manipulation, or natural processes of fertility restoration under pasture or trees. This implies that the soil must be resilient, i.e. after being subjected to the stresses involved in crop production, it must have the ability to return to its former condition, or an improved condition (Greenland and Szabolcs, 1994).

Most farmers consider land management in terms of the land that they own themselves, or to which they have access. This implies that the effects of their soil management practices which occur off-site may not be given due attention without some form of regulation. Off-site effects may include the deposition of eroded soil or material washed out of the soil into waterways and onto fields of neighbouring farms. It can also include the effects of materials volatilized from the soil, such as greenhouse gases and other potential pollutants. Good soil management must not only serve the immediate needs of the farmer but should also be acceptable to the wider community. For farmers other than those working at the subsistence level, the system must also be economically viable if the farmer is to continue to manage the land successfully, and improve the standard of life of his or her family.

The broader problems of sustainable land management are discussed fully in the World Soil Resources Report 73, *FESLM: An International Framework for Evaluating Sustainable Land Management* (FAO 1993b). In this paper, the pillars on which sustainable land management is based are stated to be: *Productivity; Security; Protection; Viability; Acceptability.*

The land must produce on a secure basis, the natural resources must be protected, and the management system must be economically viable and socially acceptable. However it must also be recognized that land cannot be managed sustainably unless the soil, which is a component of the land, is properly managed. This requires maintaining and improving soil productivity, avoiding and rectifying soil degradation, and avoiding environmental damage.

Maintaining and improving soil productivity

If a soil is to sustain the production of crops it must:

- provide the nutrient requirements of the crop;
- provide a physical medium:
  - in which the plant roots can grow adequately so that water and nutrients can be absorbed;
  - which stores sufficient water for the crop; and
  - which allows water to enter and move in the soil to maintain the water supply as it is transpired by the crop and evaporates from the soil;
- provide a medium in which soil organisms are able to:
  - decompose organic materials, releasing nutrients to the plants;
  - assist the transport of nutrients to plant roots;
  - compete successfully with pathogens which might otherwise infect roots and damage the plants; and
  - form the soil organic compounds which will have a favourable effect on other soil properties.

Managing soil nutrients

A few soils contain sufficient nutrients to allow them to be mined for many years without significant loss of yield, but the majority of soils can only be exploited for a few years before their ability to supply nutrients falls to a low level. If yields are to be maintained, and the soils used to produce crops on a continuing basis, a method by which nitrogen, phosphorus, potassium and other nutrients can be replaced has to be found.

Nitrogen is a special case because it can be fixed from the air. This natural fixation process is due to certain micro-organisms that live freely within the soil, and on the soil and leaf surfaces; in the case of rice crops, they are found on and in the paddy water. Other micro-organisms are symbiotic with plants, for example, *Rhizobia* with the legumes, *Actinorhizae* with the genus *Alnus,* and in rice paddies and other wetlands, *Anabaena* with *Azolla* (see Figure 9). A great deal of effort has been taken to quantify and maximize the contributions that can be made to the nitrogen nutrition of crops by natural nitrogen fixation processes, and to find soil management systems in which biological nitrogen fixation is maximized.

Professor D.J. Greenland, F.R.S.

Figure 9 *The water fern* Azolla *supports nitrogen-fixing* Anabaena, *and is seen here growing in a rice paddy in China.*

It is sometimes suggested that mycorrhizal (root inhabiting) fungi can contribute phosphorus and other nutrients to crops. Certainly in the short term they can increase crop uptake. They do so by collecting phosphorus from the soil more efficiently than crop roots. However. this is also a more effective way of mining the soil, and eventually depletes the soil still further.

Thus maintaining phosphorus, potassium and other nutrients normally requires the use of inorganic fertilizers. The amount of nutrients accumulated annually in vegetation is often less than that required to produce a satisfactory crop yield. Only if nutrients can be accumulated over several years and made available to just one or two crops are economic yields likely to be produced. Similarly, unless animals or trees are used to accumulate nutrients from large areas and concentrate them on a much smaller area of cropland, nutrient levels will only be sufficient to sustain a low level of crop production. Organic manures contain a balanced supply of essential nutrients as well as having additional beneficial effects on the soil, but the cost—in time and labour—of carrying organic manures to where they are needed is often considerable. In contrast, inorganic fertilizers are much less bulky and easier to use. For example, 100 kg of urea contains as much nitrogen as about 2 000 kg of animal manure or 4 000 kg of forest litter; and it would be necessary to use 1 000 kg of even a good compost to provide an equivalent amount of nitrogen. The lower energy consumption involved in the production of organic manures is often cited as an advantage, although individual farmers may still prefer to pay the higher costs of inorganic fertilizers simply because they are more convenient to handle and distribute. This may be especially true in a system that would require large amounts of excrement to be carried into the field—when the farmer's own labour costs may be even higher. In China, over recent years, there has been a substantial decline in the amount of organic manures used, whilst the use of inorganic fertilizers has increased rapidly.

Managing soil physical conditions

Soils under natural vegetation normally support an active population of soil animals. These live on the roots and on litter from the vegetation, and they dig and burrow, keeping the soil loose and friable. When the vegetation is cleared to grow a crop, the soil is exposed to the impact of rain, and to the effects of people, animals and machines, treading and compacting the soil. Compaction will make the soil less suitable for the proliferation of plant roots, and reduce its ability to retain the water that plants need to survive. Exposure and subsequent drying of the soil can also lead to surface crusting. This reduces the rate at which water can enter the soil, and can cause water to run off the surface leading to soil erosion.

In arid and semi-arid regions, exposure of some soils by overgrazing, or by annual burning of the vegetation, may also lead to compaction and the formation of surface crusts, even when the soil is not subjected to cultivation. Managing water on heavy clay soils is often a serious problem, and simple tillage implements have been designed to form cambered beds which will discharge excess water while not provoking erosion (Figure 10.)

Managing a soil's physical properties must therefore aim to preserve the structure of the soil (where this is already favourable for crop production) or to create a favourable structure by suitable tillage or other practices where such a structure does not exist (FAO, 1993c). Tillage is also important for weed control, and this is often the most significant reason for ploughing. However, the advent of herbicides has in many cases removed the need to plough, and made zero- or minimum-tillage techniques successful. Damage to the soil structure from ploughing can be avoided by the use of these techniques. They also reduce the rate of loss of organic material and the development of 'plough pans', which inhibit root development and water movement in the soil.

If the soil is naturally well structured—as is often the case after a long period under a forest canopy—it is easy to seed. Indeed, in shifting cultivation systems, a satisfactory crop stand can be obtained by dibbling the seed into the soil, subject to the important proviso that the land is cleared in such a way that the topsoil is left in place. Manual or shear-blade techniques are usually satisfactory but bulldozer clearing without a shear-blade has been shown to cause serious damage to surface soils and make crop establishment unsatisfactory. Many simple hand-seeders have been designed


IBSRAM

Figure 10 *The two photographs above show examples of heavy clay soils* (Vertisols). *They often suffer from waterlogging (left), but can be managed successfully by the development of cambered beds to discharge excess water (right).*

Professor D.J. Greenland, F.R.S.

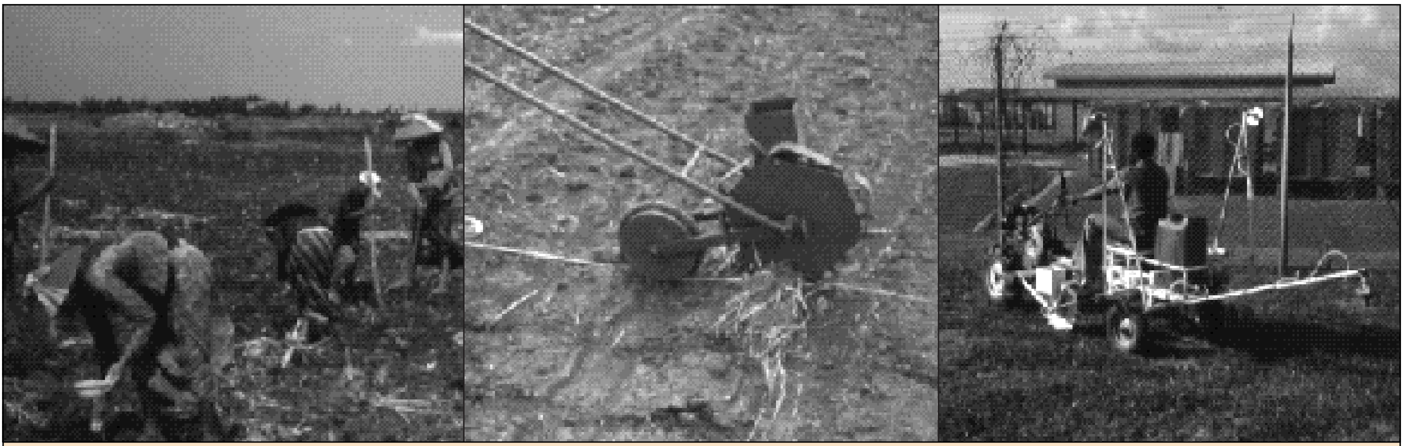


Figure 11 *Three examples of no-till planting methods: dibble stick (left); hand powered (centre); and mechanized direct seeder (right).*

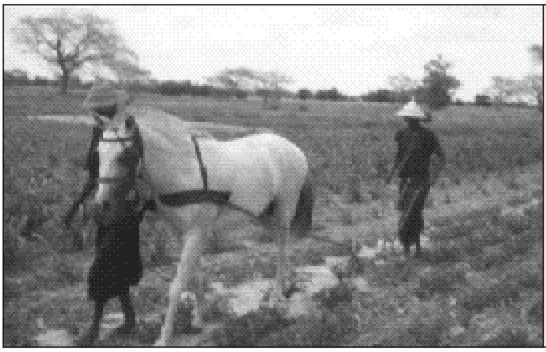
for use on untilled land, as well as more elaborate machines for use on large areas (Figure 11).

A major advantage of zero- and minimum-tillage techniques is that they can be used to leave a cover of crop residues on the soil to protect it from the impact of direct rainfall. This prevents the dispersion of soil material from aggregates, and maintains the infiltration capacity of the soil, so minimizing run-off and the consequent soil erosion problems. In drier areas the cover is also important in protecting the soil from erosion by the wind. Keeping a cover on the soil is now widely recognized as the most important factor in soil conservation. Where there is a pronounced dry season, termites may destroy the crop residues so that the soil is exposed and vulnerable at the start of the rainy season. Other sources of mulch must then be found (e.g. grass or loppings from trees grown close by) or alternative methods used to avoid erosion, such as grass strips or contour barriers (Figure 12). The barrier can be a simple earth bund, constructed so that it will lead water into a grassed channel in order to avoid gully formation. Grass hedgerows on the contour slow down run-off and filter out moving soil material. Vetiver grass (*Vetiveria zizanioides*) is particularly useful for these purposes.

The wind can cause soil erosion in drier areas, and is best controlled by trees planted as windbreaks, although crop

Left and centre: IBSRAM; right: P.K. Yoon

Figure 12 *Hedgerows (left) for erosion control; contour bunds (centre); and vetiver grass (right) for slope stabilization.*



Professor D.J. Greenland, F.R.S.

Figure 13 *Harrowing to remove weeds and prepare a seed bed, Senegal.*

residues can be equally effective if they persist on the soil. After the long dry season in most semi-arid areas, few residues persist and crops can usually be established following a simple surface harrowing (Figure 13).

Management of the physical conditions of a soil intended for wetland rice production is in complete contrast to that required for upland crops. The objective is to destroy, not preserve, soil structure in order to minimize the infiltration rate and cause the water to remain on the soil surface. This is normally achieved by cultivating the soil when it is water saturated—a process known as puddling. This process will produce a distinct plough pan which minimizes water losses from the paddy due to percolation, and softens the surface soil so that rice seedlings are easily transplanted (Figure 14).

Professor D.J. Greenland, F.R.S.

Figure 15 *Contrasting soil conditions after growing a rice crop in puddled soil*

Professor D.J. Greenland, F.R.S.

Figure 14 *Preparing rice paddies (top), and transplanting rice (bottom)*

In many parts of Asia it is common practice to grow an upland crop after the rice crop, at the start of the dry season following the monsoon. The previously puddled soil in which the structure has been destroyed must be restructured as far as possible to create a seedbed for the upland crop, which may often be wheat in the sub-tropics, and mungbean or another pulse crop in the tropics. In some soils, the inherent shrink-swell properties cause the soil to restructure naturally. More commonly, a cloddy structure is formed and tillage is difficult or impossible (Figure 15). Simple seeders such as the inverted-T seeder have been developed to manage the physical condition of the soil along the seed row and avoid the expenditure of energy that would be required if all the soil were to be cultivated.

Managing soil organic matter and soil biological conditions

It is difficult to exaggerate the importance of soil organic matter to soil productivity, and particularly so for the poorer soils of the tropics. Its direct contributions to nitrogen and sulphur nutrition of crops, and its role in stabilizing soil aggregates and supporting the soil animals which create the pores through which air and water move, have already been mentioned. In addition, soil organic matter plays a major role in the retention of cationic nutrients by the dominant soils of the tropics which have clays composed of kaolinite, and iron and aluminium oxides—low activity clays, with only a weak ability to hold the nutrient cations. Furthermore, under acid conditions, some of the organic compounds present in the soil form complexes with aluminium which would otherwise be toxic to plants. Finally, soil organic compounds hinder the formation of insoluble complexes of iron and aluminium with phosphate—thus avoiding a reduction in the amount of phosphate available to plants.

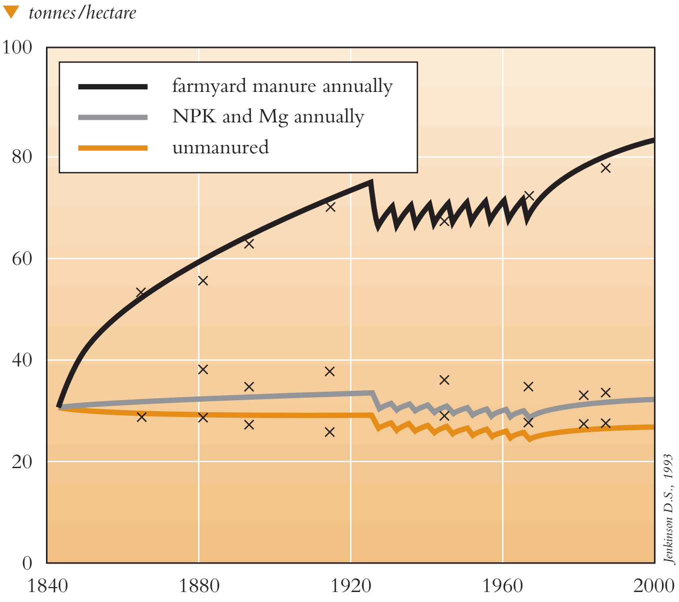
In addition to these physical and chemical effects, organic matter provides the substrate that supports almost all biological life in the soil. An active soil population is known to contain organisms that are directly beneficial to the soil, such as those related to nitrogen fixation and the maintenance of a favourable soil structure. But it also prevents the proliferation of pathogenic organisms, which are forced to compete with a larger and more diverse population than in soils of a low organic matter content.

Under natural vegetation the amount of organic matter in the soil tends to be established at a relatively high level. The actual amount depends on the quantities of organic matter added from the vegetation, the soil characteristics and the moisture and temperature regime prevailing in the soil. When the soil is cultivated, the addition from the crop is usually much less than from the natural vegetation, and consequently the level of organic matter tends to fall. This is especially so if the soil cultivation method increases the openness of the soil and the rate at which the organic matter is decomposed.

The greatest losses occur when a tropical rain forest is cleared and the forest replaced by an arable cultivation system. Regeneration of the forest after an arable period, as in the shifting cultivation system, will lead to a gradual increase in organic matter level, but it will normally take one or more decades for the original level to be restored.

Tropical grasslands are frequently subject to an annual burn. This destroys much of the organic matter that would otherwise be returned to the soil, with the consequence that organic matter levels are established much below those commonly found under forest vegetation. If good crops are grown and all residues returned to the soil, the level established after cropping may be little different to that under natural grassland. However, where a vigorous pasture is alternated with a cultivation period, the organic matter level under the pasture may be much above that under a crop, particularly where the pasture includes leguminous species that contribute the nitrogen required for the build-up of organic matter.

Figure 16 Organic carbon in soil (0–23 cm)



Long-term changes in soil organic carbon in the continuous wheat plots on Broadbalk Field, Rothamsted, UK. The crosses are measured data, the lines are derived from model calculations. Between 1925 and 1965 a bare fallow was taken once every five years to control weeds.

It is therefore clear that alternating cultivation with a forest fallow or pasture period will lead to successive rises and falls in the amount of organic matter in the soil. These changes can be approximated mathematically, and appropriate models developed, which can help to predict the effects of different management practices on the level of soil organic matter. The results of such modelling for three different soil management systems are illustrated in Figure 16.

A general principle of sustainable soil management systems must therefore be to return as much organic material as possible to upland soils used for arable cropping—subject to the organic matter being free from toxic contaminants, and to the costs and problems of collecting and spreading the material being socially and economically acceptable.

In low-lying wetland soils, toxic organic materials can be formed during the anaerobic decomposition of added organic matter, and the active greenhouse gas, methane, may be released. Hence the use of organic materials for paddy rice production must be managed with care.

For soils other than the peats and mucks of some wetlands where very high levels of organic matter have accumulated, organic matter is so important that the amount contained in the soil is the best single indicator of the state of the soil, and of changes in its productivity potential.

Avoiding and rectifying soil degradation

The major forms of soil degradation are due to the displacement of soil (erosion by water and wind), and the deterioration of soil without displacement, which usually involves deterioration of both chemical and physical properties. Chemical degradation includes the following:

- loss of nutrients and organic matter;
- acidification (mostly associated with the removal of soil nutrients or the misuse of fertilizers);
- increased leaching (when the vegetative cover is removed and the soil is exposed);
- increased temperatures and oxidation of the soil organic matter (due to exposure and cultivation);
- salinization and sodication (often associated with inappropriate irrigation practices and inadequate drainage); and
- pollution (most commonly from improper management of industrial and mining wastes).

Physical degradation mostly involves crusting and compaction, and sometimes, partly as a result of these, waterlogging.

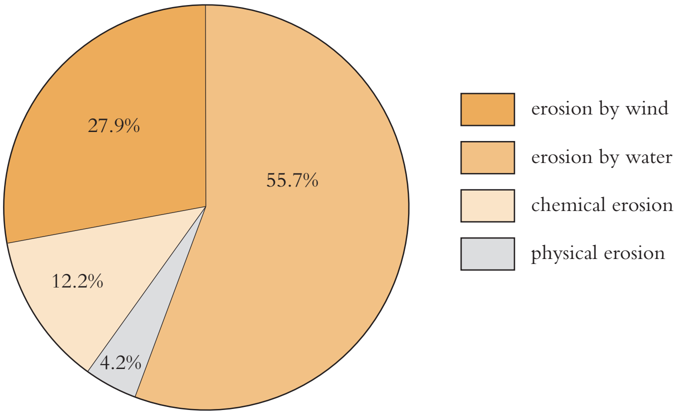
An attempt to make a global assessment of the causes and extent of soil degradation—the GLASOD Project—has recently been completed (Oldeman, Hakkeling and Sombroek 1991). The data for the project were obtained from a compilation of assessments, made on a common basis by national scientists, of the extent and degree of soil degradation in their country or region. Not all the data represent degradation due to inadequate management practices, and in some instances the data had to be compiled on the basis of crude estimates. Nevertheless, they do provide an indication of the global extent of the problem and the causes (see Figure 17).

Some forms of soil degradation are readily reversed. These include surface soil crusting and compaction, which may be reversed in many arable soils by cultivation, although such improvements may be rather temporary. Increasing soil organic matter content by resting the land or incorporating organic manures can make the improvements more stable. Other forms of soil degradation, where the effects are more severe, are less readily corrected. These include the problems of salinization (an increase in salt content) and sodication or alkalinization as it was formerly known (an increase in the proportion of sodium held by the soil). Sodication causes dispersion of the clay and inhibits water movement into and through the soil.

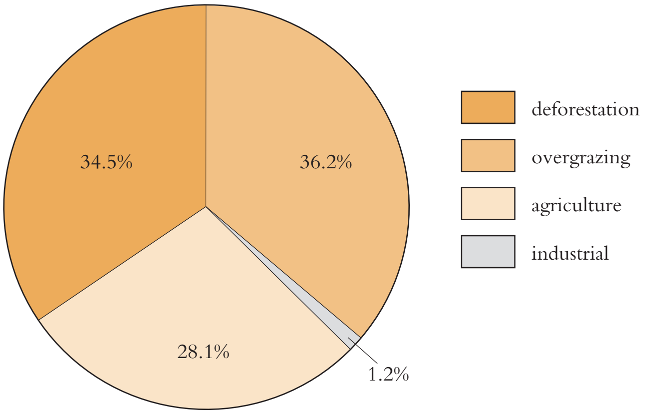
Whether or not the effects of soil degradation can be easily corrected depends on the extent to which the problem has developed. This, in turn, may be controlled by good soil management. Some soils are more resistant to certain forms of

Figure 17 Global soil degradation

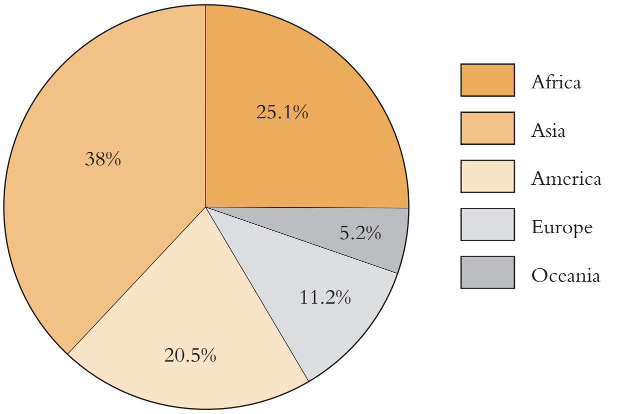
a) types of degradation



b) causative factors

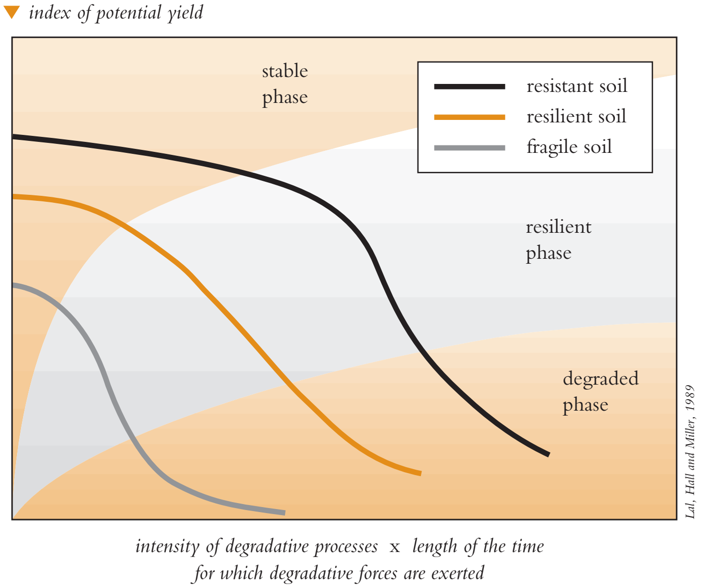


c) proportion of total by continent



Oldeman, Hakkeling and Sombroek, 1991

Figure 18 Soil behaviour in response to degradation stress



Lal, Hall and Miller, 1989

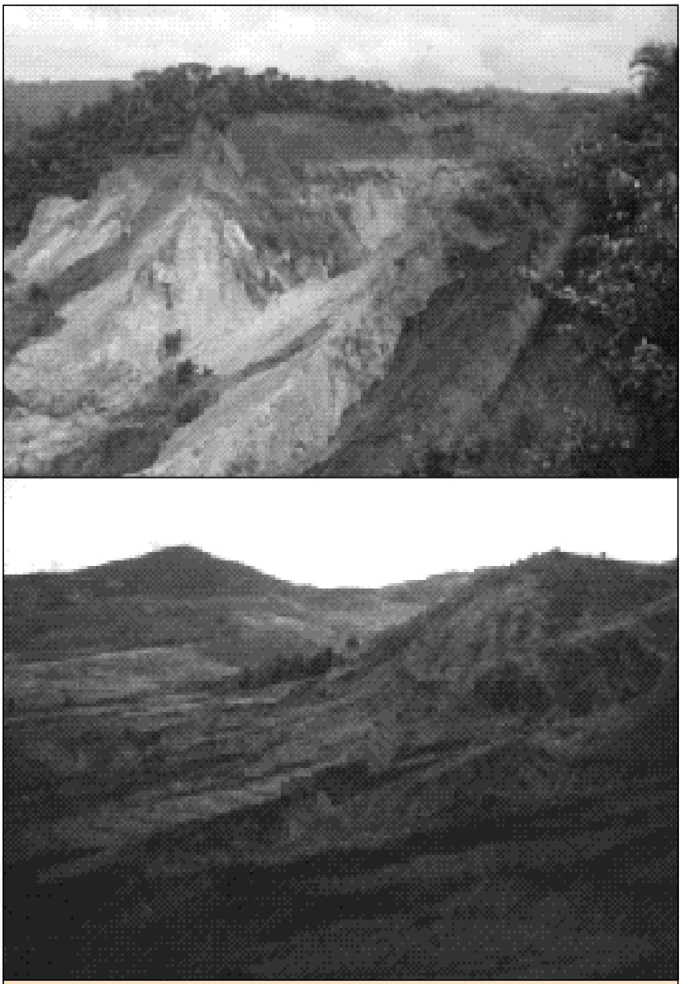
A diagrammatic representation of the behaviour of different soils under degradative stress. Resistant soils are able to withstand the effects of stress for a relatively long period when their productive potential will be little affected; they also have the potential to recover after a long subsequent period of stress. Resilient soils have a shorter resistant phase, but a similar ability to recover afterwards. Fragile soils have little resistance or resilience against degradative stress.

degradation than others, and the ease with which degradation can be corrected also differs between soil types (see Figure 18).

Many soils in the sub-humid and semi-arid tropics show some properties which place them in the category of 'fragile soil', notably those with easily erodible surface soils. These soils require careful management if degradation—which is difficult and costly to repair—is to be prevented. Subsoil compaction, leading to poor drainage, is another form of degradation which is often difficult to reverse. Many soils, on the other hand, are resilient in terms of their chemical properties—nutrients can be restored by the use of manures and fertilizers, and acidity corrected by liming or at least ameliorated by the use of organic manures.

Avoiding erosion

Erosion is a natural process and is difficult to eliminate completely. However, on cultivated land there is a real risk of accelerated erosion if the natural vegetative cover of the soil is



Professor D.J. Greenland, F.R.S.

Figure 19 *Catastrophic erosion in Nigeria (top) and Mexico (bottom)*

removed, as is normally necessary if the land is to be cultivated for crop production. On particularly vulnerable landforms the effects of erosion by water can be devastating (Figure 19).

Management practices that aim to control the erosion of soil by water require, firstly, that every possible effort should be made to keep a cover over the soil. This will usually be some form of vegetation, but may also be a mulch of organic material, or even plastic or gravel. A cropping system which ensures that there is always a crop in the ground can also be valuable as a method of erosion control. Perennial crops or intercropping systems offer a convenient way of providing a cover which is compatible with economic land use (FAO, 1983, 1989). Such methods are not usually compatible with the cultivation of large areas by machinery. Trees used as windbreaks to control soil erosion by the wind are usually essential in drier areas of light textured soils, as are contour bunds and channels designed to drain away run-off water in areas subject to erosion by water. Other techniques such as tied ridge cultivation and alternate strip cropping can also be effective for erosion control (FAO, 1983, 1984, 1987, 1989).

Rectifying chemical degradation

Chemical degradation due to nutrient removal in crops cannot be avoided for the majority of soils. It can, however, be readily corrected (Figures 20, 21) by the use of fertilizers or manures, or both. Continued crop removal, or the use of

Professor D.J. Greenland, F.R.S.

Figure 20 *The response of maize to applied phosphatic fertilizer, Tanzania*

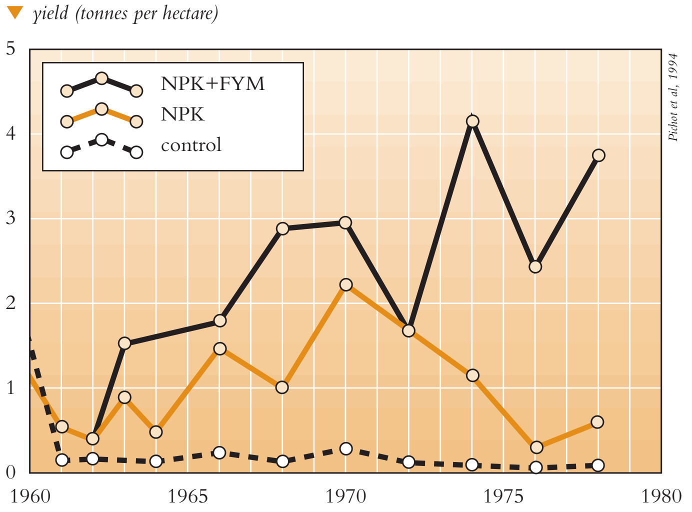
Professor D.J. Greenland, F.R.S.

Figure 21 *A long-term fertilizer experiment (NPK +/– weeding) at the International Institute of Tropical Agriculture, Ibadan, Nigeria. From left to right: –NPK+weeding; +NPK–weeding; +NPK+weeding; and –NPK–weeding.*

ammonium fertilizers, leads eventually to acidification. This in turn may be corrected by judicious use of lime, or by resting the soil for several years under a restorative fallow following one or two years of cropping. For many upland soils in the tropics, the most satisfactory methods of ensuring sustainability appear to be those which involve the use of both inorganic fertilizers and organic manures. Experiments in Burkina Faso and Ghana have shown that, using management methods such as these, yields have been maintained and even increased for up to thirty years (Figure 22).

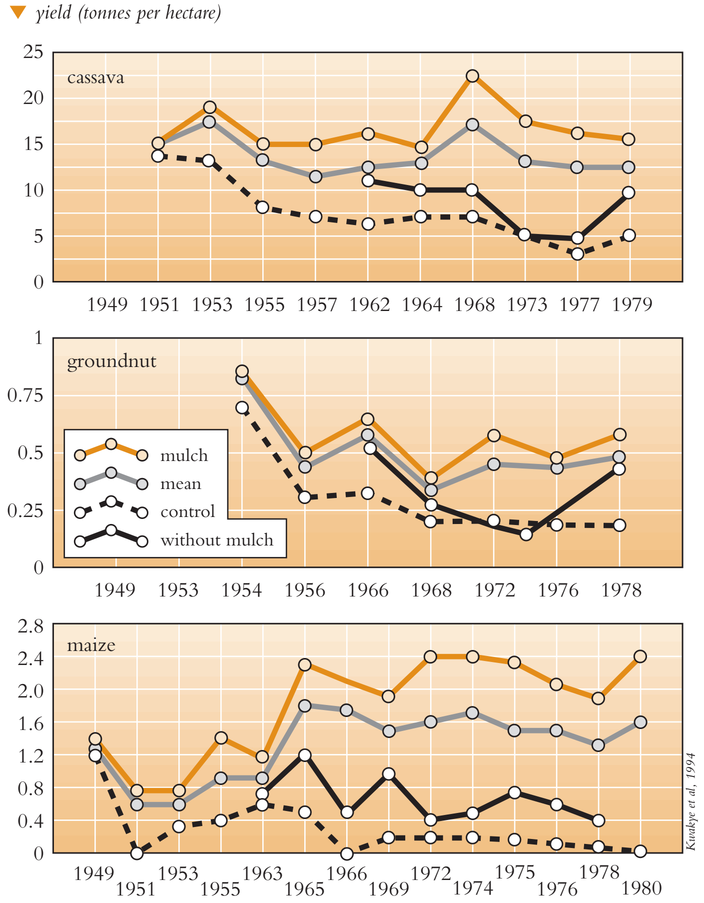
Figure 22 Effects of fertilizers and organic amendments on long-term yield trends

a) sorghum yield in response to fertilizer and manure, Burkina Faso



Pichot et al, 1994

b) cassava, groundnut and maize yields in response to a grass mulch, and NPK and lime 2^5 factorial trial, Kwadaso, Ghana



Kwakye et al, 1994

It is possible to maintain yields by correcting both nutrient losses and acidification with inorganic materials alone. However, in many soils of the tropics it appears to be extremely difficult to maintain the correct balance of nutrients without the use of organic amendments to buffer the changes of nutrient ion concentrations in the soil solution, and to complex the toxic ions, such as aluminium, which are released as the soil acidifies.

Loss of organic matter is a form of soil degradation, not so much because of the direct effects of organic matter, but more importantly because of the many indirect effects. In addition to the buffering effect on nutrient ion concentrations, and the complexing of potentially toxic ions, the indirect benefits include the stabilizing effects on soil aggregates, and the support offered to the soil population, both faunal and microbial.

Another form of soil degradation is associated with the cultivation of soils which are poorly drained, or where the water table is close to the soil surface. Salts and sometimes potentially toxic ions such as boron may be carried into the irrigated fields with the irrigation water. Unless there is adequate drainage, and sufficient water is supplied to wash out excess salt and undesired ions, salt will accumulate until it reaches levels at which plant growth is reduced. This problem is commonly found in areas where dams have been constructed, and where areas below the dam receive irrigation water. The water stored behind the dam is also likely to raise water tables in areas below the dam. Where groundwaters are saline, this may not only induce salinity problems but will inevitably make drainage of the area receiving irrigation more difficult.

In addition to salinity, sodication can be a serious problem. This is not necessarily associated with poor drainage, but arises when irrigation water with a high content of sodium is used, or when sea-water flooding of the land occurs. Sodium displaces other ions in the exchange complex, and at about 15 percent of sodium saturation the clay will disperse. This makes the soil extremely difficult to manage for crop production—it becomes extremely sticky when wet, cloddy when dry, and the smaller clay particles will tend to move down the soil profile, a process sometimes known as internal erosion. This leads to an extremely compact subsoil, in which water movement and root development are largely inhibited. In most situations these soils are also alkaline, and as such are often referred to as alkaline soils. However, many saline soils are also alkaline due to the presence of sodium carbonate, but these do not show the features of sodic soils because the salts prevent dispersion of the clay. Management of sodic soils involves the addition of gypsum, which provides a concentration of calcium sulphate in the soil solution sufficient to flocculate the clay, thus giving rise to a more easily manipulated structure. The calcium will also gradually displace sodium from the exchange complex, so eliminating the cause of the condition.

Most problems of salinity and sodicity are associated with irrigation schemes. Drainage, and application of gypsum, are the remedies. Drainage should always be a part of the initial design of an irrigation system, and only if the water quality is satisfactory should it be used for agricultural purposes (FAO 1985a, 1985b, 1988, 1990).

Avoiding and rectifying physical degradation

Deterioration of soil structure is the commonest form of physical degradation, and involves:

- loss of stability of aggregates in surface soils, leading to crusting and compaction, and consequently poorer infiltration rates and greater run-off and erosion; and
- translocation of clay particles to subsurface layers and loss of porosity in the subsurface and deeper soil layers, with consequent loss of water transmission and storage capacity.

Physical degradation of soil is most commonly found where heavy machinery is used to clear and cultivate the soil. Problems occur mostly in soils of intermediate texture and low organic matter content, particularly sandy and silty loams.

Difficulties can be avoided by using no-till and mulch farming techniques, and by giving careful attention to the need to restrict cultivation times to those when the soil is not too wet—a wet soil is readily damaged by cultivation. Maintaining a relatively high organic matter content can help to increase soil aggregate stability, although even soils of high organic matter content are subject to damage by wet cultivation. As noted earlier, most rice soils are deliberately ‘damaged’ by wet cultivation to minimize seepage of the paddy water.

Physical degradation is often underestimated, as much of it is insidious, occurring in the subsoil over a period of several years. For this reason, it is likely that the GLASOD data are underestimates. Under fallow vegetation, soil animals can reopen pores in both surface and subsoils, but the rate at which they can do so is slow, taking several years even under tropical forest cover. Prevention is more successful than attempting to cure the problem.

Avoiding environmental damage

Soil management practices affect not only the site where the crop is being produced but also areas remote from the site. The off-site effects include those associated with the deposition of eroded soil material, the pollution of water supplies due to inefficient use of fertilizers and pesticides, and the production of gases contributing to the greenhouse effect. These problems do not arise when good soil management practices are followed.

Off-site damage due to soil erosion

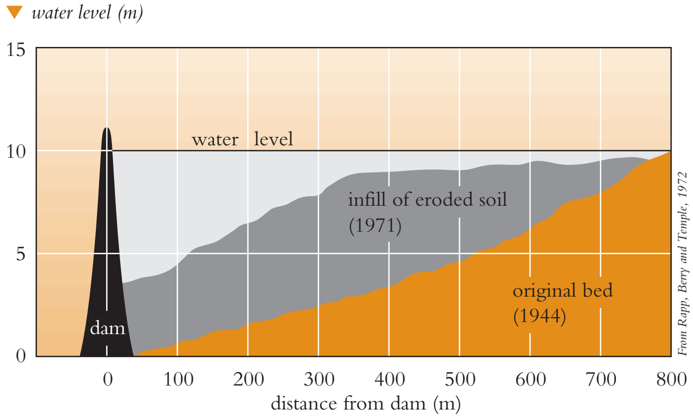
In semi-arid areas, periods of drought are often accompanied by dust storms as the vegetation dies and the soil is exposed to wind erosion. Deposition of the dust gives rise to many problems, and dunes may be formed, covering otherwise valuable land with non-productive fine sand and coarse silt. In arid areas where droughts may persist for years, control is difficult. In semi-arid areas, the planting of drought resistant trees as windbreaks can be of considerable help. Strips of tough, drought resistant grasses (such as vetiver grass) can also be invaluable to trap blowing sand and stabilize moving dunes. Deposition of water-borne, eroded soil material can also be a serious problem, as it may also bury good land beneath less fertile material. More commonly, it causes damage by blocking waterways, including streams and rivers. This may lead to further problems due to rising water tables and the associated problems of waterlogging and salinity. The sediment may also be deposited in reservoirs (Figure 23), reducing their storage capacity and, in extreme cases, blocking the outlets to hydroelectric generators. Failure to take adequate account of the problems of erosion arising in the catchment areas of dams has meant that the life and total economic value of dams have often been seriously overestimated (see box).

Siltation of reservoirs, India
(Narayana and Babu, 1983)

reservoir	*catchment area (1 000 km2)*	*sedimentation rate (ha m/100 km2)*	
		predicted	*observed*
Hirakud	83	2.5	3.6
Tungabhadra	26	4.3	6.6
Mahi	25	1.3	9
Rana Pratap	23	3.6	5.3
Nizamnagar	19	0.3	6.4
Pong	13	4.3	17.3
Pamchet	10	2.5	10.1
Tawa	6	3.6	8.1
Kaulagarh	2	4.3	18.3
Mayurakshi	2	3.6	20.9

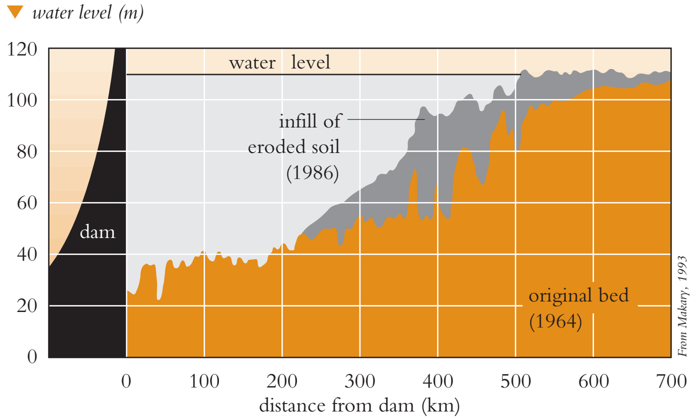
Figure 23 Reduction of water storage capacity due to siltation in two reservoirs: a) a small reservoir in Tanzania; b) a major reservoir in Egypt

a) Msalatu reservoir, Tanzania, 1944–1971



From Rapp, Berry and Temple, 1972

b) High Aswan Dam, Egypt, 1964–1986



From Makary, 1993

Where the catchment is in mountainous or hilly areas it is vitally important that deforestation of the catchment is avoided. Where the catchment includes cropped areas, it is necessary to maintain a soil cover to minimize run-off. The careful design of channels and canal systems to dispose of unavoidable run-off is also imperative.

In arid and semi-arid regions, overgrazing is a notorious factor in land denudation. It occurs frequently above small reservoirs where animals have direct access for drinking. Control depends on proper stock management, and on the construction of well-distributed watering points rather than direct soil management measures.

Damage due to misuse of fertilizers

When farmers purchase fertilizers their intention is to use them to feed their crops as efficiently as possible. However, nitrogen recovery efficiencies greater than 50 percent are rarely achieved, and phosphorus recovery is often lower. Much of the unrecovered nitrogen ends up in groundwater in the form of nitrate, or in the wetlands as ammonia in the atmosphere. In contrast to nitrogen, phosphate is normally adsorbed to soil clay and iron oxides and does not move out of the soil except where the soil is essentially devoid of them. When it is washed off the soil surface—or through extremely sandy soils—and into waterways, it may cause eutrophication problems, proliferation of algal growth, and exhaustion of dissolved oxygen. These in turn, may lead to the death of fish and other water inhabiting species. The problems due to surface wash are best controlled by ensuring that the phosphate applied is incorporated in the soil. Although agricultural practices have often been blamed for phosphate contamination of water supplies, sewage and industrial effluents discharged directly into waterways are the more common cause of this problem.

In whatever form nitrogen is added to the soil, most will normally be converted to nitrate—except in anaerobic conditions. Nitrate is freely mobile in the soil and so may be leached into groundwater unless it is intercepted by plant roots. A problem may arise if the groundwater feeds sources used for drinking. The WHO (World Health Organization) upper limit for acceptable drinking water is a concentration of 10 ppm (parts per million) of nitrate nitrogen, a level rarely found except where excessively high amounts of nitrogen fertilizers are being used. Such levels have seldom been observed in tropical water supplies, and where they do occur it is almost always due to contamination of the water supply with animal excrement or sewage. Nevertheless it is important that nitrogen fertilizers are used as efficiently as possible to avoid potential contamination problems as well as to obtain best economic advantage from the fertilizer. Many studies have been made to determine optimal practices for different conditions. Often a low basal or starter dressing is recommended. This would be followed by a further dressing at the time of maximum crop demand, so avoiding concentrations in the soil which exceed the ability of the crop to absorb nitrogen. In general the most important cause of degradation of soils in the tropics is failing to replace nutrients in the crops—the use of fertilizer rates which are too low or non-existent, rather than excessive.

However, where rice is grown in flooded soils it is now common practice to use significant amounts of nitrogen fertilizers. Although nitrate will not be formed, significant losses can still occur as ammonia which escapes to the atmosphere. Ammonia is not known to be a serious atmospheric pollutant. In fact, because of its high solubility, it is probable that much of the ammonia volatilized is returned to the soil in rainfall, close to the site where it originated.

If a paddy soil is allowed to dry so that nitrification occurs, nitrous oxide—a greenhouse gas—will be formed, albeit in small amounts. If, after drying and nitrate formation, the soil is flooded again, much larger amounts of nitrous oxide are normally formed by biological denitrification processes. When organic manures are used on wetland soils, and anaerobic decomposition occurs, another greenhouse gas, methane, is formed in large amounts. Methane, like nitrous oxide, has a greenhouse effect several times greater than carbon dioxide. Hence, for rice paddies, good soil management practice should avoid the use of organic manures, and rely on:

- the residues of the rice crop to maintain soil organic matter levels; and
- nitrogen fixation by blue-green algae, azolla, loppings from leguminous trees, etc. to supplement nitrogen fertilizers.

APPLYING THE PRINCIPLES

The practice of good soil management

The principles of good soil management are universally applicable. The practices which embody those principles vary quite widely according to specific soil, climate and other environmental conditions. The shifting cultivation system, with fallow periods long enough to ensure full restoration of soil fertility, is a sustainable system. It is still used in each of the three climatic zones discussed here, but because land pressures are increasing everywhere and it is a system which is not economically viable except at the subsistence level, it is not discussed in further detail. Various transitional states between shifting cultivation and semi-permanent and permanent cultivation systems exist. In the great majority of these transitional systems, the productive capacity of the soil is being degraded as a result of decreasing organic matter contents, deteriorating structural condition, or declining nutrient levels.

Sustainable systems in the humid tropics

Perennial crops, such as oil palm, rubber, cocoa, and bananas and plantains, have been grown for many years throughout the humid tropics (Figure 24). The crops provide a cover for the soil and usually return sufficient residues to the soil to maintain a satisfactory organic matter level. Nutrient replenishment is necessary if the system is to sustain productivity. Where nitrogen fertilizers are used, acidity may need to be regulated by liming (Figure 25.) Maintaining a leguminous cover under the canopy of the perennial crop can provide nitrogen to the crop and complement the protection against erosion afforded by the tree canopy. The greatest risk of erosion arises during the initial establishment phase, when it is normally necessary to use a cover crop to protect the soil until the canopy of the perennial closes.


IBSRAM

Figure 24 *Intercropping of rubber and pineapple in Malaysia, providing soil protection and an economic return.*


Professor D.J. Greenland, F.R.S.

Figure 25 *Effects of rectifying acidity arising from excess use of ammonium fertilizers with lime in an experiment with maize at the International Institute of Tropical Agriculture, Ibadan, Nigeria.*

The system is only sustainable as long as it is economically viable and the value of the produce is sufficient to cover the costs of essential inputs. The size of the world market for many of the perennial crops of the humid tropics is limited, and this in turn limits the extent to which land is used for such crops.

In arable cropping systems the dominant soils of the humid tropics are often simple to manage as far as their physical properties are concerned. They have relatively stable aggregation and are free draining. However, efficient drainage and high rainfall means that they are often severely leached of nutrients, and are strongly acid. Hence, management of their chemical properties becomes critically important. It has been demonstrated at Yurimaguas, in the lowland humid tropics of Amazonian Peru (Sanchez *et al*., 1982), that productivity can be maintained by careful management of fertilizers and lime, but it has yet to be demonstrated that such systems are economically sustainable.

Combining tree crops with arable cropping systems is widely practised, as is the rotation of forest plantations with food crop production (the taungya system). These systems can be sustainable, depending on the efficiency of the tree crop in recycling nutrients, and on the effects of the trees on soil organic matter and acidity. Such systems are potentially of great importance for the humid tropics.

Sustainable systems in the sub-humid tropics

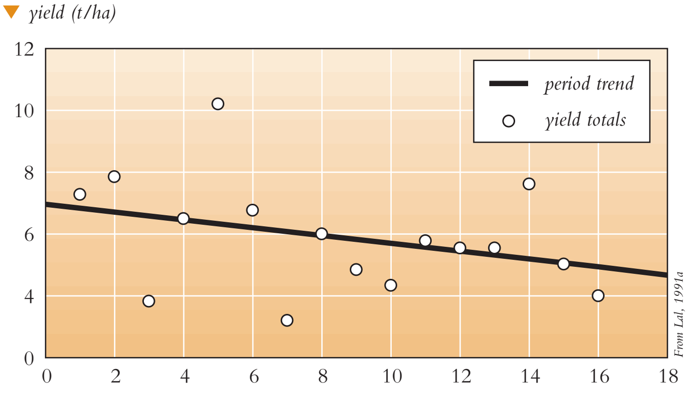
In the wetter parts of the sub-humid tropics, plantation agriculture with perennials has sometimes been sustainable, but usually with coffee or tea, and at moderate elevations where the potential for erosion is not too great. Arable crop production has posed considerable problems for sustainable soil management. While the chemical condition of the soil is usually better than in the more humid areas, the dominant soils are usually physically weak, and therefore readily eroded. Long-fallow shifting cultivation systems were sustainable, but broke down when demographic pressure forced a reduction in the length of the fallows, and an extension of the cropping periods. These changes led to deterioration of organic matter levels and structural condition, which in turn led to erosion and the associated problems. Agro-forestry offers the best route to a sustainable system (Nair, 1989; Young, 1989), but requires that the trees in the system offer an economic return.

Alley farming, in which rows of trees are planted along the contour, and crops grown between them, has been widely promoted as a sustainable system for the sub-humid tropics. In what must be regarded as a model system, rows of the fast-growing legume *Leucaena leucocephala* are planted, and maize or cowpeas grown between the rows. Loppings from the trees are used as a mulch to protect the soil and provide nitrogen. If economic yields are to be obtained, phosphorus and perhaps other fertilizers are needed, including supplemental nitrogen. Although it is inevitable that the trees will compete with the crop for water and nutrients, they too have the potential to provide an economic return. Indeed, if this system is to be accepted more widely than it is at present, an economic return from the trees—in addition to their value in controlling erosion and building soil fertility—must be an important consideration. Indigenous agro-forestry practices at present appear to offer a better basis for sustainable farming systems for the semi-arid tropics than alley farming, except on some larger farms where the alleys are of a size which allows mechanized cultivation between the tree rows. For the smaller farmer, the land required for the trees cannot normally be spared unless the tree is producing a short-term economic return, as well as its long-term contribution to preventing soil degradation.

Continuous arable farming under no-till mulch conservation systems, and using fertilizers to maintain nutrient levels, is certainly superior to the plough-till system in terms of productivity maintenance (Figure 26). Although current evidence indicates that yields decline under no-till systems, they do so more slowly than under plough-till systems. It also appears that, at intervals of several years, a break in cropping can rebuild soil productivity. It is not clear why this break should be necessary, but control of pests may well be the main

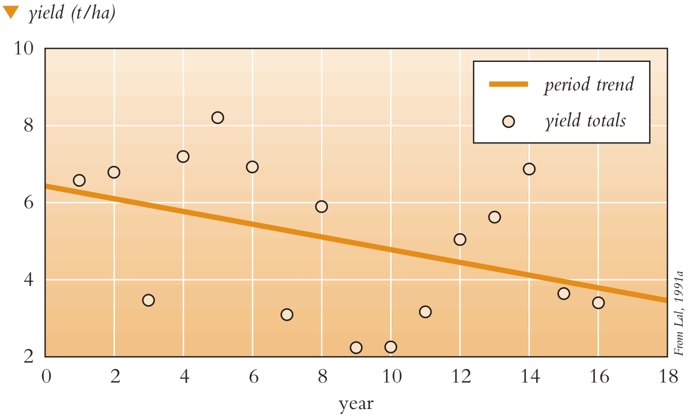
Figure 26 Maize yields for no-tillage and ploughed tillage systems over 17 consecutive years (34 growing seasons) on a Luvisol in western Nigeria. Yields are expressed in t/ha/year as a cumulative total for two seasons per year.

a) no till system



From Lal, 1991a

b) plough till system



From Lal, 1991a

reason. For the system as a whole to be sustainable, it requires that the 'fallow' crop offers some economic advantage, and a legume based pasture may well be the best provided that livestock can be economically raised.

Sustainable systems in the semi-arid tropics

Uncertain rainfall and long dry seasons make sustainable crop production difficult in the semi-arid tropics. Pastoralism, rather than crop production, offers the greatest prospect of sustainability, but subject to the important proviso that stocking rates are kept below the carrying capacity of the land. This ensures that the vegetation persists, and continues to provide the essential ground cover. In most parts of the semi-arid tropics the demand for food has meant that stocking rates have often exceeded sustainable limits, and arable cropping has continued to invade traditional grazing areas. The cropping practices have been based on shifting cultivation systems in which fertility restoration depends on the regrowth of native grasses. The extent to which fertility is restored is often limited. This has lead to falling productivity, sometimes partly arrested by the introduction of fertilizers to supplement the animal manure used on the crops. In some instances, shorter duration crop varieties, e.g. sorghum, have helped to overcome water shortages by reducing the length of time that the crop is using water. The demand for nutrients, however, is not reduced. Legumes nearly always require an adequate level of soil phosphorus, and so fertilizer phosphorus has normally to be used together with a suitable legume.

In order to maintain the productive capacity of land in the semi-arid tropics, a cropping system is required where the rate at which soil fertility can be restored (under a rest crop) is much improved, compared with the changes under native grassland. Unfortunately, after many years of experimentation, there are only a few areas where combinations of grasses and legumes have been identified as suitable for soil improvement and grazing use. Most notable among these is the system developed in Australia for the semi-arid tropical areas of Queensland.

Sustainable systems in the wetlands

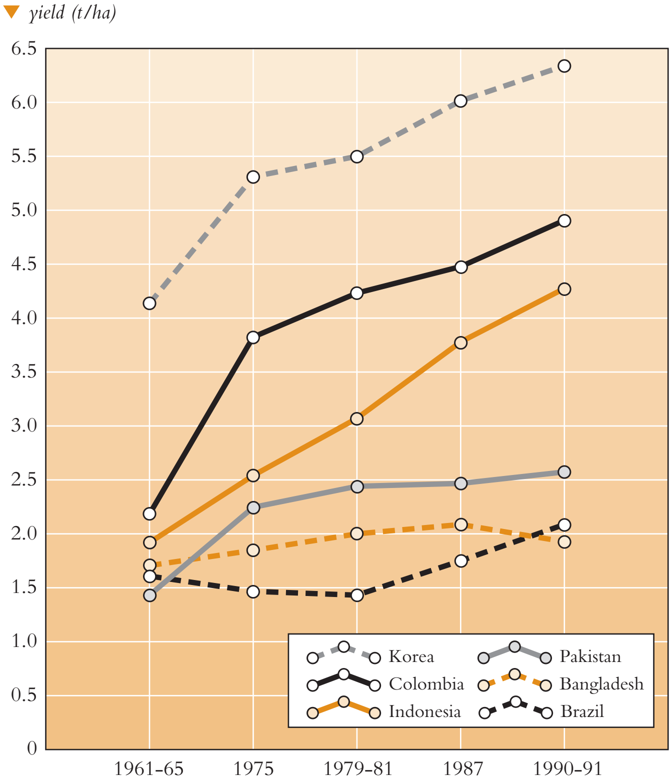
The rice-based farming systems of the wetlands are the example *par excellence* of a sustainable system. The factors which contribute to this are:

- nutrients are washed into rather than out of the soil;
- water supplies are normally assured by irrigation and bunding of the fields to retain water;
- erosion is not a problem as the bunds prevent run-off and the water held on the surface prevents soil displacement by raindrop impact;
- acidity is not a problem as flooded soils will always approach the near neutrality of the flood water;
- nitrogen fixation in the flooded system is relatively high;

- phosphate availability in flooded soils is relatively high because iron is present in the ferrous rather than ferric state; and
- weed problems are less in flooded than in dryland conditions.

Thus it is not surprising that rice production systems have been maintained for several thousands of years in parts of Asia, and that in many areas their productivity continues to increase (Figure 27). The increases have been greatest where the rice crop has been produced with fully controlled water supplies from irrigation systems, and with necessary inputs of fertilizers. Although organic manures, including green manures, have been widely advocated for use on rice, actual use has decreased considerably as rice yields and the use of nitrogen fertilizers have been increasing. As noted above, most of the advantages associated with higher levels of soil organic matter are not relevant in rice production. Higher levels may well be harmful due to the formation of phytotoxic by-products formed when the decomposition of fresh organic materials occurs in the soil under anaerobic conditions. A further benefit of reduced use of organic manures for rice is that evolution of the highly active greenhouse gas methane is decreased.

Figure 27 Rice yields in selected countries (1961–1991)



Data from FAO Production Yearbooks and IRRI Rice Almanac, 1993)

Professor D.J. Greenland, F.R.S.

Figure 28 *Measuring ammonia volatization from nitrogen fertilizers applied to rice at the International Rice Research Institute, Los Baños, Philippines.*

The high yields of rice are dependent on high levels of nitrogen fertilizers (of the order of 50–100 kgN per crop) being used. This will not lead to nitrate pollution of ground waters as nitrate is not formed in the flooded conditions of rice paddies. Inefficiencies in the use of nitrogen fertilizer on rice are primarily due to ammonia losses (Figure 28). These can be largely avoided by incorporation into the soil of a basal dressing prior to transplanting, and delaying a second dressing until the crop is well established so that escape of ammonia to the atmosphere is hindered by slow air movement at the water surface.

The greatest threats to the sustainability of irrigated rice production are those relating to the water supply system. The problems of poor soil management in the catchment areas of dams feeding the irrigation are often the greatest threat. Eroded soil can both reduce the storage capacity of the dam and choke distribution canals. Where saline waters exist beneath the service area of the dam rising water tables can bring salt into the root zone and reduce yields—something which appears to have been responsible for static and declining yields in many of the drier parts of the Indian subcontinent. Poor management of the water supply can mean overwatering at the upper end of the distribution system, and droughts at the lower end. With less water becoming available from the dam, the disruption of water supplies can lead to occasional water shortage in all of the command area, with drastic effects on yields.

Where the irrigation system is based on stream diversion or natural flooding (i.e. rainfed, as opposed to controlled irrigation), rice management is more difficult, and the risk factor is such that investment in fertilizers may not be acceptable to farmers. Thus, rice yields in these areas have not risen as they have done in areas of controlled irrigation. Rainfed areas constitute almost half of the total area in which rice is produced and, in much of this area, an upland crop is grown after the rice crop. This presents further difficulties with regard to the task of creating conditions suitable for wheat or a pulse crop in a soil previously puddled for rice. Much research remains to be done to make these systems more productive.

THE NEED FOR ACTION

Building on today's knowledge for a sustainable future

A great wealth of knowledge has been acquired about soils, their distribution and their management (see box on following page). There is now a sound understanding of the biophysical principles on which sustainable soil management must be based. But in spite of this, we have seen that sustainable management systems for those areas where they are most needed have not been widely used. This means that not only are the farmers in poor areas struggling to survive, but that the struggle is likely to become more difficult as soils become increasingly degraded and water supplies less assured.

The basis for changing this situation has been established in the knowledge and understanding of agricultural production systems available today. What is needed now is an evaluation of how the principles of sustainable soil management are being, or need to be, applied in areas where agricultural productivity is either static or declining. This evaluation must be done taking account of the wide range of biophysical and socio-economic conditions prevailing throughout these areas. Sustainable systems require the use of fertilizers and other inputs, including the use of organic manures and the recycling of nutrients from residues. Low input organic farming and recycling systems often imply recycling of poverty conditions. The intention must be to escape from the poverty trap and, although this is likely to require the use of appropriate economic inputs, there is no reason why these cannot be used within a sustainable system. As long as demographic pressures continue to increase, the problems will become more difficult to resolve, and urgent action is required to arrest the spread of land degradation and to establish sustainable systems where non-sustainable farming methods are currently in use. Much work needs to be done to evaluate the sustainability of soil and land management systems in different environments, and to develop policies and incentives to ensure that these systems are socially acceptable and economically attractive.


IBSRAM

Figure 29 *Adaptive research in land management; the site at Luodian, China, where IBSRAM and national scientists collaborate in studies of improved land management practices.*

The principal responsibility for action must be with national governments and agricultural administrations. They will need to be fully supported by international organizations and, of course, by the farming and scientific communities. Among the international bodies, FAO will continue to play a leading role, supported by various organizations such as the International Board for Soil Research and Management (IBSRAM). IBSRAM already assists several national programmes through a number of networks conducting studies of the application of soil management technologies in problem areas (Figure 29). Assistance in strategic research will be needed from universities and others including:

- the International Agricultural Research Centres supported by the Consultative Group for International Agricultural Research (CGIAR);
- the United Nations Environment Programme (UNEP);
- those concerned with global climate change and how it may effect agriculture; and
- other bodies, including non-governmental organizations.

Sustainability is not simply a matter of identifying effective biophysical solutions. The solutions must be economically viable and socially acceptable. It is therefore essential that the applied studies and adaptive research necessary to identify effective biophysical techniques are conducted in association with socio-economic studies, by which the voice of the farmer is heard. Social and economic factors will need to be

Components of sustainable soil management systems

humid tropics

trees
to avoid erosion
to recycle nutrients

for mulch:
to maintain organic matter
to suppress weeds

fertilizers
to increase yield
to replace nutrients

lime
to control acidity
to replace Ca (and Mg)

relay and intercropping
to minimize soil exposure
to control erosion

terracing and contour bunding
to control erosion
to remove excess water

sub-humid tropics

trees
to avoid erosion
to recycle nutrients

for mulch:
to maintain organic matter
to suppress weeds

fertilizers
to increase yield
to replace nutrients

lime
to control acidity
to replace Ca (and Mg)

green manures
to provide nitrogen
to maintain organic matter
to minimize soil exposure

contour bunding
to control erosion

semi-arid tropics

animals
to transfer nutrients
to provide manure

fertilizers
to increase yield
to replace nutrients

grassed contour strips, hedgerows or bunds
to control erosion
to provide animal feed

raised beds
to control water on heavy clays

tree windbreaks
to control erosion by wind

irrigation and drainage
to supplement rainfall
to avoid salinity and waterlogging

wetlands

terracing or bunding
to retain water

puddling
to minimize drainage
to control weeds

irrigation
to supplement rainfall and natural floodwaters

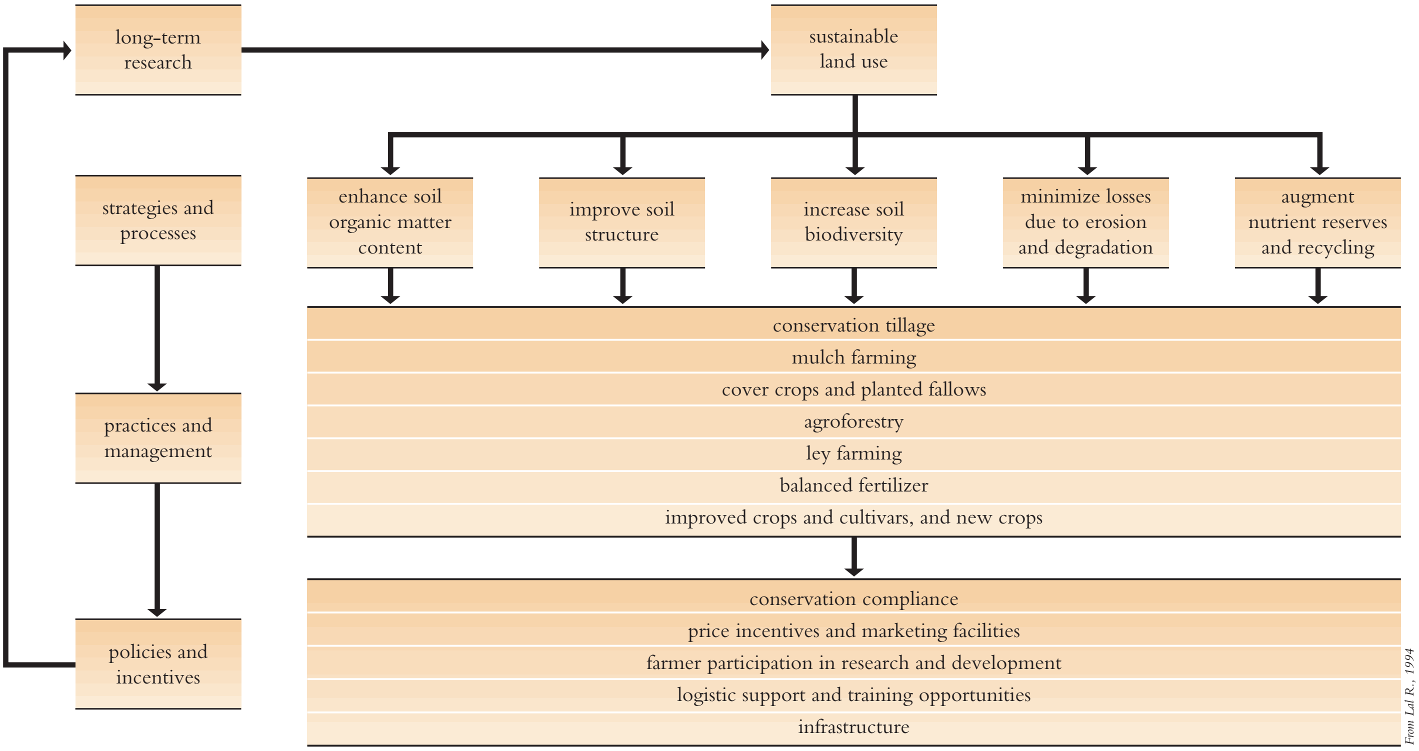
fertilizers
to increase yield
to replace nutrients

surface drainage
to remove excess water

Examples of sustainable soil management systems

humid tropics	*sub-humid tropics*	*semi-arid tropics*	*wetlands*
plantation crops with legume groundcovers long-fallow shifting cultivation	agroforestry systems where trees provide an economic return zero-till mulch farming with fertilizers and lime, and an economic source of organic matter	fertilized legume-based pastures with controlled grazing, either continuous or alternating in space and time with arable cropping	flooded rice systems with controlled water supply and fertilizer

Figure 30 Processes, practices and policies involved in land use and soil resilience



From Lal R., 1994

taken into account when adapting known methods of sound soil management to specific local situations. Similarly, where adaptation is only possible within a changed policy framework, policy-makers must be kept informed of the social and economic implications in order that the appropriate change of policy may be considered (Figure 30).

Sustainability is seldom achievable without cost. Most societies in the developed world have supported agricultural development in one way or another, either by direct subsidies for fertilizers, liming, irrigation, drainage and erosion control methods, or indirectly, by crop price support schemes or investment in scientific and technical support. The current sustainability of many irrigated rice production systems owes much to the earlier investments (perhaps of time and labour rather than cash) in the development of water control and distribution systems. At the present time, the threat to these systems—whether it be from erosion in the catchments of reservoirs or, in drier regions, from salinization in the service areas—has to be recognized. Much further investment may be needed if the systems are to continue to be sustainable.

The present non-sustainability of the farming systems and soil management practices of most tropical areas has also to be recognized. There is now much experimental evidence to show that long-term arable crop production in the humid and semi-arid tropics is only possible if soil organic matter levels are maintained. Even in the artificially well-managed experiments of research stations this has been difficult. While declining inherent soil fertility may not result in declining yields where increased inputs are used, the returns per unit input used will always tend to decrease, so that the system becomes economically unsustainable.

Most indigenous sustainable systems have depended on organic matter maintenance, and are only viable as long as land remains plentiful. The major sources of organic material are trees and pastures. To make these sources economically accessible to the small arable farmer may well require some modifications of policy.

The broader environmental issues, and the long-term problems of resource degradation, are not matters that individual farmers should be expected to manage alone—they are also the responsibility of government. The significance of these problems now demands that urgent action be taken at both national and international levels, to achieve sustainable and adequate production and halt the spread of land degradation. An additional two thousand million people will be living in the tropical regions of the world before another 25 years have passed. If they are to be fed, a massive increase in the productivity of the land resource base will be required. At the present time, the prospect is for diminished rather than increased productivity. A greatly increased effort is needed to apply existing knowledge and techniques to better management of soil and water resources, and to seek new technology where existing knowledge is inadequate.

References and Further Reading

FAO (1965), Dark Clay Soils of Tropical and Subtropical Regions, Dudal, R. and Bramao, D.L. (eds). *Agric. Development Paper* no. 83.

FAO (1977), Organic Materials and Soil Productivity. *Soils Bulletin* no. 35.

FAO (1983), Keeping the Land Alive: Soil Erosion—Its Causes and Cures. *Soils Bulletin* no. 50.

FAO (1984), Tillage Systems for Soil and Water Conservation. *Soils Bulletin* no. 54.

FAO (1985a), Guidelines: Land Evaluation for Irrigated Agriculture. *Soils Bulletin* no. 55.

FAO (1985b), Water Quality for Agriculture. *Irrigation and Drainage Paper* no. 29, Reg. I.

FAO (1987), Soil and Water Conservation in Semi-arid Areas. *Soils Bulletin* no. 57.

FAO (1988), Salt-affected Soils and their Management. *Soils Bulletin* no. 39.

FAO (1989), Soil Conservation for Small Farmers in the Humid Tropics. *Soils Bulletin* no. 60.

FAO (1990), Management of Gypsiferous Soils. *Soils Bulletin* no. 62.

FAO (1991), *FAO/Netherlands Conference on Agriculture and Environment.* S-Hertogenbosch, The Netherlands, 15–19 April 1991.

FAO (1992), The Use of Saline Water for Crop Production. *Irrigation and Drainage Paper* no. 48.

FAO (1993a), *Agriculture Towards 2010.*

FAO (1993b), FESLM: An International Framework for Evaluating Sustainable Land Management. *World Soil Resources Report* 73.

FAO (1993c), Soil Tillage in Africa: Needs and Challenges. *Soils Bulletin* no. 69.

FAO (1994), *Introduction à le gestion conservatoire de l'eau, de la biomasse et de la fertilité des sols* (GCES).

Greenland, D.J. (1974), Evolution and Development of Different Types of Shifting Cultivation, in FAO (1974), Shifting Cultivation and Soil Conservation in Africa. *Soils Bulletin* no. 24.

Greenland, D.J. (1994), Long-term cropping experiments in developing countries: the need, the history and the future, in Leigh, R.A. and Johnston, A.E. (eds), *Long-term Experiments in Agricultural and Ecological Sciences*. CAB International, Wallingford, UK.

Greenland, D.J. and Lal, R. (eds) (1977), *Soil Conservation and Management in the Humid Tropics*. Wiley, Chichester, UK.

Greenland, D.J. and Szabolcs, I. (eds) (1994), *Soil Resilience and Sustainable Land Use*. CAB International, Wallingford, UK.

Hillel, D. (1991), *Out of the Earth: Civilisation and the Life of the Soil*. University of California Press, Berkeley, California.

IBSRAM (1987), Management of Acid Tropical Soils for Sustainable Agriculture. *Proceedings no. 2.*

IBSRAM (1987), Tropical Land Clearing for Sustainable Agriculture. *Proceedings no. 3.*

IBSRAM (1987), Management of Vertisols under Semi-arid Conditions. *Proceedings no. 6.*

IBSRAM (1990), Organic Matter Management and Tillage in Humid and Subhumid Africa. *Proceedings no. 10.*

IBSRAM (1991), Evaluation for Sustainable Land Management in the Developing World. *Proceedings no. 12.*

IBSRAM (1991), Soil Management for Sustainable Rice Production in the Tropics. *Monograph no. 2.*

India National Bureau of Soil Survey and Land Use Planning (1991), *The Suitabilities of Vertisols and Associated Soils for Improved Cropping Systems in Central India.* NBSS.

Jenkinson, D.S. (1991), The Rothamsted Long-Term Experiments: Are They Still of Use? *Agronomy Journal,* 83, pp. 2–10.

Jenkinson, D.S. (1993), Continuity in Agricultural Research—Benefits for Today and Lessons for the Future. *The Massey Ferguson National Agricultural Lecture, 1993.*

Kwakye, P.K., Dennis, E.A. and Asmah, A.E. (in press), Management of a Continuously Cropped Soil through Fertilizer Use. *Experimental Agriculture.*

Lal, R. (1991a), Tillage and Agricultural Sustainability. *Soil and Tillage Research,* 20, pp. 133–146.

Lal, R. (1991b), *Tropical Agricultural Hydrology and the Sustainability of Agricultural Systems.* IITA and Ohio State University, Columbus, Ohio.

Lal, R. (1994), *Sustainable Land Use Systems and Soil Resilience,* in: Greenland, D.J. and Szabolcs I. (eds), *Soil Resilience and Sustainable Land Use,* pp. 41–67. CAB International, Wallingford, UK.

Lal, R., Hall, G.F. and Miller, F.P. (1989), Soil degradation: I. Basic Processes. *Land Degradation and Rehabilitation,* 1, pp. 51–69.

Makary, A.Z. (1993), Sedimentation Front Progress in the High Aswan Dam Reservoir, *Proceedings, International Conference on Development of the Nile and Other Major Rivers*, 2, 9/10–1 to 9/10–15. Nile Research Institute, Delta barrages, Egypt. Quoted by: Shahin, M.M.A. (1993), An Overview of Reservoir Sedimentation in Some African River Basins, in *Sediment Problems: Strategies for Monitoring, Prediction and Control,* pp. 93–100. IAHS Publication no. 217.

McCown, R.L. and Jones, R.K. (1992) Agriculture of Semi-Arid Eastern Kenya: Problems and Possibilities, in Probert M. (ed), *A Search for a Strategy for Sustainable Dryland-Cropping in Semi-arid Eastern Kenya,* pp. 8–15. ACIAR, Canberra.

Nair, P.K. (1989), *Agroforestry Systems in the Tropics.* Kluwer Academic Publishers, Dordrecht and ICRAF, Nairobi.

National Research Council (1993), *Vetiver Grass: A Thin Green Line Against Erosion.* National Academy Press, Washington DC.

Narayana, V. and Babu, R. (1983), Estimation of Soil Erosion in India, *Journal of Irrigation and Drainage Engineering,* 109, pp. 419–434. Quoted by Randhawa, N.S. and Abrol, I.P. (1990), Sustaining Agriculture: the Indian Scene, in: Edwards, C.A., Lal, R., Madden, P., Miller, R.H. and House, G. (eds), *Sustainable Agricultural Systems,* pp. 438–450. Soil and Water Conservation Society, Ankeny, Iowa.

Nye, P.H. and Greenland, D.J. (1960), *The Soil Under Shifting Cultivation.* CAB International, Wallingford, UK.

Oldeman, L.R. (1994), The Global Extent of Soil Degradation, in Greenland, D.J. and Szabolcs, I. (eds), *Soil Resilience and Sustainable Land Use,* pp. 99–118. CAB International, Wallingford, UK.

Oldeman, L.R., Hakkeling, R.T.A. and Sombroek, W.G. (1991), *World Map on the Status of Human Induced Soil Degradation (Revised Edition).* ISRIC and UNEP, Nairobi.

Pichot, J., Sedogo, M.P., Poulain, J.F. and Arrivets, J. (1981), Évolution de la fertilité d'un sol ferrugineux tropical sous l'influence de fumures minéral et organique, *Agronomie Tropicale,* 36, pp. 122–133.

Pieri, C.J.M.G (1992), *Fertility of Soils: A Future for Farming in West Africa.* Springer Verlag, Berlin.

Rapp, A.L., Berry, L. and Temple, P. (1972), Erosion and Sedimentation in Tanzania. *Geografiska Annaler,* 54A, nos. 1 and 2.

Robison, D.M. and McKean, S.J. (1992), *Shifting Cultivation and Alternatives: an Annotated Bibliography, 1972–1989.* CIAT and CAB International, Wallingford, UK.

Ruthenberg, H. (1976) *Farming Systems in the Tropics.* Oxford University Press, London, UK.

Sanchez, P.A., Bandy, D.E., Villchica, J.H., and Nicholaides, J.J. (1982), Amazon Basin Soils: Management for Continuous Crop Production. *Science,* 216, pp. 821–827.

Syers, K. and Rimmer, D. (eds) (1994), *Soil Science and Sustainable Land Management in the Tropics.* CAB International, Wallingford, UK.

Wilding, L.P. and Puentes, R. (eds) (1988), *Vertisols: Their Distribution, Properties, Classification and Management.* SMSS Texas A & M University Tech. Monograph No. 18, 193pp.

Young, A. (1989) *Agroforestry for Soil Conservation.* CAB International, Wallingford, UK.

For technical advice on
soil management problems and programmes, write to:

Land and Water Development Division
Agriculture Department
Food and Agriculture Organization
Viale delle Terme di Caracalla
00100 Rome
Italy