#253

Desertification Control Bulletin

United Nations Environment Programme

Number 23, 1993

Introduction of new method of irrigation to extend the land under cultivation. Lodar area in Yemen, UNEP/AGFUND project. Photo: UNEP.

Cover: Terraces have formed naturally above soil conservation hedges. Photo: ICRAF

Agricultural Sustainability and Soil Resilience

By Rattan Lal

Department of Agronomy
The Ohio State University
Columbus, Ohio 43210, USA

Introduction

The origin of all living things on earth can be linked, directly or indirectly, to soil. Soil resources of the world are finite in geographical extent. Only 11% of the earth's total land area of 13.4 x 10^9ha is currently being cultivated. The remaining potentially cultivable land is marginal for agricultural use because most of it is either inaccessible or is severely constrained by unfavorably steep terrain, shallow rooting depth, extremes of moisture and/or temperature regimes, shortages of essential inputs, or is located in ecologically sensitive regions.

The per capita arable land area of 0.3 ha in 1990 is expected to decrease to 0.25 ha in the year 2000, 0.15 ha in the year 2050 and about 0.10 ha in the year 2150. Human needs, with per capita arable land area of 0.10 ha, can only be met with the assistance of science-based and innovative technology. Consequently, there is an overwhelming interest in instigating sustainable land use systems that prevent or minimize soil degradation and restore productive capacity and life support processes of degraded lands.

Agricultural sustainability and *soil degradation* are complex concepts with subjective values. What these concepts are understood to mean varies according to the user's immediate and longterm concerns and needs. The scientific community needs to develop objective, consistent and operational definitions of both *agricultural sustainability* and *soil degradation* which can then by used to create a rational and science-based strategy for resource management. The objective is to have practical and operational ways to achieve agricultural sustainability and to prevent soil degradation and thereby to alleviate the pressing problems of modern agriculture. In other words, to increase per capita productivity and decrease the risks of soil and environmental degradation. In this context, agricultural sustainability means 'an increasing trend in per capita productivity per unit consumption of the non-renewable or the limiting resource, or per unit degradation of soil and environmental characteristics or per unit reduction in soil's life support processes'. The aim is not only to increase per capita productivity but also to maximize production per unit of soil loss, per unit of energy input, per unit of reduction in soil organic carbon, per unit of efflux or radiatively active gases, per unit of consumption of ground water and per unit of increase in concentration of NO_3, PO_4 or other pollutants in natural waters.

Soil Resilience

Soil is a dynamic entity, and dynamism is life. Because early civilizations originated and flourished on fertile soils, many ancient cultures developed reverence for the soil on which they depended. They believed that humans originated from the land and that land is a living entity worthy of worship. For example, the Maori of New Zealand believe that 'the land is a mother that never dies'. These beliefs are similar to the modern 'Gaia Hypothesis' that proposes that 'earth is a living organism' and 'is a complex entity involving the biosphere, atmosphere, oceans and soil; the totality constituting a feedback or cybernetic system which seeks an optimal physical and chemical environment for life' (Lovelock, 1979).

Soil dynamism is evidenced by continuous formative and evolutionary changes until a dynamic equilibrium is achieved. Anthropogenic perturbations alter this state of equilibrium and may change the rate and direction of principal processes (Rozanov, 1990). With the advent of modern technology, human actions are becoming progressively drastic due to the development of bigger and faster machines, and concentrated and highly active chemicals designed to enhance soil fertility and accentuate plant growth. The greater the human demands, the more potent are the technologies likely to have drastic effects on soil processes.

The 'Magic of Mother Earth' is her ability to heal herself and the term 'soil resilience' refers to the soil's ability to bounce or spring back into shape or position after being stressed. As a dynamic and an organic entity, soil has an in-built ability to restore its life-support processes, provided that the disturbance created by human intervention is not too drastic and sufficient time is allowed for the recovery processes to take effect. However, soil can undergo irreversible degradation if it is drastically disturbed and its life support processes are severely jeopardized. Through constant misuse and mismanagement 'man may sap the vitality of Gaia by reducing productivity and by deleting key species in her life-support systems' (Lovelock, 1979). Soil resilience can, therefore, also be defined as the ability of soil to restore its life-support processes after it has been degraded by natural or human-induced perturbations. Soil resilience depends on balance between soil restorative and soil degradative processes. It is a function of the harmonious and symbiotic action of all living organisms in that it creates favourable environments for life to thrive. Although humans value only crops and livestock, other unwanted species are not necessarily pests, weeds or vermin - they too play an important role in the self-regulatory mechanisms of Mother Earth (Lovelock, 1979).

Soil resilience depends on close interrelationships between soil degradative and soil restorative processes, and the factors and processes that influence their magnitude and direction. Soil degradative processes are set in motion when the soil structure starts to deteriorate, the carbon cycles are disrupted, nutrient reserves within the soil are depleted and nutrient recycling mechanisms are weakened. Soil restorative or self-regulatory processes are strengthened by science-based agriculture, discriminate and judicious land use, reduction of pressure on marginal lands and fragile ecosystems, and adoption of improved technology.

Rate of New Soil Formation

Soil is a renewable resource as long as the balance between the rate of soil formation and soil degradation is positive, otherwise it is a non-renewable entity - at least within a human lifetime. The time frame is an important consideration in this analysis. Most available data are based on informed opinion and indirect evaluation and vary enormously. Some estimates put the rate of soil formation at about 2.5 cm (1 inch) in a thousand years. However, Friend (1992) estimated that worldwide the rate of soil formation is about 2.5 cm (or 1 inch) per 150 years. In general, soils of volcanic origin develop faster than those developed on gneiss or basement complex rocks. The rate of new soil formation for Andisols in the humid tropics is <1 mm/year. In contrast, the rate of new soil formation for Alfisols and Ultisols is <0.01 mm/year. Under normal conditions, however, new soil is formed at the rate of about 2.5 cm (1 inch) in 300 to 1,000 years. It would seem, therefore, that most soils are non-renewable within a human life span. The major exception to this rule is the formation of alluvial flood plains by rivers carrying heavy sediment loads, such as the Yellow River, the Ganges, etc.

Soil Degradation Rate

Soil degradation, or the decline in a soil's capacity to produce goods of value to humans, has plagued the earth ever since human exploitation of land began. Many ancient civilizations thrived on 'good soil' and declined as soils became degraded through misuse. Typical examples are the Riparian and Harappan Kalibangan culture in the Indus Valley, Mesopotamian and Lydian Kingdoms in the Mediterranean region, and the Mayan civilization in Central America. These great civilizations declined along with depletion of the original mantle of fertile topsoil. The problem of soil degradation has been drastically accentuated by changes in land use since the 18th century. It is estimated that out of the world's total land area of 13.4×10^9ha, about 2.0×10^9ha is degraded to some degree (World Resources Institute, 1992-1993). Asia and Africa combined account for a total of 1.24×10^9ha of degraded land. There are several processes of soil degradation. Most prominent among these are wind and water erosion, chemical degradation and fertility depletion, and physical degradation resulting from decline in soil structure. Estimates of soil degradation in dry climates are equally alarming. Such statistics play an important role in creating awareness about the magnitude and severity of the problem and in formulating a global strategy in addressing it. Indeed, if these statistics are correct, soil degradation presents one of the greatest challenges to the human race because soil resources are finite and, to all intent, may be considered non-renewable. Even though the statistics can only be approximately correct, it should be a matter of the greatest urgency for decision-makers and opinion-shapers to do something about the problem.

However, careful analyses of these data on land/soil degradation reveal several problems. First, there may be a problem with the statistics themselves. As explained earlier, the term 'soil degradation' is vague and highly subjective: to avoid ambiguity, it is important that soil degradation by different processes be defined quantitatively. To do so is to delineate threshold values or critical limits of soil properties beyond which soil's life support processes are severely jeopardized. The important soil properties for which critical limits need to be defined are rooting depth, plant-available water capacity, soil organic matter content, soil structural attributes, capacity and intensity factors and limiting levels of principal nutrients. These limits vary among soils, climatic conditions, farming systems, land uses and managerial inputs.

Second, there is a problem even with this data since ignorance about the critical limits and threshold values of soil properties often makes global data vague and unreliable.

Third, soil degradation and productivity must be considered in relation to land use, inputs and management using improved technology. The World Map of the Status of Human-Induced Soil Degradation (GLASOD) project by ISRIC/UNEP (1990) and FAO's (1991) map of soil resources are steps in the right direction and the information provided can lead to the development of cause-effect relationships between soil degradation and agronomic productivity.

Inputs and Improved Technology

It is true that the majority of soils in ecologically sensitive regions have undergone drastic changes in their properties due to intensive cultivation, land misuse and other anthropogenic perturbations. However, the impact of these changes on productive potential has not been determined. The productivity of degraded soils can be greatly enhanced by improved management and proper land use. Soil degradation must, therefore, be determined scientifically according to its degree and the processes affecting it so that improved management and judicious land use can be implemented to set in motion the restorative processes, even on drastically disturbed lands.

Improved technology reduced soil erosion and degradation on crop land in the USA, according to measurements made by Lee (1990). Using similar erosion survey techniques, Lee observed that sheet and rill erosion from crop land in USA declined by 11.5% between 1982 and 1987 thanks to conservation management improvements. In the Conservation Reserve Program authorized in the Food Security Act of 1985, the adoption of conservation-effective technology reduced soil erosion in the USA by about 0.5 billion tons (or roughly one third) in its first five years from 1986 to 1991. The projected reduction for a 10-year period from 1986-1995 is estimated at about 60%. This dramatic reduction in soil erosion in the USA is not only a major success story but also an example of how improved technology can assist natural soil resilience to restore soil productivity and prevent further soil degradation.

Wolman (1967) developed a schematics of sequence of land use changes in the USA with sediment yield over a period of two centuries from 1800 to the year 2000. As the forests were cleared and cultivated, grasslands ploughed and construction activity increased, so did the sediment yield. However, adoption of conservation practices reduced sediment yield for the same land use system. This pattern of sediment yield in relation to landuse and conservation technology was similar for all soils, except that the amplitude of change differed depending on soil properties, terrain characteristics and the climatic environment. In addition to benefits in crop yield, scientific management can also set in motion soil restorative processes. Vast areas of land that were once the 'dust bowl' of the south-central USA have been transformed into highly productive lands by science-based agriculture. Similarly, vast areas of salt-crusted, barren lands in Haryana and Punjab provinces in India have been transformed into highly productive lands by science-based improved land use systems.

Agriculture in North America, Western Europe and other developed economies has undergone several phases of development. Per capita productivity has drastically increased with each phase, beginning with human power, moving on to horse power,

Endogenous Factors	Exogenous Factors
1 Rooting depth	1 Land use and farming system
2 Soil texture and clay mineralogy	2 Technological innovations
3 Parent material	3 Inputs and management
4 Landscape and terrain	
5 Moisture regime	
6 Micro- and meso-climate	
7 Soil biodiversity, eg, flora and fauna	

Table 1: Factors affecting soil resilience (Lal, 1992b)

improvements in farm implements, use of motorized equipment and chemical fertilizers and pesticides, and use of improved and input-responsive varieties of crops. These technological innovations have been used most successfully on undegraded, naturally-resilient, prime agricultural land. Similar innovations need to be developed for soils degraded by different processes since improved technology and appropriate land use vary according to the processes of soil degradation and the extent to which they have progressed.

Time Scale

The issue of time scale is highly pertinent. Soil may be a renewable resource over the geological time scale but not over the human life span. However, with increasing demographic pressure, issues of productivity and sustainability must be addressed over the human life span, if not over the even shorter, common economic-planning time span. In fact, there is tremendous pressure to produce needed goods and services over the economic-planning time span of five to 10 years, or less. Therefore, it is appropriate to test the impact of innovative technologies on soil restoration or resilience over the human or scientific time span of 20 to 25 years. As was previously explained, with the exception of volcanic soils and some aeolian and alluvial deposits, the amount of new soil formation over the scientific and human time span may be small, if not negligible, in real terms.

Factors Affecting Soil Resilience

There are a multitude of interacting factors that affect soil resilience. These factors can be broadly grouped into two categories: (a) endogenous, and (b) exogenous (table 1). Endogenous factors are related to inherent soil properties and micro- and meso-climate.

Factors that enhance soil resilience are sufficient rooting depth, loam to clay-loam texture, structurally-active soils containing high activity clay minerals, a high proportion of stable micro-aggregates, gentle to rolling terrain, good internal drainage and a favorable micro-climate.

High soil organic matter content and other characteristics of fertile soil depend on these conditions. There are several examples of such highly productive soils, eg, alluvial soils along major rivers, Mollisols, Inceptisols, Andisols and soils formed on highly basic parent materials. Because of their high inherent nutrient levels and favorable soil physical properties, these soils are remarkable resilient even with poor or lax management. Life support processes of such soils can withstand some degree of mistreatment and neglect without being seriously harmed or suffering lasting deleterious effects.

Land use, soil, crop and livestock management are important exogenous factors. The choice of an appropriate use for the land and the adoption of science-based, improved technology play a major role in restoring soil productivity. Together they can enhance and sustain high productivity and accentuate the resilience of even fragile soils in ecologically sensitive regions. Improved scientific technology also acts synergistically with prime agricultural lands to improve soil resilience. And adopting an appropriate land use and implementing science-based, improved technology are particularly crucial to sustainable use and resilience of soils which have either been degraded due to past misuse, or which have

Rotation Treatment	Plow-till from 1973-79			No-till from 1973-79*		
	1979	1984	% Change	1979	1984	% Change
Maize-maize	10.5	7.1	-32.3	10.2	07.8	-23.5
Maize-pigeon pea	10.2	4.7	-53.9	15.6	04.2	-73.0
Maize-mucuna	09.0	4.6	-18.0	19.2	07.3	-61.9
Maize-leucaena	04.2	6.4	+52.3	16.2	16.6	+02.5
Natural fallow	07.2	6.5	-09.7	06.0	07.8	+30.0

* No-till system was adopted from 1974 to 1984 in all treatments

Table 2: Restorative effects of crop rotations and agroforestry systems on infiltration rate of an eroded Alfisol in western Nigeria (IITA, Block D; Lal, 1992b)

inherent constraints, such as shallow depth, steep terrain or high erodibility, etc.

The important effect of science-based inputs, judicious land use and adoption of modern technology on soil resilience becomes evident when comparing soil erosion data from the USA in the 1930s and in the 1980s. Estimates of soil erosion by Bennet (1939) showed that half of the USA land area had been affected by erosion before and during the 1930s. In addition to 40 million ha of essentially ruined crop land, the process of soil erosion had already damaged or was threatening to damage more than one-third of the arable land. Approximately 75% of USA crop land in the 1930s was susceptible to some degree of erosion.

Bennet (1939) also observed that the lack of increase in yields of corn and cotton for the 60-year period from 1971 to 1930 was due to the impact of severe soil erosion. However, estimates of soil erosion 50 years later showed that the extent and magnitude of soil erosion were drastically less in 1989 than in 1939. Technological advances and use of energy inputs apparently resulted in high production without excessively stressing these resources.

Miller *et al* (1985) observed that much of the 'ruined' land described by Bennet in the 1930s was used for producing timber and forages in the 1980s and 1990s. The 'ruined' land of the 1930s had been restored, at least partially, to be agronomically productive and environmentally safe in that it contributed less sediments to the ocean, waterways, lakes and reservoirs.

Land Use, Soil Management and Sustainability

Evaluating land capability, adopting an appropriate land use and employing farming systems and soil and crop management practices that realize the potential of the land and restore its productivity are important considerations in long range planning for effective development and sustainable use of land resources. Scientific management of any land use is just as, if not more, important than the land use itself. In the context of soil degradation and restoration, 'how' to use the land is as important as 'what' to use it for. Furthermore, the amount and quality of biomass produced depends on the efficiency, magnitude and total flux of (i) nutrients (ii) water, and (iii) energy through the soil-plant-management system since these govern productivity and sustainability.

Soil Structure and Sustainability

Soil structure management is crucial to soil resilience and agricultural sustainability. Although it is a complex attribute that is difficult to characterize and quantify, soil structure regulates the fluvial and transport pathways, and circulatory and respiratory processes of soil. It regulates fluid retention and movement, nutrient transformations and translocation, faunal activity and species diversity, and the strength and rigidity of rooting media.

For most soils, the maintenance and enhancement of soil structure depend on land use. Land use systems that enhance soil structure are those practices that optimize (which for most soils means increase) soil organic matter content, and the activity and species diversity of macro- and meso-fauna. These systems include mulch farming, conservation

Treatment	Cultivation Duration (years)								
	Pre-clearing 1978	1	2	3	4	5	6	7	8
Continuous cropping (watershed 4)	146.0	30.6	28.2	12.6	12.6	20.4	13.8	10.2	10.8
Traditional cropping (watershed 7)	156.0	46.8	37.8	19.8*	19.2	24.0	43.2	115.8	193.0

*Reverted to natural fallow

Table 3: Restorative effects of natural fallowing on infiltration rate (cm/hr) of an Alfisol (Lal, 1992a)

Rotation Treatment	Plow-till from 1973-79 1982	% increase over 1979	No-till from 1973-79 1982	% increase over 1979
Maize-maize	1.10	7.8	1.30	0.0
Maize-pigeon pea	1.50	47.1	1.41	8.5
Maize-mucuna	1.40	37.3	1.48	13.8
Maize-Leucaena	1.22	19.6	1.34	3.0
Natural fallow	1.30	27.5	1.46	12.3

Initial level of organic carbon in 1979
Plow-till = 1.02%
No-till = 1.30%

Table 4: Restorative effects of crop rotations on soil organic carbon content (%) for 0-10 cm depth of an eroded Alfisol in western Nigeria (Block D, IITA: Lal, 1992b)

tillage, frequent use of planted fallows and cover crops, appropriate rotations and crop sequences and combinations, etc.

Through the judicious use of organic manures and inorganic fertilizers, nutrient management and soil fertility improvement also play an important role in improving the soil structure.

Soil Erosion Management

Soil erosion control is crucial to the sustainable management of soil resources and to soil resilience. In some cases, taking the pressures off marginal lands is probably the best solution for controlling accelerated erosion. In other cases, intensive cultivation of prime agricultural land, creating off-farm employment and developing income-generating capabilities in non-agricultural sectors can be important options.

When science-based, intensive agriculture is limited to prime agricultural land, there are several options for erosion management. The choice of an appropriate option should be carefully made with due consideration to soil types, land form and terrain characteristics, rainfall regime and hydrology, cropping/farming systems and socio-economic factors.

Farming Systems and Erosion Control

Conservation effective measures are those that enhance soil structure, decrease raindrop impact, improve infiltration capacity and decrease runoff rate and amount. These techniques are judicious systems of soil and crop management and include practices such as no-till or conservation-tillage, mulch farming through cover crops and planted fallows, multiple cropping and multi-storey canopy including agro-forestry.

Several longterm soil restorative experiments were conducted at the International Institute of Tropical Agriculture (IITA), Ibadan, Nigeria. The data from these experiments are shown in tables 2 to 4. It seems that the growing of deep-rooted shrubs or woody perennials is crucial to improving the infiltration rate and restoring the structure of a severely degraded soil with compacted sub-soil. The data in table 2 show that improvements in the infiltration rate were brought about only by growing *Leucaena leucocephala*. In this severely eroded soil, a natural fallow period of about five years was not effective in restoring soil structure. However, bush fallowing can improve infiltration rate and soil structure if the soil is not severely degraded. For example, the data in table 3 show gradual improvements over time in the infiltration rate after the land reverted to bush fallow. The data in table 4 show that an increase in organic carbon content of the surface layer was achieved by growing annual/seasonal cover crops that produce large amounts of biomass, eg *Mucuna utilis*. Woody shrubs or deep-rooted perennials were not as effective in producing a large quantity of biomass as aggressively grown cover crops.

Residue Management and Erosion Control

A regular and sizable addition of organic material is essential to maintain a favorable level of soil organic matter content and to stimulate biotic activity of soil fauna, eg earthworms and termites. Structural collapse of soils with predominantly low-activity clays can be avoided by maintaining high organic matter content (about 2% soil organic carbon content) and by enhancing the activity of soil fauna. Crop residue mulch is an important ingredient of any improved farming/cropping system. Frequent applications of 4-5 t/ha of residue mulch applied to the soil surface is beneficial for soil and water conservation, regulating soil moisture and temperature regimes, improving soil structure, enhancing the biological activity of soil fauna, and protecting soils from high intensity rains and from ultra-desiccation. Mulching also suppresses weed growth.

While the beneficial effects of mulching are widely recognized, economic procurement of mulch material in sufficient quantities is a serious practical problem. Management of crop residue as a source of mulch is, therefore, closely linked with the cropping system, tillage methods and planted fallows. A range of cultural practices are available to procure adequate amounts of residue mulch for soil protection and fertility enhancement, eg, cover crops, conservation tillage, sod seeding, agroforestry, etc. Live mulch, alley cropping, ley farming, planted fallows and the use of industrial by-products are some of the cultural practices specifically adopted to procure mulch. Once again, suitability of a practice depends on the local-specific, biophysical and socio-economic environment.

Plant	Soil	Water
1. Biomass production	1. Soil structure	1. Water balance
2. Productivity	2. Net rate of soil renewal	2. Water quality
3. Nutritive quality	3. Nutrient fluxes & cycling	3. Water:air ratio in the root zone
4. Soil organic matter content		
	5. Rooting depth	
	6. Gaseous fluxes	

Table 5: Some indices of sustainability for plant, soil and water resources (Lal, 1992b)

Crop Management and Erosion Control

A continuous ground cover is necessary to provide a buffer against sudden fluctuations in micro- and mesoclimate, and to prevent the degradative effects of raindrop impact or high velocity winds. Timely planting, use of viable seed at optimum rates, use of improved cultivars and cropping systems, correct fertilizer use and pest management are all important aspects of good farming practices. The benefits of timely planting include the provision of a buffer against uncertain rains, unfavourable soil temperature regimes, pest infestation and unfavorable markets. Planted fallows, both legume and grass covers, are generally more effective in restoring soil fertility and improving soil physical properties than natural fallows. Soil organic matter can often be increased and soil structure improved over a short period of two to three years.

There are several methods of managing cover crops. Live mulch is a system of growing grain/food crops through a low-canopy cover crop. Mixed cropping creates diversity and decreases soil erosion risks. Agroforestry and mixed farming are also important techniques to create diversity. Mixed farming can be a stable system for small land holders provided that pastures are lightly grazed, the stocking rate is low and animal waste is applied to the land to replenish soil fertility. Whether this system is economic or not will depend on price structures. Economic circumstances can force farmers to adopt some practices. Mixed farming with excessive stocking rates and uncontrolled grazing is usually unsuccessful and degrades the soil and the environment, as is the case in the African Sahel.

Energy Management

The overall energy input and output must be regulated to enhance the output:input ratio and to attain a positive thermodynamic energy balance with respect to biological yield vs production inputs. Both energy efficiency and flux must be increased. A low output subsistence system can be highly efficient in terms of energy use but is unsuitable because of low productivity. However, the energy of a high-input system can be improved by reducing nutrient losses by effectively containing leaching and erosion, and enhancing nutrient capital through judicious inputs of chemical fertilizers and organic or other amendments (liming). Nitrogen deficiency is a major constraint in most soils of the tropics and subtropics. Local-specific research is needed to ensure an adequate supply of nitrogen for the desired level of economic yields through the input of synthetic fertilizers, wherever these can be economically used, supplemented by alternative sources of nitrogen, eg, symbiotic nitrogen fixation through legume-based rotations and agroforestry systems, organic manures and composts, and azolla, etc.

Similarly, productivity of soils notably deficient in available phosphates can only be enhanced through substantial and regular additions of phosphatic fertilizers.

The efficiency of fertilizer use can no doubt be increased by the use of new cultivars and through mycorrhizal infection.

Since the use of synthetic fertilizers is inevitable, the strategy is to decrease the rate of application through better systems of soil and crop management. Plant nutrients depleted through harvesting and other losses must be replenished. The source of nutrients, organic or inorganic, is not crucial as long as nutrients are supplied in adequate quantity and in a readily-available form. However, hoping to increase and sustain agricultural production by adding chemicals alone, without improved and efficient systems of soil and crop management, is bound to cause frustrations and disappointments. It is the judicious combination of both management and inputs that is crucial to a sustainable use of natural resources.

Technological Options for Sustainable Land Use

A truly sustainable land use system meets the following criteria:

- a it enhances soil resilience through longterm maintenance of biological and ecological integrity of natural resources;
- b it sustains a desirable level of support to the social, political and economic well being of a farm, community or regions, and
- c it enhances quality of life.

In the context of agriculture, sustainability of a land use system can be assessed by evaluating characteristics of plant, soil and water resources (table 5). The system is sustainable if:

- i a favourable level of soil structure is maintained;
- ii soil erosion is controlled;
- iii nutrients are effectively recycled;
- iv soil organic matter content is optimized, and
- v water and energy regimes are maintained favorable to the ecological integrity of the system.

The basic principles of sustainable use of soil and water resources are the same for all ecoregions. However, technological options may be soil and site specific. Some basic principles and underlying technological options for sustainable use of soil and water resources for the humid and sub-humid/semi-arid tropical regions are outlined in tables 6 and 7 respectively. Judicious use of these options is likely to sustain productivity and life support systems of soil and water resources.

Conclusions

Soil, the essence of all life on earth, is a non-renewable and a finite resource. The rise and fall of ancient civilizations depended in part on the quality and managerial ability of occupants to maintain and enhance life support processes of soil resources. The judicious use through discriminate and objective management of the eternal trinity of soil, water and climate is as crucial to human survival and welfare now as it was for the extinct civilizations who could not manage these most basic of all resources. The sustainability of soil resources must be assessed in terms of trends in per capita productivity with reference to changes in soil properties, water characteristics and climatic factors.

The rate of soil depletion and degradation of soil productivity depend on land use and soil management, and may be independent of profile depth for soils with root-restrictive, sub-soil characteristics. Choice of appropriate land use and use of science-based, improved technology can enhance and sustain soil productivity and accentuate resilience of even fragile soils in ecologically sensitive ecoregions.

Science-based land use, (how it is used rather than what it is used for) is important to sustainability and resilience. There are also important policy issues involved in sustainable land use. The principal processes involved in soil resilience are:

i control of soil organic matter content;
ii improvement in soil structure;
iii increase in soil biodiversity;
iv reduction in soil degradation and erosion rates below the soil formation rate, and
v increase in nutrient capital and recycling mechanisms.

The basic technological principles to achieve these are known and include practices of good farming, eg, conservation tillage, mulch farming, crop rotations involving cover crops and planted fallows, mixed farming with controlled grazing and low stocking rate, agroforestry, and use of inorganic fertilizers and organic manures. Above all, it is important to use improved crops and cultivars, and to introduce new crops and species with the potential to develop into agro-based industries. More specifically, a long term research programme is needed with the following objectives:

i To standardize criteria, delineate threshold values of soil properties,

Arable Land Use

1 Use prime land and avoid steep and shallow slopes.
2 Forest removal by manual methods, or by shearblade.
3 Use cover crop and mulch farming techniques for soil and water conservation.
4 Frequent use of planted fallows is necessary.
5 Wherever feasible, integrate woody perennials and livestock food crop annuals.

Pasture Development

1 Use prime land and avoid steep/shallow slopes.
2 Proper clearing methods are essential, eg, manual, slash and burn, etc. Tree defoliants can also be used in regions with low tree density. Dead trees can be left standing.
3 Seeding with suitable and ecologically adapted mixture of grass and legumes is necessary.
4 Maintain soil fertility as per soil test values. Balanced fertilization is important.
5 Stocking rate should be low. Controlled and rotational grazing should be adopted.
6 Use live fences and vegetative hedges.

Agroforestry

1 Use prime land of high inherent fertility.
2 Land should be cleared by manual methods or shearblade.
3 Choice of native tree species which do not aggressively compete with annuals is critical.
4 Proper tree management is crucial.
5 Choice of appropriate crops and cropping sequences is critical.
6 Soil fertility should be managed in relation to cropping intensity and soil test values.

Forest Plantations

1 Use prime land with no severe limitations.
2 Clear existing vegetation by manual methods, slash and burn or shearblade. Some roots and stumps can be left intact.
3 Seed a leguminous cover crop immediately.
4 Establish tree seedlings through the leguminous cover by suppressing it through chemical or mechanical means. Cover crop management is crucial to tree establishment.
5 Use balanced fertilizer based on soil test value and tree requirement.
6 Use effective soil and water conservation techniques.

Table 6: Best management practices for sustainable land use in humid tropics (Lal, 1992b)

and develop quantitative and reliable methods of assessment of soil degradation by different processes at the local, regional and global scale. There is a need to improve the reliability and accuracy of statistics on soil degradation.

ii To develop objective and quantifiable criteria of soil resilience and assess resilience of major soils in relation to parent material, soil properties, land use and management systems.

iii To develop appropriate land uses and restorative measures for enhancing economic productivity of degraded soils. Assessing accurately the extent of soil degradation, establishing the cause-effect relationship, choosing appropriate land use and developing restorative measures are important research and development priorities. However, it is also important to identify what land is restorable and for what use.

iv To identify the reasons why farmers do not accept available research information.

v To evaluate soil dynamics and evolution under different land uses and farming systems for principal soils and ecoregions.

vi To increase per capita productivity per unit input of non-renewable resources and per unit decline in important soil properties, and

viii To develop an index of agricultural sustainability and soil resilience. To be functional, the sustainability and resilience concepts must be based on quantitative indices.

Water Conservation

- Rough seedbed, deep plowing at the end of rains.
- Tied ridges.
- Micro-catchments.
- Use broadbed and furrow system in Vertisols.
- Supplementary irrigation where needed.
- Use wind breaks of leguminous shrubs and trees
- Reduce weed competition

Soil Fertility Management

- Apply farm yard manure, organic wastes, and nitrogenous fertilizers.
- Apply micro-nutrients where needed.
- Turn under as much crop residue and biomass as possible.
- Increase fertilizer use efficiency through water conservation, split dose application and placement in the vicinity of row zone.
- Use cover crops and green manures.

Crop Management

- Improved crops and cultivars developed/adapted for harsh environment.
- Multiple cropping based on inter-cropping, ration cropping, relay cropping and mixed cropping systems.
- Use agroforestry systems based on native tree species where appropriate.
- Use ley farming based on growing appropriate forages, light/controlled grazing, and relevant cropping sequences.
- Improve crop stand through use of good seed, high seed rate, appropriate seeding equipment.
- Seed in furrow to minimize sand blasting and decrease the adverse effects of high soil temperature.

Table 7: Best management practices for sustainable land use in semi-arid and arid tropics (Lal, 1992b)

References

Bennett, H.H., 1939. *Soil Conservation*, McGraw-Hill Book Co., New York.

FAO, 1991. *World Soil Resources*, report 66, FAO, Rome, Italy.

Friend, J.A. 1992. Achieving soil sustainability, *Journal of Soil and Water Conservation*, no. 47, pp 156-157.

ISRIC/UNEP, 1990. *World Map of the Status of Human-Induced Soil Degradation (GLASOD)*, Wageningen, Nairobi.

Lal, R., 1992a. Tropical agricultural hydrology and sustainability of agricultural systems: A ten year watershed management project in southwestern Nigeria, in *Technical Bulletin*, The Ohio State University/IITA, pp 303.

Lal, R.. 1992b. *Sustainable land use systems and soil resilience*, paper presented at the International Symposium on Soil Resilience and Sustainable Land Use, 28 September-2 October 1992, Budapest, Hungary.

Lee, L.K., 1990. The dynamics of declining soil erosion, in *Journal of Soil and Water Conservation*, no. 45, pp 622-624.

Lovelock, J.E., 1979. *Gaia. A new look at life on earth*, Oxford University Press, Oxford, U.K.

Miller, F.P., W.D. Ramussen and L.D. Mayer, 1985. Historical perspective of soil erosion in the United States, in R.F. Follett and B.A. Stewart (eds), *Soil erosion and crop productivity*, ASA-CSSA-SSSA, Madison, WI, pp 23-48.

Rozanov, B.G., 1990. *Human impacts on evolution of soils under various ecological conditions of the world*, 14th International Congress of Soil Science, Plenary Payers, 12-18 August 1990, Kyoto, Japan, pp 53-62.

UNEP, 1991. *Status of desertification and implementation of the United Nations Plan of Action to combat Desertification*, UNEP, Nairobi, Kenya, pp 77.

Wolman, M.G., 1967. A cycle of sedimentation and erosion in urban river channels, in *Geogr. Ann.*, no. 49A, pp 385-395.

World Resources Institute, 1992-1993. *Towards sustainable development. A guide to the global environment*, World Resources Institute, Washington D.C., USA, pp 385.