METHODS AND GUIDELINES FOR ASSESSING SUSTAINABLE USE OF SOIL AND WATER RESOURCES IN THE TROPICS

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PREFACE

Increasing demographic pressures on a finite land resource base is now recognized as the major problem confronting food security and enhanced quality of life for future generations, particularly in developing countries. A collateral issue is environmental degradation and specifically, land degradation. It is becoming increasingly recognized that agriculture, particularly the increased use of marginal lands, is an important cause of environmental degradation. The solution recommended is to manage the resources so that they are neither degraded nor depleted and ensure a sustained production for future generations.

This monograph provides rationale and some methods for assessing the sustainable use of the land resources. There are few persons who have the ability to compile such information and in this respect, we are very fortunate that Dr. Rattan Lal, with his wide experience agreed to this immense task. The Monograph provides scientists and decision-makers in developing countries a quick reference to the subject. It is not intended to provide a recipe for every situation one can encounter but broad guidelines for consideration. The extensive reference list gives the reader an information base to consult.

The Soil Management Support Services (a component project of the Soil Management Collaborative Research Support Program) of the US Agency for International Development and USDA Soil Conservation Service, welcomes any comments and criticisms. If there is sufficient demand for this, we will try to produce a second edition.

Hari Eswaran
National Leader
World Soil Resources, USDA-SCS

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LEGEND FOR FIGURES

SUMMARY

Degradation of soil and water resources, and environmental pollution are perceived to be major problems in the tropics. Vast areas of land are claimed to be degraded, some of it irreversibly, by a wide range of degradative processes e.g., accelerated erosion and desertification, compaction and hard setting, acidification, decline in soil organic matter content and biodiversity, and depletion in soil fertility. The land area degraded by different processes in the tropics is estimated to be 915 x 10^6 ha by water erosion, 474 x 10^6 ha by wind erosion, 50 x 10^6 ha by physical degradation, and 213 x 10^6 ha by chemical degradation.

Soil and environmental degradation, low productivity, and resource-based low-input agriculture go hand-in-hand. Soil and environmental degradation are perpetuated by land misuse, and exploitative and fertility-mining systems of subsistence agriculture. Resource-poor farmers of the tropics are trapped in the ever-tightening grip of the soil degradation-low productivity-poverty-low input-more degradation cycle.

The concept of sustainability, useful and relevant as it is, needs to be made quantitative, objective, and reliable. There is a need to develop criteria and methods for quantitative assessment of sustainable use of soil and water resources. To do this is to: (i) identify soil and water indicators of sustainability, (ii) establish quantitative relationships between soil and water indicators and soil-modifying degradative processes on the one hand and productivity on the other, (iii) define critical limits of soil and water indicators in relation to threshold values beyond which productivity decline is severe and rapid, and beyond which soil and water resources are degraded to the point of no return, (iv) establish indices of soil sustainability and soil quality, and (v) develop standardized methods for assessment of soil and water indicators.

Degradation of soil and water quality, and sustainability of resource use must be expressed in terms of their impact on productivity and environmental quality. Productivity is related to land use and management system. Agronomic productivity should be assessed in relation to key indicators e.g., top soil depth, texture, structure, available water and nutrient capacity, pH, soil organic carbon content, CEC, and toxic levels of some elements. Productivity loss is permanent and irreversible only if it cannot be restored by alternate land use and science-based inputs.

There is a sequence of steps and checklist that needs to be followed while assessing sustainable use of soil and water resources. The first step is to define objectives of assessing sustainability. The next step is to conduct a detailed resource survey to evaluate potential and constraints of the resource base, and identify predominant soil degradative processes. Evaluation of changes in soil indicators and productivity due to soil modifying processes is the next step. If productivity decline or change in soil indicator is drastic and severe, the next step is to change the land use and management systems and follow the iterative process.

The science of quantification of sustainability, development of indices of soil quality and productivity is new and at informative stages of development. Consequently, there are numerous researchable topics of high priority which require inter-disciplinary, multi-institutional, and long-term ecological experiments established on benchmark soils in principal ecoregions of the tropics. Research is needed in several relevant issues including: (i) development and standardization of analytical procedures for *in situ* assessment of soil physical and hydrological indicators, (ii) identification of techniques for establishment of the cause-effect relationship between soil indicators and degradative processes on the one hand and productivity on the other, (iv) development of indices of sustainability, soil resilience, and soil quality with relevance to the impact on production and environment, and (v) development of appropriate predictive models.

It is equally important to involve farmers and practitioners in the process of research and development on issues of sustainable use of soil and water resources. Innovative farmer can be a valuable source of information and an interested partner with vested interests. Farmer participation can be useful in selecting: (i) practical indicators of prevalent degradative processes affecting soil and water resources and economic productivity, and (ii) remedial or alternate land use, cropping systems, and inputs for reversing degradative trends. Application of the methodology and guidelines suggested in this report can help improve the data base and provide reliable and objective assessment of the extent and severity of soil degradation in relation to its input on productivity, sustainability, and environmental quality.

I. INTRODUCTION

Soil and water resources of the tropics are under pressure and prone to degradation because of harsh environments, fragile soils in ecologically-sensitive ecoregions, high demographic pressure, alternate demands on limited resources, resource poor farmers, and limited or lack of institutional supports. Consequently, there is an increasing concern about sustainability of soil and water resources in terms of meeting the present needs and enhancing productivity and resilience of these resources for future requirements. The relative importance of present needs vs. future requirements must be carefully evaluated because the demands on these limited and non-renewable resources are rapidly increasing. The per capita arable land area in several regions of the tropics (e.g., Asia) is low and decreasing. The per capita arable land is 0.29 ha in latin America, 0.27 ha in Near East, 0.25 ha in Africa, 0.13 ha in the Far East, and only 0.06 ha in several other developing countries. In those regions, most potentially available land is either marginal, inaccessible, or in ecologically-sensitive ecoregions e.g., tropical rainforest, steep slopes, or in regions prone to desertification.

Despite enthusiastic interest by scientists and policy makers, soil degradation and sustainability concepts remain to be vague, qualitative and emotional rhetoric. Standardizing of these concepts and developing quantitative measures of their assessment are essential to transforming emotions and myths into scientific facts. Soil degradation, decline in soil productivity and its environmental regulatory capacity due to misuse and mismanagement, should be quantified by measuring management-induced changes in soil properties or processes and their impact on actual and potential productivity and capacity to regulate environment. Establishment of the cause-effect relationship between soil properties and processes on the one hand and crop productivity and environmental regulatory functions on the other is crucial to enhancing soil productivity, restoring degraded lands, and improving environmental quality. To do this is to develop guidelines and methods for assessment of sustainability.

II. GOALS AND PRINCIPLES OF ASSESSMENT OF SUSTAINABILITY

Some causes of lack of progress in achieving goals of sustainability in agricultural production and in environmental quality include the lack of focus, setting up mutually exclusive and multiple objectives, a wide range of spatial and temporal scales of measurement, and unstandardized criteria in assessment of sustainability. Agronomic objectives of attaining high production must be reconciled with high standards of environmental quality. Achieving high productivity and maintaining or enhancing environmental quality are neither mutually exclusive nor difficult to attain. The goal of sustainable agriculture is to maintain a non-negative and preferably an increasing trend in per capita productivity while maintaining or enhancing soils capacity to produce economic goods and services and regulate environment. Concomitantly, the goal of assessment of sustainability is to quantify the impact of management on soil properties and processes relevant to agronomic productivity and environmental quality. This implies that land use and soil management systems are commensurate with land's capability and are based on prior knowledge and detailed inventory of natural resources e.g., climate, vegetation, terrain, hydrology, and soil.

Principal goals of assessing sustainable use of soil and water resources are:

- Conserve and enhance natural resources for long-term use,
- Characterize and quantify major degradative processes,
- Identify resilience and restorative characteristics of soil and water resources,
- Identify management options that are compatible with resource's potential and constraints,
- Evaluate magnitude and trends in changes in properties and processes of soil and water resources under different systems of management, and
- Describe policy options for encouraging sustainable use of resources.

Quantification of sustainability implies precise measurement of productivity. Productivity includes all costs and benefits, including indirect costs e.g., cost of growing nitrogen through biological nitrogen fixation vs. buying nitrogen in the form of inorganic fertilizers or organic amendments, loss in productivity due to erosion caused by plowing vs. the cost of herbicides for weed control, cost of managerial skills vs. that of buying off-farm inputs, etc. These costs and benefits can be assessed by using some indices based on parameters involving plant, soil, climate and hydrology.

Indices of Sustainability

Quantification of sustainability is essential to objectively assess the impact of management systems of actual and potential productivity, and on environment. Sustainability can be assessed by one or several indices. Indices may be simple involving one parameter or complex involving several parameters. Although general principles may be the same, these indices must be fine-tuned and adapted under locales environments. Some indices of sustainability include the following:

1 Productivity (P): Production per unit of resource used can be assessed by Equation 1:

$$P = p/R \quad \text{(Eq. 1)}$$

where P is productivity, p is total production, and R is resource used.

2 Total Factor Productivity (TFP): It is defined as productivity per unit cost of all factors involved (Herdt, 1993) as per Equation 2:

$$TFP = \frac{p}{\sum_{i=}^{n} (R_i \times C_i)} \text{ --------------------------------- (Eq. 2)}$$

where p is total production, R is resource used, and C is cost of the resource, and n is the number of resources used in achieving total production.

3 Coefficient of sustainability (C_s): It is a measure of change in soil properties in relation to production under specific management system (Lal, 1991) as is defined in Equation 3:

$$C_s = f(O_i, O_d, O_m)t \text{ -------------------------------- (Eq. 3)}$$

where C_s is coefficient of sustainability, O_i is output per unit input that maximizes per capita productivity or profit, O_d is output per unit decline in the most limiting or non-renewable resource, O_m is the minimum assured output, and t is time. The time scale is important and must be carefully selected.

4 Index of sustainability (I_s): It is a measure of sustainability relating productivity to change in soil and environmental characteristics (Lal, 1993; Lal and Miller, 1993) as shown in Equation 4:

$$I_s = f(P_i * S_i * W_i * C_i)t \text{ ------------------------------(Eq. 4)}$$

where I_s is index of sustainability, S_i is alteration in soil properties, W_i is change in water resources and quality, C_i is modification in climatic factor, and t is time.

5 Agricultural sustainability (A_s): It is a broad-based index based on several parameters associated with agricultural production as defined in Equation 5 (Lal, 1993):

$$A_s = d(P_t * S_p * W_t * C_t)dt \text{ --------------------------- (Eq. 5)}$$

where A_s is agricultural sustainability, P_t is productivity per unit input of the limited or non-renewable resource, S_p is critical soil property e.g., rooting depth, soil organic matter content, W_t is available water capacity including water quality, and C_t is climatic factor such as gaseous flux from agricultural activity, and t is time.

6 Sustainability coefficient (S_c): It is a complex and a multi-purpose index based on a range of parameters, and is similar to A_s. It is defined as per Equations 6 and 7:

$$S_c = f(P_t * P_d * P_m)t \quad \text{------------------------------} \quad (\text{Eq. } 6)$$

$$S_c = d(P_i * W_t * C_t)dt \quad \text{----------------------------} \quad (\text{Eq. } 7)$$

where P_t is productivity per unit input of the limited resource, P_d is productivity per unit decline in soil property, P_m is minimum assured productivity, S_c is critical level of soil property, W_t is soil water regime and quality, C_t is climatic factor, and t is time.

The choice of an appropriate index depends on several factors (Fig. 1), most important among these are the objectives and goals e.g., production, resource management or environmental quality. In addition, land characteristics and land use are also important considerations. In general, a simple index based on one or two parameters is more relevant than a multi-parameter and a complex index.

The choice of parameters to be used in these indices is also locale specific and depends on inherent soil characteristics. The most desirable parameter is the one whose use is to be optimized or which represents the limited or the critical resource. Most relevant soil parameters to be considered are soil depth, soil structure, soil organic matter content, plant-available water capacity, soil pH, salt concentration, etc. It is the most limiting or the most critical factor that should be included in the sustainability index. Production and per capita productivity are important choices with regards to the ever increasing demand for food, feed, fuel and other basic necessities in the tropics.

III. SCALE OF ASSESSMENT OF SUSTAINABILITY

Conceptual problems in sustainability assessment can be resolved by relating the data to an appropriate scale. The data are of little use unless it refers to the scale of assessment. The assessment of sustainability can be made at different temporal, system or spatial scales.

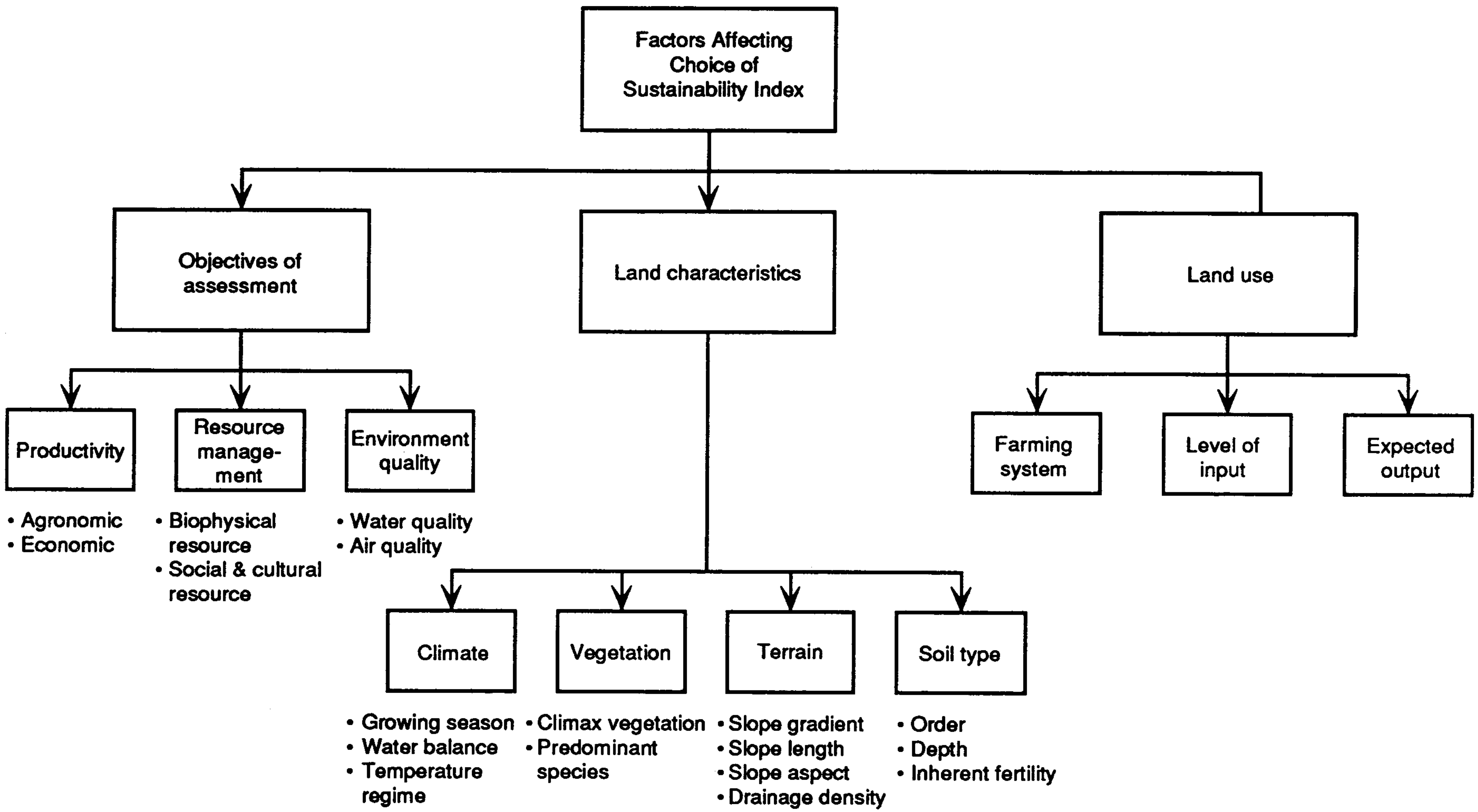

Fig. 1. Factors affecting the choice of sustainability index.

A. Temporal Scale

There are different temporal scales of assessment of sustainability. The choice of an appropriate time scale depends on the objectives. Economic assessment of sustainability is generally done on a short-term basis ranging from one to several growing seasons. In comparison, assessment of social and biophysical aspects of sustainability is better done on long-term basis spanning over several generations lasting from several decades to centuries. In general, assessment of sustainability of the biophysical resource is done over several decades. Similarly, environmental aspects of sustainability are assessed on long-term basis because it is difficult to assess environmental impact on short-term basis. Ecological studies should always be conducted over long-term basis of several decades to produce tangible results that provide guidelines for resource management. Such studies require careful planning and flexible design to accommodate future changes in treatments or management systems. Time scales for different aspects of sustainability assessment are listed in Table 1, and should be carefully chosen for specific goals and objectives.

Table 1 Time scale for assessment of different aspects of sustainability

Aspect	Time Scale
1 Economic assessment and profitability	One or several seasons
2 Yield trends	Five to twenty years
3 Soil properties	One to several decades
4 Hydrological characteristics	One to several decades
5 Ecological parameters	Several decades to centuries
6 Social and cultural aspects	Few to several generations

B. System Scales

System scales of assessing sustainability are outlined in Table 2. Genetic biodiversity is assessed at gene level, production at cropping system level, profitability at farming system level, water quality and ground water resource at watershed or aquifer level, changes in water balance or meso- and macro-climate at ecoregion or biome level, gross national product and per capita productivity at national level, and climate change at global level. Once again the choice of appropriate scale depends on the objectives.

Assessment of management induced changes in soil and water resources and their sustainability requires careful consideration for choice of appropriate temporal and system scales (Table 3). These scales vary depending on the parameter to be characterized and the objective of sustainability assessment. Meaningful results can only be obtained if measurements of chosen parameters are made at appropriate scales. Frequency of measurement of these parameters is also important, and will be discussed in a later section.

Table 2 System scales for assessment of sustainability

Aspect	System Scale
Biodiversity	Gene
Photosynthesis	Plant
Yield	Crop
Production	Cropping system
Profitability	Farming system
Water quality and ground water resource	Watershed or landscape unit
Water balance and microclimate	Ecoregion or biome
Gross national product, per capita productivity	National or political unit
Climate change at meso- and macro-scale	Regional
Atmospheric concentration of gases, ocean temperature, etc.	Global

Table 3 System scale for assessment of management-induced changes in soil properties and hydrological characteristics

Property/Process	Temporal Scale (years)	System Scale
Soil Processes		
Erosion	Five to twenty years	Hillside, watershed
Compaction	One to several seasons	Field plot, farm
Acidification	One to several seasons	Soil association
Fertility depletion	Five to twenty years	Soil association, farm
Soil Properties		
Physical properties	One to several years	Soil association, farm
Chemical properties	One to several years	Soil association, farm
Nutritional properties	One to several years	Soil association, farm
Water Regime		
Water balance	Few to several years	Landscape unit, watershed
Available water capacity	Few to several years	Soil association, farm
Water quality	Five to twenty years	Watershed, aquifer, farm
Micro-climate		
Energy budget	Ten to fifty years	Field Plot
Soil and air temperature	Few to several years	Field plot
Effective rainfall and rainfall probability	Few to several decades	Landscape

Assessment of sustainable use of soil and water resources is a capital-intensive undertaking. It is a long-term investment often involving well-designed field establishment with backup laboratory and analytical support services. The choice of an appropriate scale is crucial to the success and depends on many factors. Careful appraisal of these factors is important in deciding the choice of temporal and system scales (Fig. 2).

C. Spatial Scale

Sustainability indicators can also be assessed at different spatial scales (Table 4). However, not all indicators of sustainability can be assessed at all scales. Walker and Jones (1991) proposed a hierarchical structure by recognizing four tiers and identifying goals and specific indicators for each tier. The four-tier structure proposed by Walker and Jones included: (i) landscape characterization at tier 1, (ii) regional and national trends at tier 2, (iii) higher spatial or temporal resolution at tier 3, and (iv) process oriented research at tier 4. Consequently, the process-oriented research is generally done at microplot level with backup laboratory and analytical facilities. Alterations in soil properties due to soil and crop management systems are appropriately done at field plot scale. The objective and methodology should be clearly defined for each tier or scale.

Table 4 Spatial scales of sustainability assessment

Scale	Size	Sustainability Indicator
1 Microplot	$< 10\ m^2$	Soil properties, process-oriented assessment
2 Field plot	$10\text{-}100\ m^2$	Rill-interrill erosion, erodibility, crop response to management
3 Landscape or hillside unit	0.1-1 ha	Soil changes due to land use or cropping system, hydrological and fluvial processes, landscape characterization
4 Watershed	1-100 ha	Sediment yield, water and energy balance, water quality, micro-climate
5 River basin	Several thousands km^2	Denudation rate, water quality, meso-climate

The choice of a hierarchical system going from a lower to a higher scale is logical option to assess different indicators at an appropriate scale. Objectives of sustainability assessment are different at different scales. There is a need to synchronize scale and objective of sustainability assessments. It is prudent to collect data on several inter-related scales but more attention should be paid to local/regional scale or assessment of process-oriented indicators. Processes assessed across biomes or ecoregions are easy to generalize in relation to commonalties among biomes.

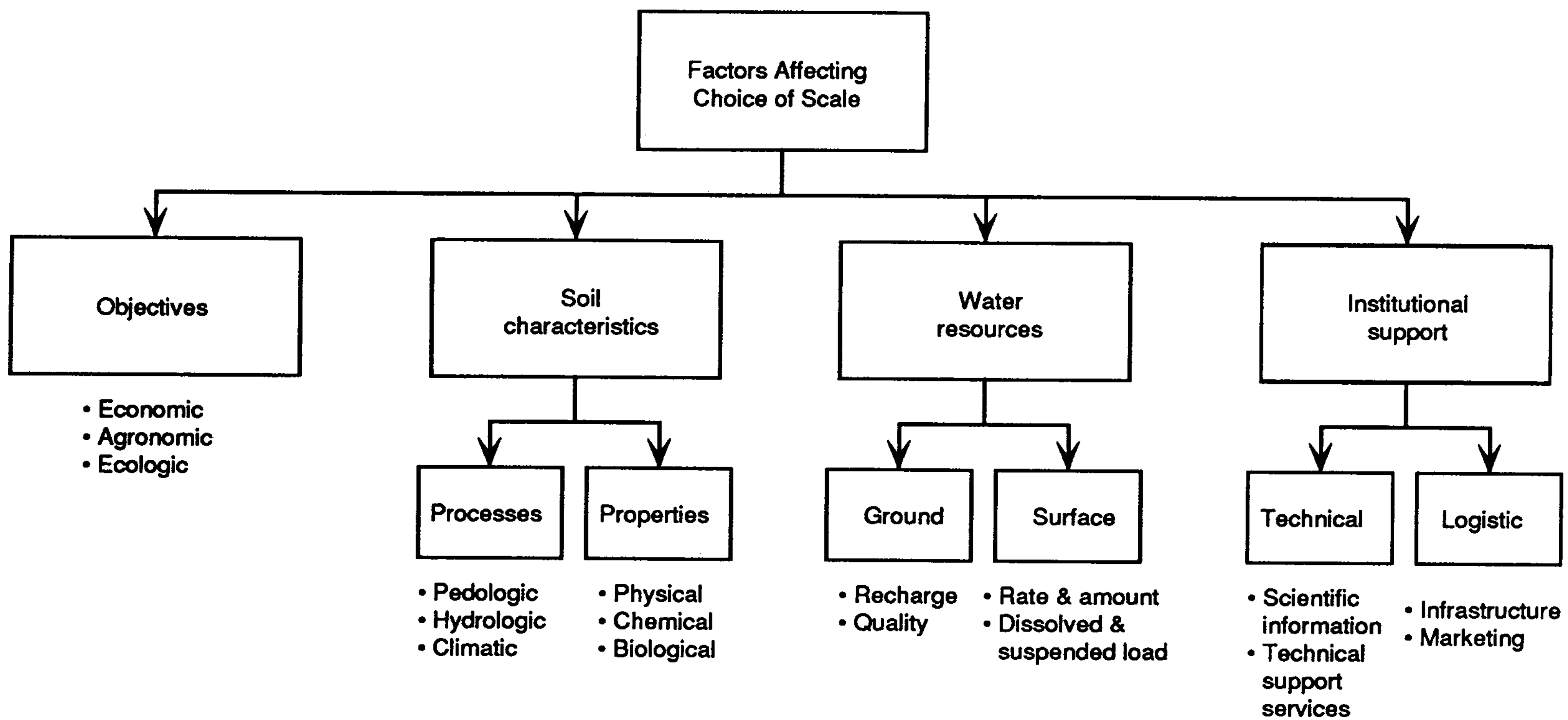

Fig. 2. Factors affecting the choice of temporal and spatial scales of sustainability assessment.

Most soil processes (e.g., runoff, erosion, compaction, leaching, etc.) are scale dependent, and are, therefore, evaluated at different temporal, systems and spatial scales. Impact of management on soil quality and processes is also scale dependent and is assessed at heterogeneous scales. Comparative evaluation of properties and processes measured at heterogeneous scales requires development of scaling rules and identification of limits to extrapolation or interpolation among scales. In some simple cases it may involve simple integration across spatial heterogeneity. In these situations, it is a matter of careful statistical sampling based on traditional methods e.g., multivariate analysis, linear filtering techniques, Bayesian hierarchical models (King et al., 1987). In other complex cases, extrapolating across scales is not simply a matter of statistics because the magnitude and nature of processes involved may also change from small to large scales. In these cases, even slight changes in scale can drastically change the processes and their impact. Consequently, scaling of these results involve complex procedures (Allen and Starr, 1982; O'Neil et al., 1986). Developing appropriate methods of prediction across scales is a researchable priority. Regardless of the scaling problem, however, use of proper statistical techniques is essential to data analyses, synthesis and interpretation. Appropriate statistical methods are outlined in several books e.g., Montgomery (1985), Ryan (1989), Gilliland (1990).

IV. SOIL SUSTAINABILITY CRITERIA OR INDICATORS

Criteria or indicators chosen to assess sustainability must have a conceptual framework. There is a broad range of indicators that can be used to assess sustainable use of soil and water resources. Walker and Jones grouped several criteria and indicators into 3 broad categories:

1 Response indicators: These are environmental characteristics and indicate biological condition of the soil resource and its productivity.

2 Sensor indicators: These are a measure of the natural processes, environmental risks or effects of management.

3 Exposure or habitat indicators: These are diagnostic indicators which provide a measure of the response indicators contact with environmental stresses.

Sustainability of soil can be assessed by periodic evaluation of indicators related to soil properties, and processes. An appropriate indicator is the one which provides a quantitative measure of the magnitude and intensity of environmental stress experienced by plants and animals. These indicators based on properties and processes can be assessed by field and laboratory analyses or predicted by modeling.

Soil sustainability can be assessed by monitoring indicators of soil quality. Attributes of soil quality assessment have been outlined and described in several reports (Anonymous, 1992; USDA, 1992; Acton, 1993). Soil survey data can also be used for assessment of soil quality and sustainable use (FAO, 1976; Bouman, 1989; Van Diepen et al., 1991). However, a clear distinction should be made between causes and factors, properties, and process that affect soil quality and its sustainability. Causes and factors that affect soil and environmental quality are driven by social factors including demographic pressure, land hunger, and social and cultural aspirations and needs (Fig. 3). These social-driven forces lead to several activities with major alterations in soil and environmental characteristics. Principal activities among these are deforestation and new land development, intensive land use especially tillage and monoculture, and use of agricultural chemicals to regulate soil fertility and minimize competitions with pests and pathogen. There is a wide range of soil properties and processes that govern soil quality (Fig. 4). Three principal categories of properties and processes are described below:

A. Soil Physical Attributes and Processes

There is a wide range of soil physical properties and processes that affect soil physical quality and health. Important soil physical properties listed in Fig. 5 are grouped under 3 attributes.

1 Mechanical characteristics: These include texture, structure and pore size distribution. These attributes influence several soil-modifying processes such as compaction and densification, crusting and surface seal formation, and water infiltration and surface runoff. Interacting with climatic characteristics, these processes may accentuate physical degradation including accelerated erosion, desertification, and denudation.

2 Hydrological characteristics: These comprise moisture retention and transmission properties, and surface and sub-soil drainage. These attributes also influence several soil-modifying processes e.g., leaching, deep drainage and interflow, and susceptibility to drought. Interacting with climate and land use these processes lead to anaerobiosis, aridization, and eutrophication of natural waters.

3 Thermal characteristics: These consist of heat capacity and thermal conductivity which interact with climate and soil moisture regime and influence soil temperature and heat flux. These attributes influence a wide range of soil modifying processes including mineralization or organic matter decomposition, microbial respiration, denitrification and soil biodiversity. Interacting with land use, management and other ecological factors these processes influence dynamics of soil organic matter content, and flux of radiatively-active gases from soil to the atmosphere.

These three mechanical, hydrological and thermal characteristics have a strong modifying effect on soil physical quality, rooting condition, and sustainability.

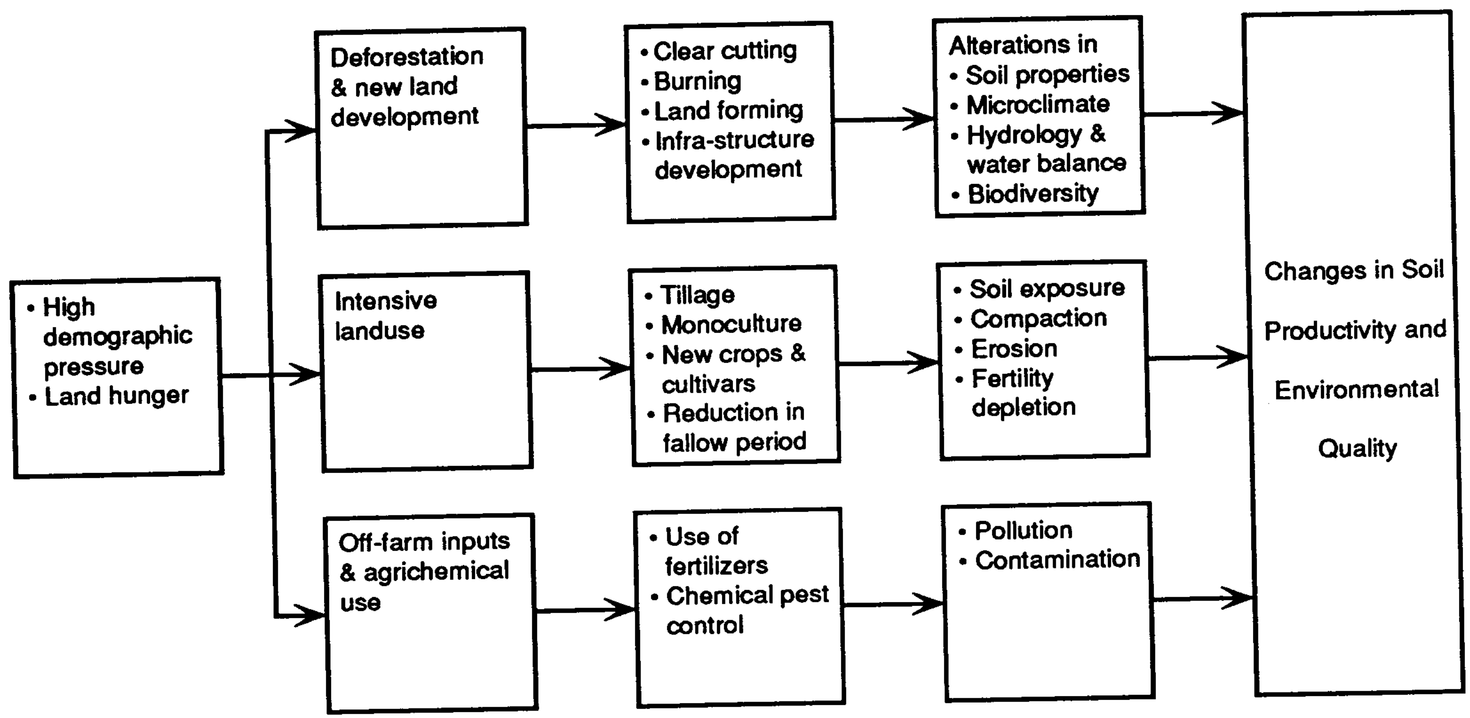

Fig. 3. Factors and causes determining soil quality and sustainability.

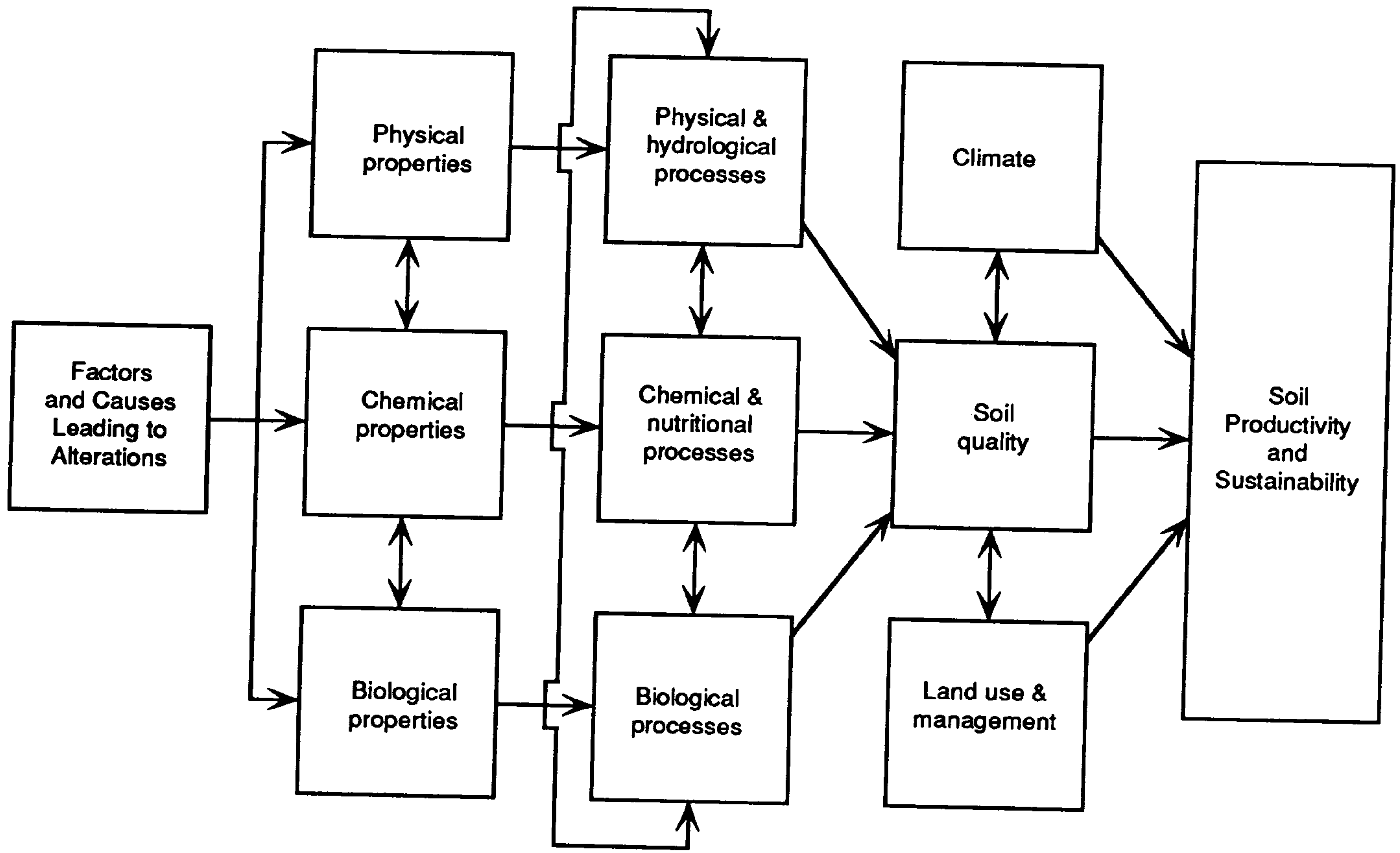

Fig. 4. Soil properties and processes in relation to soil quality and sustainability.

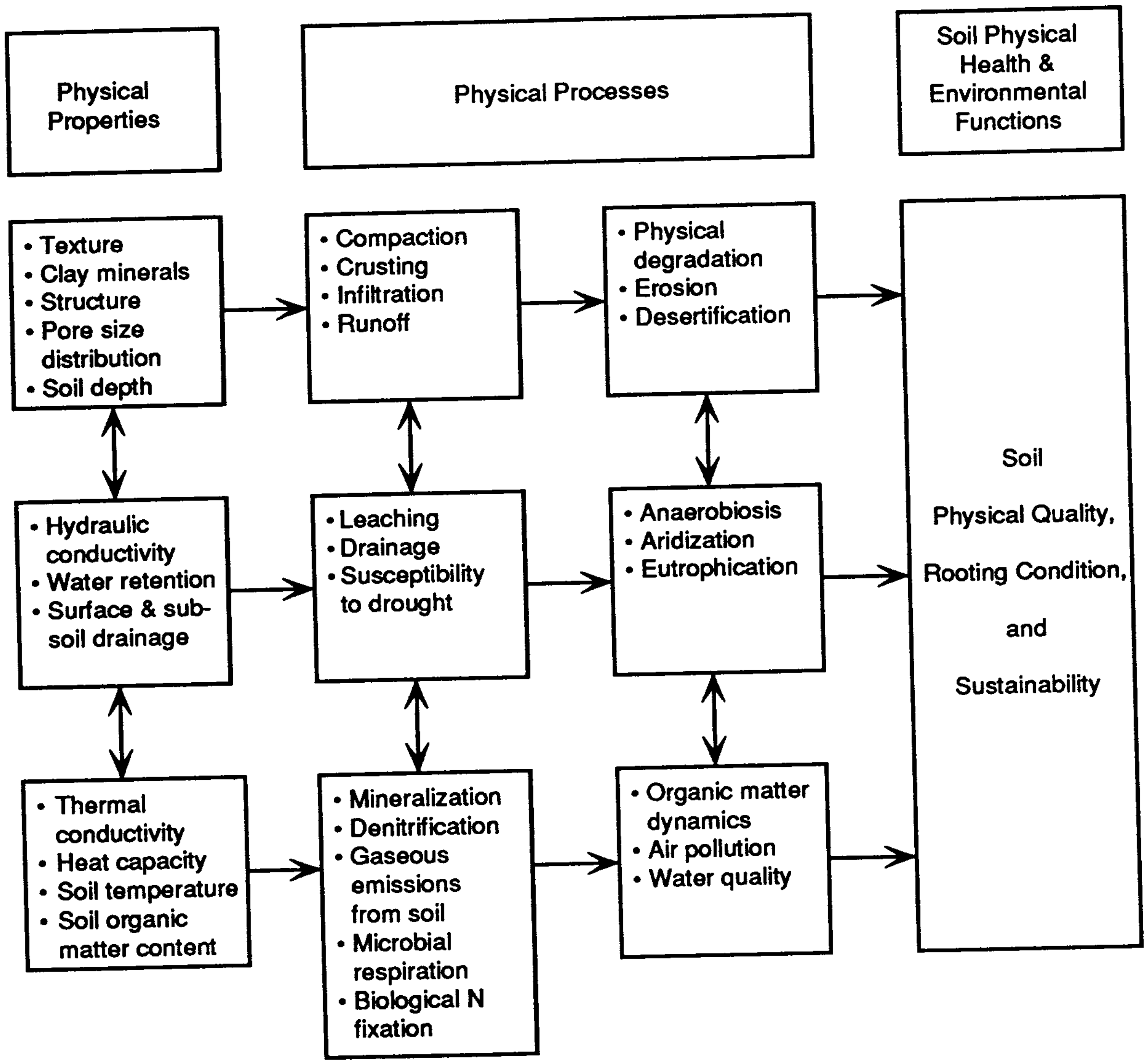

Fig. 5. Soil physical and hydrological properties and processes in relation to soil quality and sustainability.

B. Soil Chemical Attributes and Processes

Similar to soil physical and hydrological properties, there is also a wide range of soil chemical and nutritional attributes with strong influence on several soil modifying processes. Important soil chemical and nutritional characteristics listed in Fig. 6 are grouped under three categories:

1 Soil Acidity: Soil pH, total acidity, exchangeable Al, and base saturation are determinants of soil reaction. These attributes interact with climate, parent material, land use and management and influence several soil reactions including nutrient transformations, mineral weathering, and absorption and desorption processes. Alterations in and accentuation of these properties and processes, mostly due to human activities involving intensive cultivation and use of agrochemicals, lead to important soil modifying processes including acidification, calcification, eluviation, podozolization, mineral weathering and salinization. Salinization, a process that is reverse of acidification and leaching, is an important soil modifying process in arid and semi-arid regions under irrigated conditions.

2 Nutrient Capacity and Intensity Attributes: Soil nutritional attributes in terms of both capacity and intensity factors are affected by properties including cation exchange capacity, charge properties, nature and concentration of exchangeable cations, total soluble salts and electrical conductivity of saturated extract. These attributes govern direction and magnitude of several processes including leaching, osmosis and diffusion, ion exchange and nutrient absorption and desorption. Interacting with climate, land use and management these attributes influence several soil modifying processes such as nutrient dynamics including nutrient transformations and cycling, and eutrophication of natural waters.

3 Humic Properties: Soil organic matter content and total nutrient reserves are the basis of inherent soil fertility. Humic properties comprise soil organic carbon content, soil microbial biomass and the active or labile fraction of soil organic matter. These attributes influence several processes including mineralization, microbial respiration, production of organo-mineral complexes, and gaseous diffusion or fluxes from soil. Interacting with climate, land use and management, these attributes and processes influence soil organic matter dynamics, transport of carbon in natural water as dissolved organic carbon (DOC) or particulate organic carbon (POC), and emission of radiatively-active gases into the atmosphere notably CO_2, CH_4 and NO_x. Soil organic matter content plays an important role in sustainability of agricultural systems (Swift and Woomer, 1993).

These soil chemical attributes and reactions have a strong impact on several soil-modifying processes with strong influence on soil chemical and nutritional quality and sustainability under different land uses and farming systems.

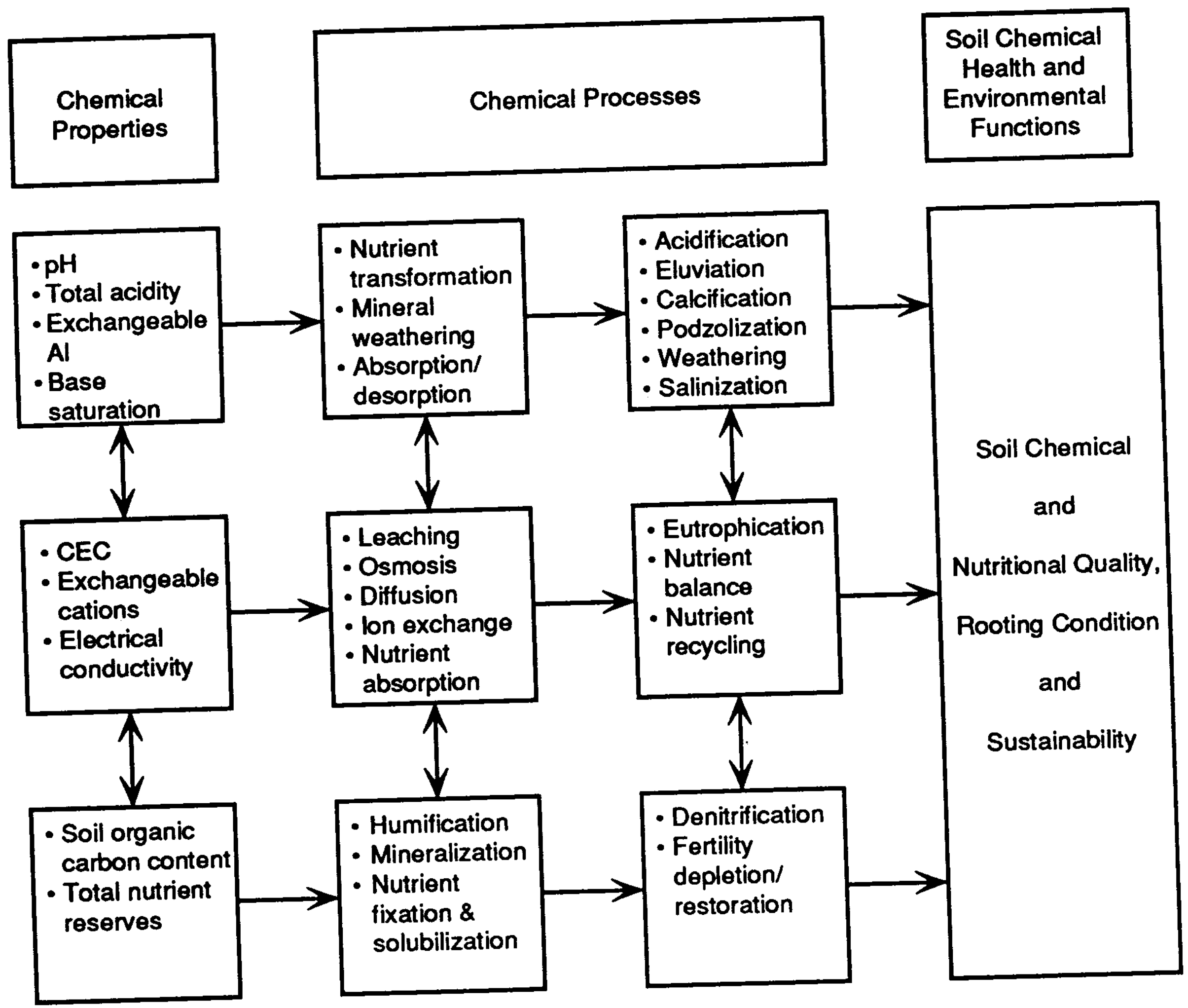

Fig. 6. Soil chemical and nutritional properties and processes in relation to soil quality and sustainability.

C. Soil Biodiversity and Biological Processes

Activity and species diversity of soil fauna and flora have an important influence on soil physical, chemical and nutritional, and biological attributes and several soil modifying processes. Important soil biological attributes listed in Fig. 7 are grouped into 3 categories:

1 Soil Macrofauna: Soil macrofauna comprises earthworms, termites, centipedes, millipedes and other large animals. Earthworm population and activity is a good indicator of soil environment that affect soil structure, soil fertility, nutrient cycling and root growth. These animals play an important role in formation and evolution of soil structure and pore size distribution. Biochannels or macropores created by the activity of soil fauna influence root growth, gaseous diffusion, and transport of water and chemicals from surface into the sub-soil horizons and ground water. Activity of soil fauna also influences nutrient cycling, decomposition of organic matter and biomass , and humic transformation. Interacting with climate, land use, and management, these attributes of soil biodiversity influence the magnitude and direction of bioperturbation, leaching and macropore flow. Macropore or bypass flow is an important process with strong influence on water quality and hydrological processes (McCoy et al., 1994).

2 Microflora: Soil microflora affects several microbial reactions in soil including microbial oxidation and respiration, biological nitrogen fixation, and several asymbiotic reactions with both positive and negative effect on soil quality, productivity and sustainability. Humification and dynamics of soil organic matter content are directly influenced by activity and species diversity of microflora. Interacting with soil physical and chemical attributes and management, these properties have strong impact on several soil modifying processes such as soil fertility enhancement and depletion, buildup of soil borne pests and pathogens including nematodes.

3 Humic Substances: Soil organic matter comprises complex biochemical substances with important influences on a wide range of soil properties and processes. Soil organic matter content includes several components such as plant residue and identifiable components (litter), and humus. There are three fractions of humic substances (Swift and Woomer, 1993): (i) soil biomass or active fraction, (ii) slow fraction, and (iii) humic, stable or passive fraction. These fractions have an important role in organic matter dynamics with significant impact on several soil-modifying processes e.g., nutrient cycling and transformations, enzymatic reactions, formation of organo-mineral complexes, etc.

This set of attributes and reactions have a strong impact on several soil modifying processes that modify and determine soil biological quality and health and sustainability of soil and water resources.

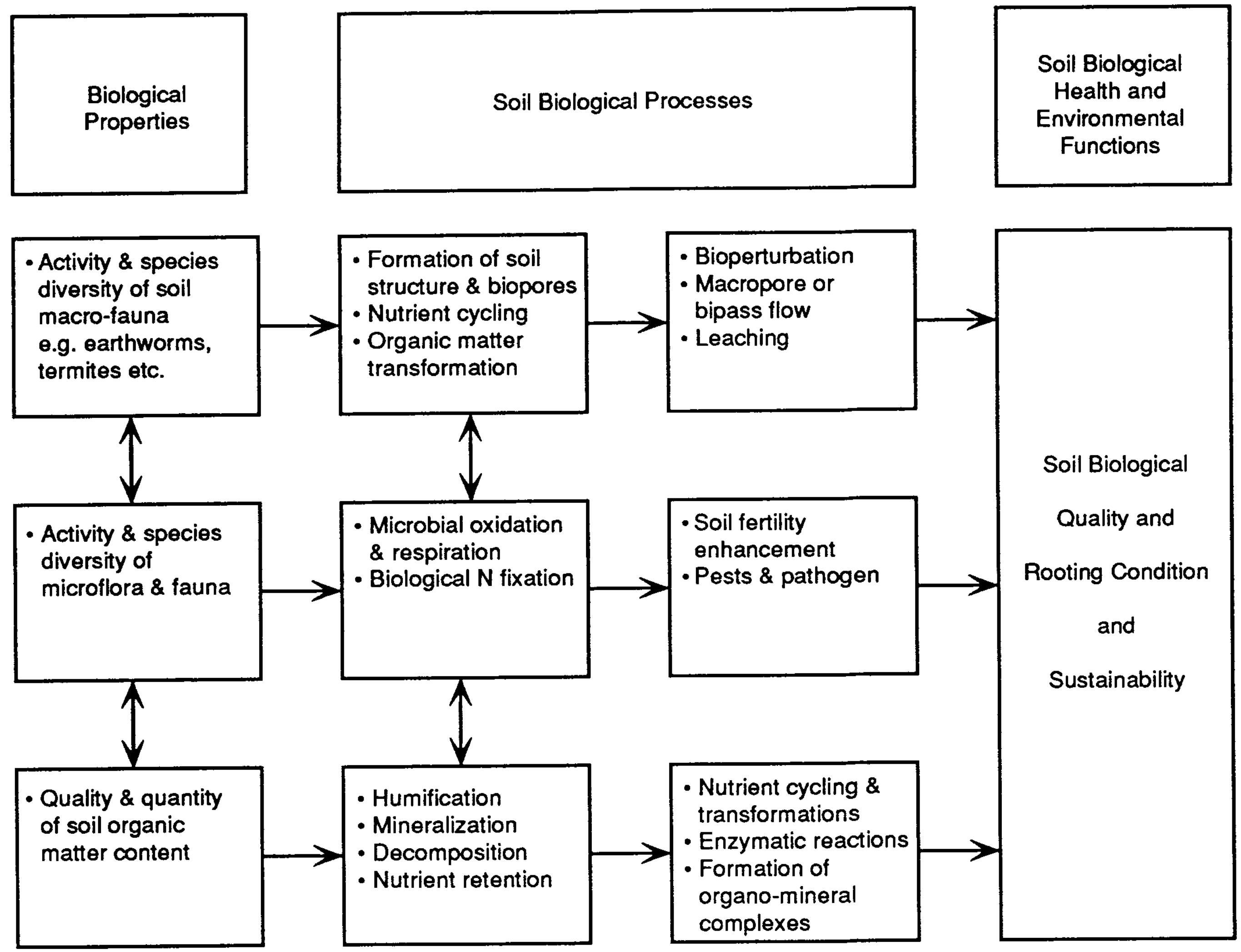

Fig. 7. Soil biological properties and processes in relation to soil quality and sustainability.

V. KEY SOIL PROPERTIES AND PROCESSES

Thorough assessment of all indicators outlined in the previous sections is neither feasible nor required. a few important indicators should be carefully chosen in relation to objectives, and properly analyzed and interpreted. Oakley (1991) outlined some desirable characteristics of indicators to be chosen with relevance to social and policy issues with emphasis on wide acceptance, simplicity to report, relevance to people's lives, and flexibility. Important and relevant characteristics to be considered for choosing soil-related indicators include the following:

1 Simple and easy to measure: An indicator or attribute should be easy to measure especially under field conditions where logistics for using sophisticated equipment and techniques may not be available.

2 Applicable across scales: Properties and processes to be measured should be preferably applicable across different scales e.g. temporal, system and spatial. For example, soil erosion processes can be measured across all three scales.

3 Extrapolatable and Predictable: Indicators chosen should be easy to predict and extrapolate to similar soils and ecoregions elsewhere. Prediction can be made on the basis of other inter-related properties or processes. This implies that relevant data required for prediction and extrapolation are readily available

4 Versatile: An indicator chosen should preferably provide a measure of several inter-related attributes and processes. The most desirable indicator should be the one that is relevant to a wide range of properties and processes including physical, chemical and biological attributes. Soil organic matter content is an example of such a versatile indicator. Infiltration rate is another process that integrates several transport properties and is related to many processes.

5 Simple to analyze and interpret: The data generated by analytical techniques should be easy to analyze and interpret in terms of diagnosing the predominant degradative processes.

6 Relevant to ecological conditions: Not all attributes are equally relevant to all biomes, ecoregions or soil orders. For example, assessment of acidification may not be relevant to calcareous soils in arid or semi-arid biomes.

7 Process oriented: Attributes and indicators chosen should be relevant to principal degradative processes observed over the watershed or biome.

Considering all factors and criteria outlined above, some suggested indicators for soil physical properties and processes are listed in Table 5, for soil chemical properties and processes in Table 6, and for soil biological properties and processes in

Table 7. These indicators provide a measure of the antecedent conditions of soil characteristics, and of the magnitude and direction of predominant processes.

Table 5 Key soil physical attributes and related processes

Attributes	Processes
Mechanical	
Texture	Crusting, gaseous diffusion, infiltration
Bulk density	Compaction, root growth, infiltration
Aggregation	Erosion, crusting, infiltration, gaseous diffusion
Pore size distribution and continuity	Water retention and transmission, root growth, gaseous exchange
Hydrological	
Available water capacity	Drought stress, biomass production, soil organic matter content
Non-limiting water range	Drought, water imbalance, soil structure
Infiltration rate	Runoff, erosion, leaching
Rooting Zone	
Effective rooting depth	Root growth, nutrient and water use efficiencies
Soil temperature	Heat flux, soil warming, activity and species diversity of soil fauna

Table 6 Key soil chemical and nutritional properties and related processes

Attributes	Processes
pH	Acidification and soil reaction, nutrient availability
Base saturation	Absorption and desorption, solublization
Cation Exchange Capacity (CEC)	Ion exchange, leaching
Total and plant available nutrients	Soil fertility, nutrient reserves
Soil organic matter	Structural formation, mineralization, biomass carbon nutrient retention

Table 7 Key biological properties and related soil processes

Attributes	Soil Processes
Earthworm population and other soil macrofauna and activity	Nutrient cycling, organic matter decomposition, formation of soil structure
Soil biomass carbon	Microbial transformations and respiration, formation of soil structure and organo-mineral complexes
Total soil organic carbon	Soil nutrient source and sink, biomass carbon, soil respiration and gaseous flux

Indicators listed in Tables 5 through 7 can be regrouped according to the criteria outlined above. This type of categorization of some relevant indicators is shown in Table 8. Principal types of response indicators include plant available nutrient and water reserves, rooting depth, soil structure and growing season duration. Some examples of sensor indicators include processes such as soil erosion, nutrient cycling, leaching. Example of exposure indicators are simple soil properties e.g., bulk density, pH, organic matter content, erodibility, CEC, etc. Exposure are diagnostic indicators include properties whereas response and sensor indicators refer to processes based on these properties.

Table 8 Functional categories of soil sustainability indicators

Functional Category	Indicators
1 Response indicators	Nutrient reserves, available water capacity, rooting depth, water balance, growing season, degree days, soil structure
2 Sensor indicators	Nutrient cycling, soil erosion, mass movement, leaching
3 Exposure indicators	Bulk density, pH, texture, organic matter content, infiltration rate, erodibility, CEC

VI. INDICATORS FOR SUSTAINABLE USE OF WATER RESOURCES

Similar to soil properties, sustainable use of water resources can also be assessed by a range of indicators. Indicators listed in Table 9 are grouped into four categories. Indicators of total amount of water resources include precipitation, surface and ground water resources, and size and recharge of aquifer. In addition to the total amount, it is also important to characterize the available water resources so that water resources are maintained or enhanced but not depleted. Indicators denoting processes relevant to sustainable use of water resources include rate and amount of runoff, deep drainage, evaporation and evapotranspiration, and process governing water recycling and ground water recharge. Water use efficiency for different land use and management systems can be assessed by evaluating losses due to seepage, evapotranspiration, area under irrigation and water use, on-farm water use and storage, etc. A wide range of indicators can be used to assess water quality. Most relevant among these are dissolved and suspended loads, concentrations of P, NO_3-N and other plant nutrients, pH, electrical conductivity and total soluble salts, algae growth, and concentrations of pesticides and other agricultural chemicals. Biological oxygen demand (BOD) and chemical oxygen demand (COD) are also good indicators of water quality.

Classification of these indicators of water quality into three functional categories is shown in Table 10. Response indicators of water quality include water budget, total and seasonal distribution of precipitation, ground water and its recharge, water yield from a catchment, and aquifer recharge. Sensor indicators of water quality include water cycling, runoff rate, evaporation and evapotranspiration, water deficit, etc. Water quality indicators fall under the category of exposure indicators. Some relevant indicators under this category include sediment concentration and turbidity, electrical conductivity and total dissolved solids, dissolved and particulate organic carbon, concentration of pathogens, etc.

Table 9 Some indicators of sustainable use of water resources

Objective	Indicator
1 Amount	Total water resources (hydrologic cycle) and different components, water table and its fluctuation, ground water recharge, water budget, flow characteristics of surface water
2 Processes	Waterlogging, runoff, deep drainage, ground water recharge, evaporation and evapotranspiration, water recycling
3 Use efficiency	Area of irrigated land, water use efficiency, seepage losses, evaporation losses, on-farm storage volume and type of water use for different purposes
4 Quality	Dissolved and suspended load, concentrations of P and NO_3, pH, electrical conductivity, concentration of pesticides in water (2, 4-D, atrazine, lindane) algae growth, aquatic microorganisms and pathogens, BOD and COD

Table 10 Categories of water sustainability indicators

Functional Category	Indicators
1 Response indicators	Water budget, total and seasonal distribution of rainfall, ground water and its recharge, water yield, aquifer recharge
2 Sensor indicators	Water cycling, runoff rate, evaporation and evapotranspiration, water deficit
3 Exposure indicators	Sediment and dissolved load, electrical conductivity, dissolved and particulate organic carbon, biological and chemical oxygen demand

Similar to indicators of soil quality, choice of appropriate indicators of water quality depend on the objective of assessing sustainability, resources and facilities available, and logistic support required to conduct these analyses. The choice of indicators also depend on land use, farming systems and ecoregion. In terms of water quality, dissolved and suspended loads and concentrations of agricultural chemicals are relevant indicators.

VII. INDICATORS OF CHANGES IN MICRO- AND MESO-CLIMATE

Climatic factors are important indicators of sustainable use of soil and water resources, because climate affects sustainability both directly and indirectly. Direct effects of climate on sustainable use of physical resources, indicated by the first concentric circle in Fig. 8, and include the amount and availability of water resources, duration of growing season based on water and temperature regimes, potential productivity as governed by quality and quantity of solar radiation and its effect on photosynthesis, and efficiency and scheduling of farm operations. Indirect effects of climate on sustainability are indicated by the outer concentric circle in Fig. 8 and include factors such as soil and environmental degradation due to harsh climate, efficiency of resource use (e.g., nutrient and water) as affected by losses, incidence of pests and pathogens, crop losses during harvest and post harvest processing, etc.

The choice of appropriate indicators of change in micro- and meso-climatic factors due to management should be made to reflect both direct and indirect effects on productivity and sustainability. A wide range of indicators outlined in Table 11 are grouped in 5 categories on basis of the dominant processes and issues concerned with sustainability. Water budgeting, needed for assessing available water resources and potential and actual productivity, can be achieved by knowing amount and seasonal distribution of rainfall, potential and actual evapotranspiration, runoff and deep drainage, and changes in soil-water storage. It is also important to define onset and duration of the growing season, net seasonal radiation, water surplus for recycling and supplemental irrigation, air and soil temperatures. Drought stress can be an important factor even in the humid and sub-humid tropics. It is especially a serious yield-limiting factor in semi-arid and arid tropics. There are several climatic factors that can be used as indicators of drought stress. Important among these are probability of rainfall at 5 to 7 day intervals, rainfall reliability and assured or expected rainfall, frequency of mid-season drought of different durations, potential and actual evapotranspiration, available soil water capacity, and soil and air temperatures. There are several climatic indicators of potential productivity. Important among these are net solar radiation, cloud cover or hours of sunshine, maximum and minimum relative humidity, diurnal fluctuations in soil and air temperatures, soil water storage capacity, and soil and air temperature. Difference in day and night air temperatures is an important factor affecting net assimilation rate in tropical biomes.

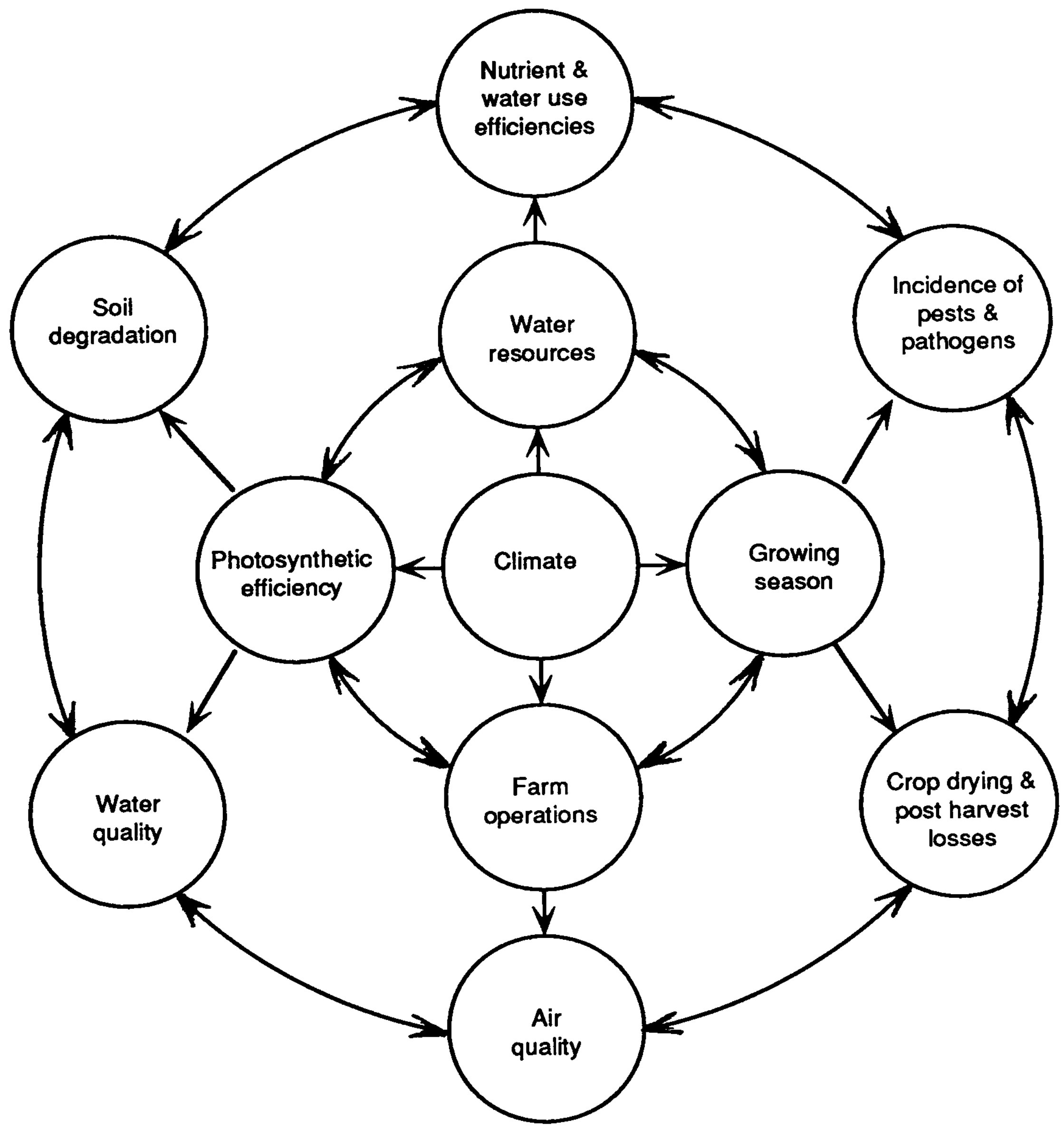

Fig. 8. Direct and indirect effects of climate on sustainable use of soil and water resources.

Table 11 Indicators of management-induced changes in micro-and meso-climate

Process/Factor	Indicators
1 Water budget	Amount and seasonal distribution of rainfall, potential and actual evapotranspiration, runoff and deep drainage, soil water storage
2 Growing season	Water budgeting, onset of rains, degree days, water cycling for supplemental irrigation, net seasonal radiation, air and soil temperature
3 Drought stress	Probability of rainfall at 5 to 7 day intervals, rainfall reliability, water budgeting frequency of mid-season drought, potential and actual evapotranspiration, available soil water capacity, soil and air temperatures.
4 Potential productivity	Net solar radiation, cloud cover, relative humidity, diurnal fluctuations in soil and air temperature, water budget, degree days, growing season duration
5 Air quality	Greenhouse gas emissions (CO_2, CH_4, N_2O, CFC's), SO_x and dust concentrations

Soil processes have also an important effect on global climate. Emissions of radiatively-active gases from soils can be substantial and affect concentration of greenhouse gases in the atmosphere. Measuring gaseous emissions of CO_2, CH_4 and N_2O can provide a useful information to that effect. In general, well-drained soils are a sink for CH_4. However, substantial amount of CH_4 may be emitted from wet soils, poorly drained soils or soils prone to anaerobiosis. Rice cultivation, a major crop in south and southeast Asia and elsewhere in the tropics, is also a major source of CH_4 emission into the atmosphere. Air pollution is also related to industrial emissions of SO_x and concentration of dust particles. Both of these factors have some indirect effects on productivity and sustainable use of soil and water resources.

Not all climatic indicators listed in Table 11 can be routinely measured especially across different scales. It is important to identify few key parameters and an appropriate scale of their measurement. Some key parameters listed in Table 12 are grouped in relation to a recommended scale of measurements. Some indicators can be measured across several scales. For example, different components of the hydrologic cycle can be assessed at different hierarchy of spatial and temporal scales. However, water use efficiency can only be assessed at cropping system or at the farming system level. Net photosynthesis and net assimilation rate can be measured at plant level. Soil and air temperatures and relative humidity can also be calculated at different temporal scales e.g., daily, monthly, or annually.

Climatic indicators can also be grouped according to different functional categories (Table 13). Response indicators of microclimate include seasonal and annual water budget, growing season duration, and degree days. Sensor indicators related to climatic risks include probability of occurrence of drought or onset and cessation of rains, or probability of crop failure due to poor seedling establishment, etc. Exposure indicators include factors such as measurements of simple climatic parameters (e.g., soil and air temperatures, relative humidity, and rainfall amount and intensity, etc.) across different temporal scales at diurnal, monthly, seasonal or annual level.

Choice of climatic indicators also depends on availability of equipment and logistic support. Because of the nature of the measurements involved, accessibility of the remote sites and availability of power and other utilities is an important consideration in choice of appropriate climatic indicators. Some climatic equipment is expensive, and requires periodic maintenance. Careful consideration should be given to these factors in establishing the climatic station for measurements of these indicators. To be cost-effective, preference should be given to those parameters that can be measured routinely and across several scales.

Table 12 Key climatic indicators and scale of their measurements

Scale	Climatic Indicators
Spatial Scale	
Watershed	Water balance including all components of the hydrological cycle, rainfall amount and distribution
Landscape	Soil water storage, runoff, microclimate in relation to slope aspect
Field plot	Soil and air temperatures, relative humidity, wind velocity and direction, net radiation
System Scale	
Cropping system	Water use efficiency, crop water use, evapotranspiration, canopy temperature
Plant	Net photosynthesis, plant-water status
Temporal Scale	
Diurnal	Mean minimum and maximum soil and air temperatures and relative humidity, pan evaporation, rainfall amount and intensity
Seasonal	Water balance, degree days, onset and end of rains
Annual	Return period of rainfall and runoff events, probability of occurrence of drought, cyclic events

Table 13 Functional categorization of climatic indicators

Functional category	Climatic indicators
1 Response indicator	Seasonal or annual water budget, growing season duration, degree days
2 Sensor indicators	Probability of occurrence of drought, onset and cessation rains, risks of crop failure
3 Exposure indicators	Mean minimum and maximum, soil and air temperatures and relative humidity, net radiation, rainfall amount and intensity. These variables can be assessed across temporal scales

VIII. CROP PRODUCTIVITY AS INDICATOR OF SUSTAINABILITY

A measure of crop productivity is a good integrator of all soil, water, climatic and biotic factors. Productivity can be assessed by several methods, some of which are listed in Table 14. It is important to assess potential vis-a-vis actual productivity. In a science-based management system, actual production may exceed potential production in soils of low inherent fertility and in harsh environments. The potential productivity, soil's productive potential within a biome, can be estimated by several models e.g., CERES (Richie et al., 1989); EPIC (Williams et al., 1984); PI (Kiniry et al., 1983; Pierce et al., 1983); and Tropical Soil Productivity Calculator (Aune and Lal, 1994). If land availability is a limiting factor, appropriate indices of productivity are Land Use Factor (L), Land Equivalent Ratio (LER), and Area Time Equivalent Ratio (ATER), etc. The Land Use Factor (L) is defined as the ratio of cropping period C plus fallow period F to cropping period C (Okigbo, 1978).

$$L = \frac{C + F}{C} \qquad \text{(Eq. 8)}$$

The factor L is generally high for low intensity systems e.g., shifting cultivation. The LER is calculated as follows (Willey and Osiru, 1972):

$$LER = \sum_{i=1}^{n} \left(\frac{Y_i}{Y_m}\right) \qquad \text{(Eq. 9)}$$

where Y_i and Y_m are yields of component crops in the intercrop and monoculture system, respectively, and n is the number of crops involved. Because crops involved vary widely in their maturity period, ATER index considers the crop duration (Hiebsch and McCollum, 1987):

$$ATER = \frac{1}{t}\left[\sum_{i=1}^{n} \left(\frac{d.\,y_i}{y_m}\right)\right] \qquad \text{(Eq. 10)}$$

where d is the growth period of the crop in days and t is the time in days for which the field remained occupied i.e., the growth period of the longest duration crop. Numerical value of ATER approaches that of LER for a mixture consisting of crops of approximately identical growth periods i.e., when t = d in Eq. 10. In comparison, productivity can also be expressed in terms of the resource use efficiency of the most limiting resource e.g., water, nutrients, energy or labor.

In addition to indicators of agronomic productivity outlined in Table 14, there are several indicators of economic productivity. Most commonly used economic indicators include benefits-cost ratio, yield or profit trends over time, supply vs. demand, total or component profit, farm budget and its trends over time, etc. Produce quality is another indicator of productivity. Quality can be expressed in several ways including cooking quality, taste quality, nutritional quality, or visual quality based on grain color or size.

Table 14 Indicators of agronomic productivity

Indicator	Scale and Objectives of Measurement
1 Total biomass	Expressed per unit area, per unit time or both
2 Agronomic yield	Calculated per unit area, per unit time or both
3 Economic yield	Determined in terms of net returns
4 Resource use efficiency	Computed in terms of water, nutrient or energy use efficiency
5 Potential vs. actual productivity	Potential productivity depends on inherent characteristics, inputs and management
6 Land equivalent ratio (LER)	Expressed as a measure of the intensity of land use
7 Cropping intensity	Computed as numbers of crops grown per year on the same piece of land
8 Area time equivalent ratio	Considers growth duration of each crop in a mixed cropping system
9 Energy flux	Total energy (caloric value) produced
10 Thermodynamics	Energy produced per unit of energy input

The choice of productivity indicators should be based on the objectives. For assessing sustainable use of soil and water resources, indicators of agronomic productivity are relevant and easy to compute. Total biomass production, agronomic yield, harvest index, and agronomic yield expressed in terms of nutrient or water use efficiency are all useful and relevant productivity indicators.

In addition to productivity, there are several plant indicators of sustainability. Plant indicators include crop or plant stand as expressed by leaf area index or canopy cover, crop vigor as determined by height or dry matter produced at specific growth stages, crop nutrient status as evidenced by symptoms of nutrient sufficiency or deficiency, incidence of disease and weeds.

IX. SOIL AND CROP MANAGEMENT INDICATORS

Sustainability of soil and water resources can also be assessed from the trends in amount and nature of off-farm inputs required to produce yields equivalent to that obtained before, and the degree of managerial skills needed to alleviate soil and crop related constraints to obtain the desired yield level. In general, the more the inputs required to produce the same yield, the less sustainable is the system (Fig. 9). Need for excessive managerial inputs to produce the same yield is indicative of soil degradation. In contrast, science-based management in relation to the expected yield is indicative of soil maintenance or enhancement. Timing of farm operations is another useful management indicator. All other factors remaining the same, farm operations done on schedule are indicative of sustainable use of soil and water resources. Delayed farm operations, due to wet soil or excessive tillage needed to prepare optimum seedbed, are indicative of non-sustainable use of soil and water resources.

X. RESOURCE BASE INDICATORS

The magnitude and nature of soil and crop management inputs required to produce the expected output are indicative of the condition or quality of the resource base. The more the inputs required, the poorer the resource base. There is a wide range of indicators of resource base, depending on the specific issues concerned. The resource base is a generic term involving all natural resources e.g., biophysical, socio-economical, and cultural. This report is concerned only with soil, water, and to a lesser extent vegetation components of the biophysical resource. Resource base indicators deal with broader issue of the overall resource use rather than with inherent properties of soil, water or vegetational components. Some important resource use indicators described in Fig. 10 are grouped under 4 broad categories:

1 Landuse indicators: A system is sustainable only if the land use is compatible with land use capability. An incompatible land use is bound to set-in-motion land degradative processes. Landscape diversity is another useful indicator of sustainability. Diverse landscape type is indicative of a sustainable land use. Land forming to remove diverse landscape type may lead to an unstable and an unsustainable landscape. Alternative and diverse land uses, within its land use capability, are also compatible with sustainable land use system. Using science-based technological options to harness benefits of alternative land uses is compatible with sustainable use of the resource base.

2 Land resilience indicators: Land degradation is an ecological disaster born of land misuse and mismanagement. Land resilience dwindles when degradative processes are set-in-motion. Appropriate land resilience indicators can be used to assess sustainability of the resource base. A common indicator of land resilience is the type(s), and intensity of degradative processes. Soil physical and hydrological degradative processes include compaction, hard setting, gullying and mass wastage, and frequent floods. Active gullying is indicative of an unsustainable land use. Soil chemical and nutritional degradation include fertility depletion and nutrient imbalance including toxicity (e.g., Al, Mn, etc.) and deficiency (e.g., N, P, K, Ca, Zn, S, etc.) of essential plant nutrients. Biological degradation may refer to vegetation, soil fauna and flora, and lack of biodiversity in general. Predominance of perennial and obnoxious weeds is also a symptom of lack of biodiversity and an unsustainable system. Low activity or absence of earthworms, termites and other soil macrofauna is also indicative of poor biodiversity and degradation of resource base. In terms of soil, biological degradation implies decline in soil organic matter content and the biomass carbon.

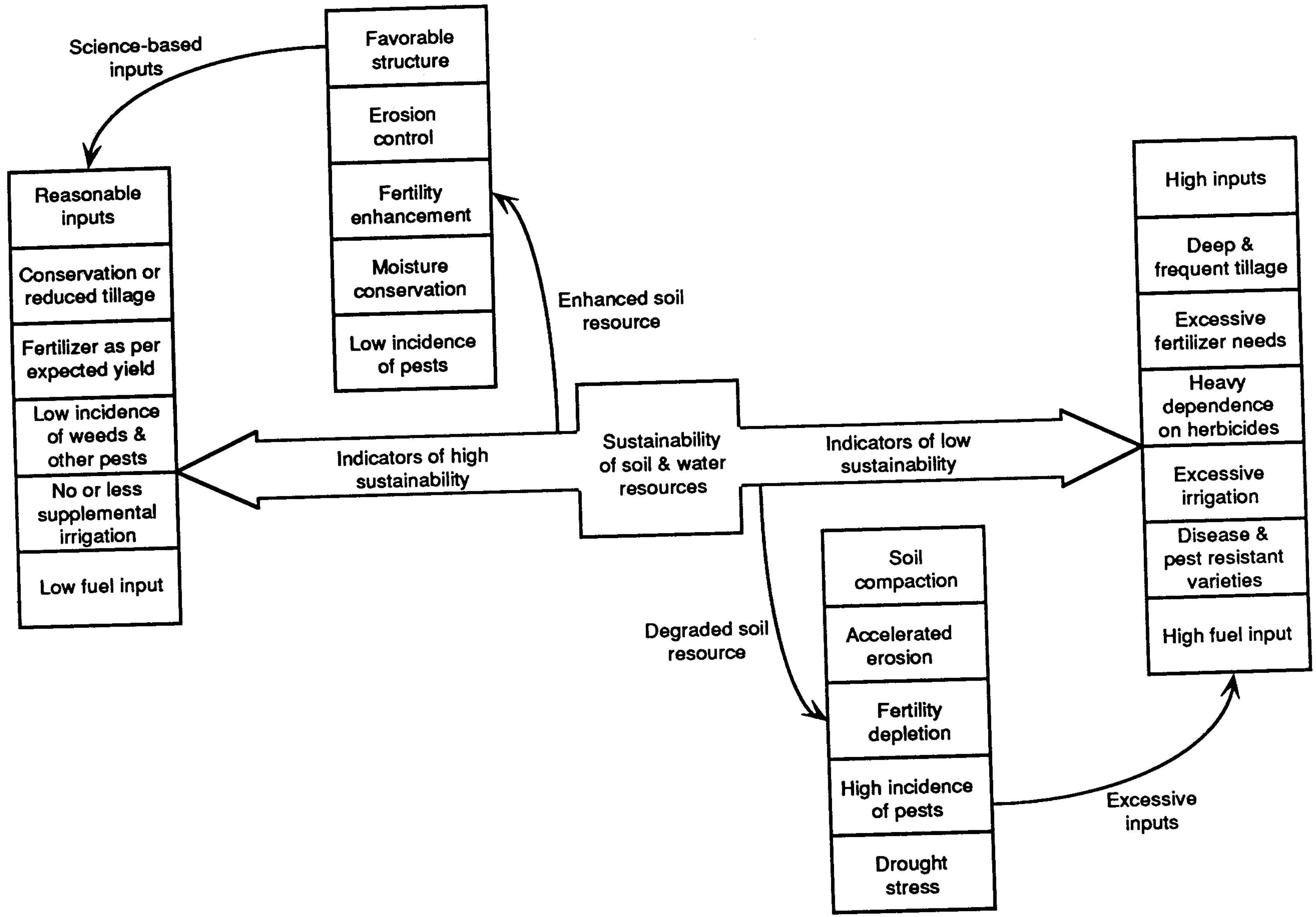

Fig. 9. Soil and crop management indicators of sustainability.

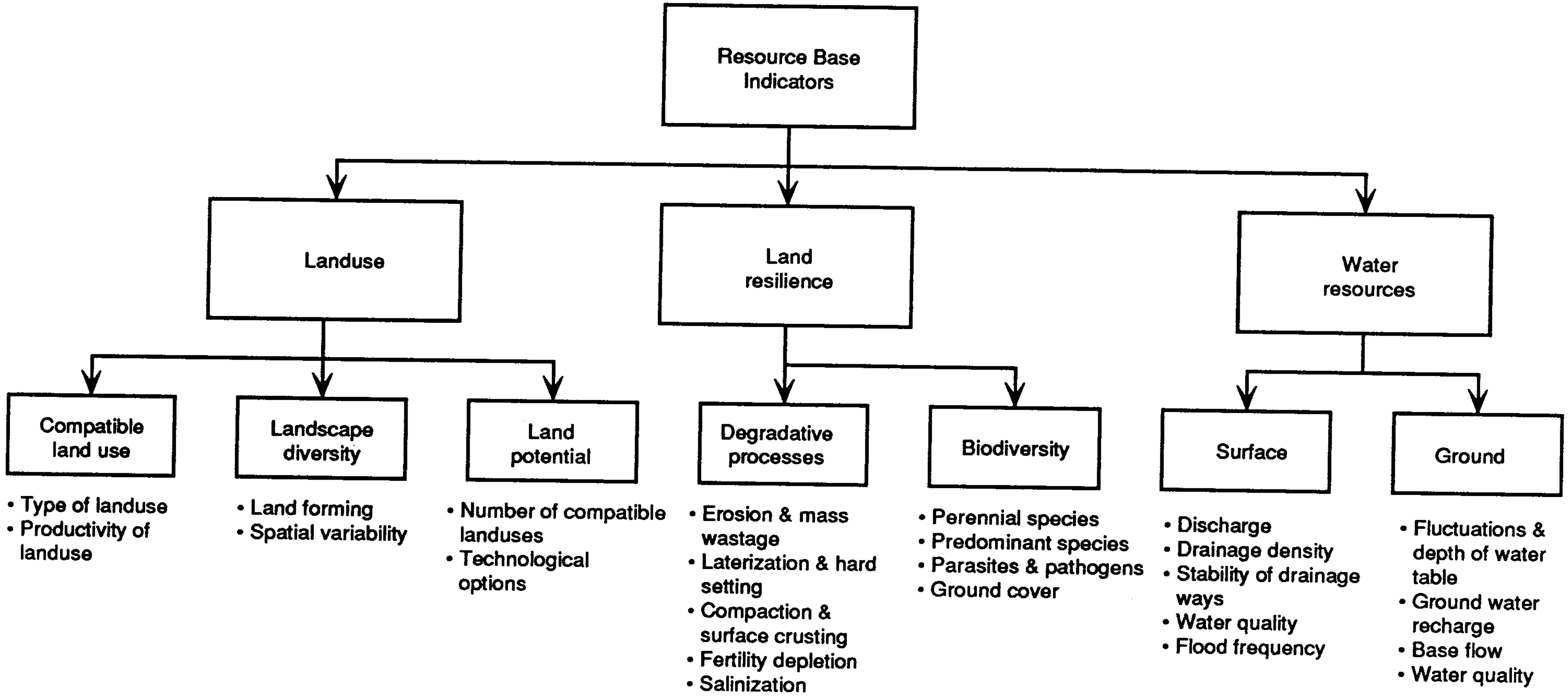

Fig. 10. Resource base indicators of sustainable use of soil and water resources.

3 Water resources indicator: Adequate water supply is an essential prerequisite of a sustainable resource base. Both surface and ground waters, in amount and quality, are important to sustainability. Surface water and amount and quality can be assessed from total discharge, and flood peak and frequency, drainage density, stability of drainage ways and stream banks, and water quality as indicated by nature and amount of suspended and dissolved loads. There are similar indicators of ground water quality.

4 Process-oriented indicators: Soil, water or environmental indicators can also be chosen relevant to the predominant land degradative process. Process-oriented indicators are especially useful for defining a restorative strategy and considering possible land use management options. Some process-oriented indicators are shown in Fig. 11. It is a useful strategy to conduct reconnaissance survey of some visual indicators prior to undertaking detailed measurements of soil and water characteristic. For example, severity of soil erosion can be assessed from soil color, stoniness of the soil surface, exposure of roots and other permanent fixtures. Similarly, coil compaction and anaerobiosis can be qualitatively assessed from water stagnation, mottling, and presence of some indicators plants. Growth of some indicator plants tolerant to specific situation is useful guideline e.g., hydromorphic species growing in wetlands, halomorphic plants growing in salt-affected soils, aluminum-tolerant species growing in acid soils, or simply poor crop stand and stunted growth in areas prone to specific degradative processes. High species diversity may also be important to a sustainable land use.

Vegetation and climate are also important components of the resource base. While climate indicators have been discussed, assessment of vegetation biomass and net productivity are also relevant measures of sustainability. These important aspects are not addressed in this report, however.

XI. SUSTAINABILITY INDICATORS FOR DIFFERENT ECOREGIONS

Resource constraints to sustainable use of soil and water resources are different for different ecoregions. Consequently, soil and water indicators also differ among ecoregions (Fig. 12).

1 Humid tropics: Soil acidity, low soil fertility, and toxic concentrations of Al and Mn in the root zone are principal soil-related constraints in the humid tropics. In addition, some soils also have poor structure and are prone to compaction and erosion. Frequent and heavy rains, low radiation, and heavy cloud cover pose serious problems to arable land use in these regions (Fig. 12).

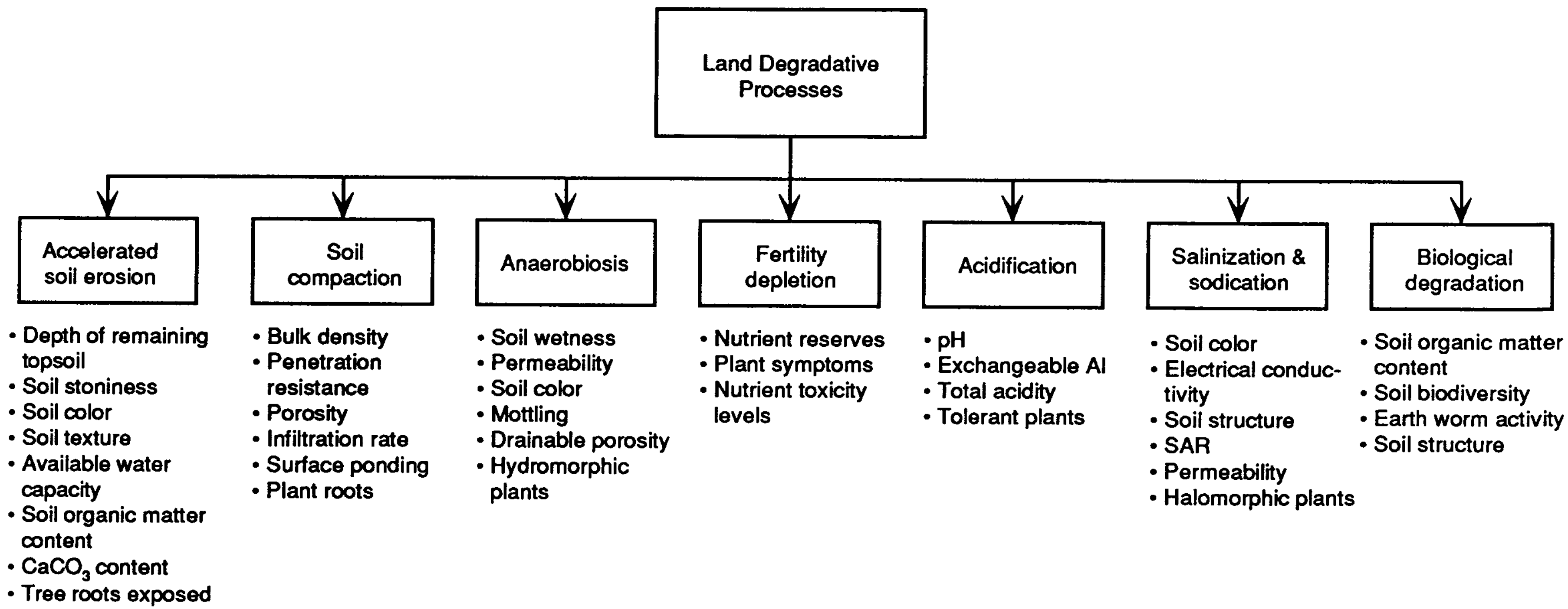

Fig. 11. Soil, water, and plant indicators in relation to predominant degradative processes.

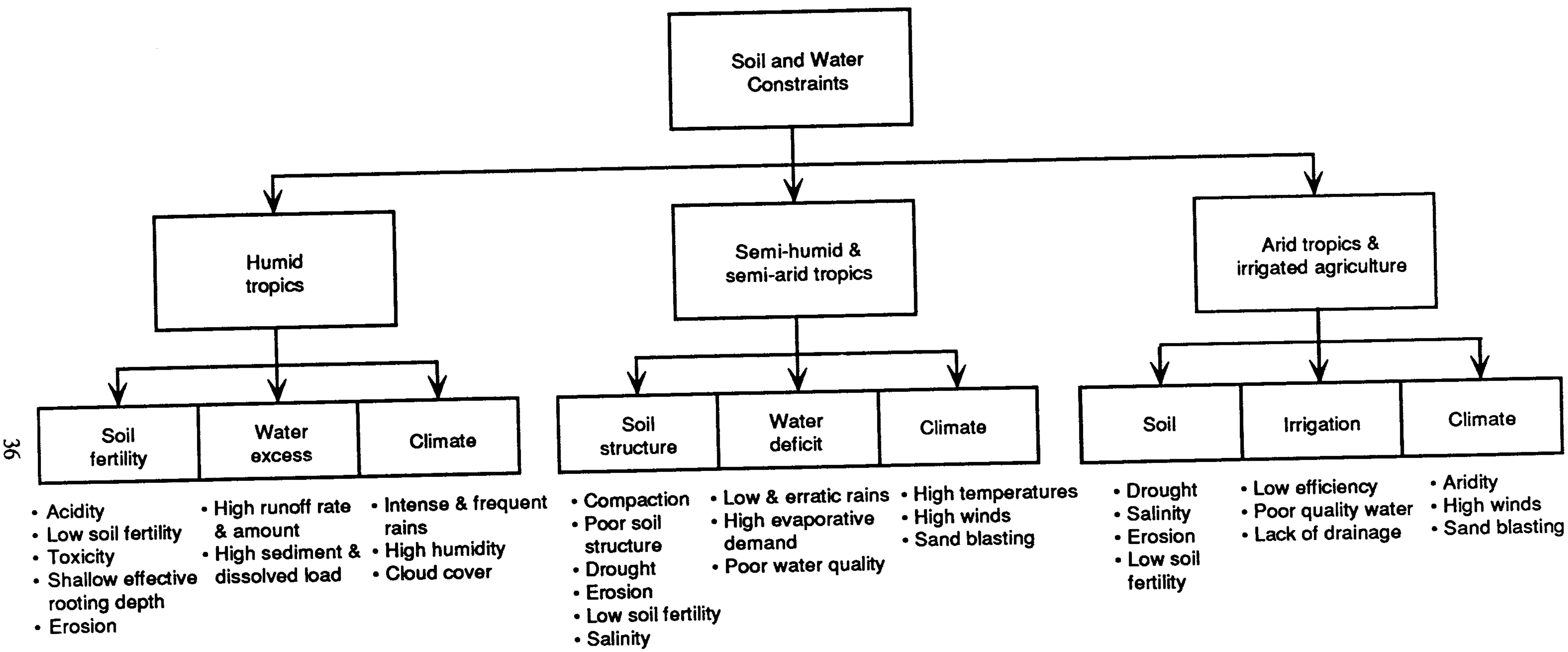

Fig. 12. Biophysical constraints to sustainable use of soil and water resources in the tropics.

Soil and water indicators for sustainable use of natural resources in the humid tropics listed in Table 15 are grouped under three categories. Soil indicators, in accord with soil-related constraints, include: (i) pH and related parameters of soil reaction e.g., total acidity, exchangeable Al and Mn, and base saturation; (ii) measure of soil fertility e.g., total and available concentration of plant nutrients, soil organic matter content, and activity and species diversity of earthworms; (iii) soil structure and related parameters e.g., percent water stable aggregates, mean weight diameter of aggregates, soil strength, bulk density, porosity and pore-size distribution, and effective rooting depth; (iv) plant-available soil water capacity, and infiltration rate; and (v) soil erosion. These indicators are listed in the order of priority. Highly weathered and leached soils of the humid tropics have comparatively more soil fertility and nutritional constraints than soil physical constraints.

Table 15 also lists indicators for water and climatic factors. Principal water indicators include: (i) components of water balance comprising runoff rate and amount, interflow, soil-water storage, and water deficit; and (ii) water quality as determined by concentration of dissolved and suspended loads, and type and concentrations of agricultural chemicals. There are two categories of important climatic indicators including: (i) rainfall characteristics comprising amount, intensity, erosivity, and return period; and (ii) energy budget based on net solar radiation, soil and air temperatures.

Table 15 Indicators of soil and water sustainability for the humid tropics

Processes/Parameters	Indicators
Soil	
Acidification	pH, total acidity, base saturation, exchangeable Al and Mn.
Soil fertility	Total and plant available N, P, K, Ca, Zn, S, soil organic matter content, and activity and species diversity of earthworms and termites.
Soil structure	Aggregation, mean weight diameter, bulk density and strength, porosity and pore size distribution, erodibility, rooting depth
Soil water	Available water capacity, infiltration rate, saturated and unsaturated hydraulic conductivity
Soil erosion	Potential risks and actual erosion rate under different management systems, soil loss tolerance, erosion and crop productivity
Water	
Water balance	Runoff rate and amount, interflow, soil water storage, water deficit
Water quality	Dissolved and suspended loads, type and concentration of agricultural chemicals, eutrophication
Climate	
Rainfall	Intensity and amount, rainfall distribution erosivity, return period
Energy budget	Net solar radiation, and soil and air temperatures, energy budget

2 Semi-humid and semi-arid tropics: Three categories of indicators relevant to semi-humid and semi-arid tropics are listed in Table 16. In these ecoregions, soil-related constraints to agricultural production and environmental quality are different than those of the humid tropics. Soil physical constraints of poor soil structure and drought stress are comparatively more severe problems than soil chemical and nutritional constraints. Consequently soil indicators include those which reflect these factors comprising: (i) compaction and hard-setting and soil surface features e.g., crusting, cracking, etc.; (ii) soil erosion by water and wind and related factors; (iii) drought stress as reflected by available water capacity and effective rooting depth; (v) soil fertility measured in terms of soil organic matter content and concentrations of total and plant-available essential nutrients; (vi) activity and species diversity of soil invertebrates notably termites; and (vi) soil salinity and relevant parameters e.g., electrical conductivity, total soluble salts, and sodium absorption ratio (SAR), etc. Stoniness, both quartz and concretionary skeletal material, is an important and often adverse factor for crop production in soils of these regions. Size distribution and concentrations of stones are good indicators of soil characteristics and potential management constraints.

Water and climatic indicators for semi-humid and semi-arid ecoregions also reflect the relative importance of drought stress in these ecoregions. Consequently, water indicators include components of: (i) water balance to provide a measure of water deficit and probability of occurrence of drought of different duration and intensity; and (ii) water quality comprising electrical conductivity, and concentration and nature of soluble salts present in surface and ground waters. Climatic indicators are those related to: (i) energy budget especially soil and air temperatures and evaporative demand; and (ii) wind velocity and prevalent direction as related to potential wind erosion hazard.

3 Arid tropics: Drought stress and resource degradation are the predominant constraints to sustained use of soil and water resources in arid ecoregions. Consequently, three groups of indicators listed in Table 17 prioritize these constraints. Important soil indicators include: (i) drought stress as measured by water balance, growing season duration, surface and ground water resources and water quality; (ii) soil salinity in relation to electrical conductivity, concentration and nature of soluble salts in the root zone, and plant indicators of the degree of salinity; (iii) wind erosion in relation to soil texture and structure, sand dune stability, and sand blasting effect on young seedlings; and (iv) soil fertility factors comprising pH, total and plant-available nutrients, and rooting depth.

Table 16 Indicators of soil and water sustainability for semi-humid and semi arid tropics

Processes/Parameters	Indicators
Soil	
Compaction and hard setting	Crust strength, bulk density, penetration resistance, porosity and pore size distribution, infiltration rate, cracking patterns and intensity
Soil erosion	Magnitude of wind and water erosion, and rate of gully advance, soil erodibility, erosion-productivity relationship, soil loss tolerance
Soil Structure	Aggregation and aggregate stability, pore size distribution
Drought stress	Available water capacity, rooting depth, water deficit, probability of drought during the season
Soil fertility	Soil organic carbon, total and plant available macro- and micro nutrients
Soil fauna	Activity and species diversity of termites
Salinization	Electrical conductivity, SAR, total soluble salts
Particle size distribution	Stoniness, texture
Water	
Water balance	Water deficit, water balance on weekly basis
Quality	Concentration and nature of soluble salts in surface and ground waters, sediment load, eutrophication
Climate	
Rainfall	Onset and cessation of rains, growing season
Energy budget	Soil and air temperatures, evaporative demand
Wind	Wind velocity and direction, sand blasting

Water availability for plant and animals being an important constraint, irrigation related characteristics are important indicators of sustainability in the arid tropics. These indicators include: (i) design efficiency in relation to losses due to seepage and evaporation, crop water requirements at critical phenological stages of growth, and irrigation scheduling; (ii) drainage characteristics of soil profile and landscape affect salinity risks as indicated by waterlogging and soil wetness, drainage outlet, and possibility of recycling of drainage water for irrigation and other on-farm uses; and (iii) water table characteristics comprising level and fluctuations, aquifer recharge, and water quality especially in relation to risks of salinization.

Important climatic indicators are also related to aridity and drought stress (Table 17). Climatic indicators for arid ecoregions include: (i) evaporative demand as reflected by soil and air temperatures, solar radiation, relative humidity; (ii) wind characteristics comprising wind velocity, and prevalent direction; and (iii) air quality especially in relation to dust concentration.

Table 17 Soil and water indicators for the arid tropics and irrigated agriculture

Processes/Parameters	Indicators
Soil	
Drought	Water balance, growing season, surface and ground water resources, water quality, soil and air temperatures
Salinity	Salt concentration in the root zone, nature of salts and SAR, drainage and leaching of salts, plant indicators for salinity
Erosion	Wind erosion, texture and structure, compaction, sand dune movement and stabilization, sand blasting of seedlings
Soil fertility	pH, total and plant available nutrients, rooting depth
Surface stoniness	Size and concentration of stones and concretions
Irrigation	
Type and availability	Design efficiency, crop water requirement, scheduling irrigation
Drainage	Profile drainage, surface drainage features, drainage outlet, waterlogging, recycling of drainage water
Water table	Level and fluctuations in water table, and aquifer recharge
Climate	
Aridity	Evaporative demand, soil and air temperatures, relative humidity
Wind	Wind velocity and duration

The minimum data set for each biome/ ecoregions may be different because of differences in environmental constraints. The minimum data set should be sufficient to indicate differences between management-induced degradation vs. irreversible degradation in soil and water characteristics. Furthermore, the minimum data set also depends on locale specific factors including institutional facilities and backup support. The minimum data set for three ecoregions are listed in Table 18. Important indicators are those that can be measured across spatial, system and temporal scales. The minimum data set for different ecoregions are based on: (i) soil fertility and nutritional constraints for the humid tropics, (ii) poor soil structure and adverse physical conditions leading to soil erosion, and degradation, and salinization for semi-humid and semi-arid tropics, and (iii) drought stress, wind erosion, and sand dune migration for the arid regions.

XII. METHODS OF ASSESSMENT OF INDICATORS

The minimum data set, reported for soil quality assessment (Lamp, 1986; Wagner et al., 1991) is also applicable for sustainable assessment of soil and water use. The minimum data set outlined in Table 18 can be obtained by a wide range of methods. However, precision, accuracy, and data credibility and reliability are important considerations in choice of appropriate methods of indicator assessment. Furthermore, the analytical procedures must be standardized so that comparative evaluation can be done for different sites and ecoregions. It is also important that indicators of soil and water sustainability are related to the principal objectives of evaluating changes in these characteristics due to differences in land use and management systems. Suitable indicators should also reflect time trends in these characteristics under different management systems. Relevant criteria for choice of suitable methods are outlined in Table 19. Important considerations are objectivity, credibility, relativity, efficiency, simplicity, sensitivity, and reflectivity in relation to management effects. In addition, analytical methods must consider spatial variability in indicators, both systemic and random. Sampling procedures adopted must ensure representativeness of the site and ecoregional characteristics.

Table 18 The minimum data set needed for soil quality assessment for principal ecoregions in the tropics

Humid	**Semi-humid/semi-arid**	**Arid**
pH, acidity, base saturation	Soil structure, bulk density, compaction, soil tilth	Plant available water, rooting depth, soil tilth, soil compaction, crusting
Bulk density, soil tilth, infiltration rate, available water capacity	pH, soil organic matter content, plant available nutrients	Soil and air temperatures, evaporative demand, wind velocity
Runoff rate and amount, water erosion	Erosion by wind and water, gully erosion	Surface and ground water and water quality
Rainfall amount and intensity, net radiation, soil temperature	Water balance, runoff	pH, plant available nutrients
	Total salinity, and types of salts	
	Soil and air temperatures, wind velocity, growing season	

Table 19 Criteria for choice of suitable methods of soil and water analysis

Factor	**Description**
Objectivity	The data obtained is in accord with objectives
Credibility	Accuracy, precision, and reliability
Relativity	Comparative analyses among sites and ecoregion based on standard methods
Efficiency	Cost-effectiveness, simple and routine procedure
Simplicity	Easy to use based on simple equipment, easy to maintain, and simple to analyze and interpret the data
Temporal changes	Time-trends in indicators are important to sustainability
Management effects	The data reflect land use management effects, and is sensitive to land use and soil and crop management systems
Sensitivity analyses	Interpretive analysis is important for decision making especially with regards to land use, cropping systems, and inputs
Variability	Sensitivity to spatial variability in indicators is important for comprehensive analyses and assessment of soil characteristics
Complementarity	Compatibility and accord with the existing data base, and complementarity with existing facilities and equipment

Measurements of indicators should be done on well designed and properly implemented long-term soil management experiments. Long-term experiments are those that are conducted with same management treatments on the same land for at least 10 consecutive years, preferably for several decades. Trends in management-induced differences in soil and water indicators, caused by environmental stress to varying degrees imposed by different treatments, can only be quantified if these treatments are continued on long-term basis. There are a few long-term experiments in the tropics (Lal and Stewart, 1994). However, it is important that not only existing experiments are maintained and continued but also new experiments are initiated to fill in the knowledge gaps for important ecoregions and management systems. Soils and ecoregions in the tropics in which such long-term experiments need to be continued or initiated are listed in Table 20. New sites are to be carefully selected to enhance complementarity and compatibility with existing sites. There is a conspicuous lack of appropriate sites in Southeast Asia, West Asia and North Africa, Central and West Africa, Central America, and South America. In collaboration with international organizations (FAO, UNDP, World Bank) and CGIAR centers, national agricultural research institutes (NARIs) should be encouraged to establish such experiments and ensure their continuity. Effective networking and coordination is essential to developing cost-effective management and ensuring complementarity of the data obtained.

Table 20 Suggested sites for long-term soil and water management experiments in the tropics

Ecoregion	Soil Order	Geographical Region
Humid	(i) Oxisols, Ultisols	Amazon basin, Congo basin, Southeast Asia
	(ii) Andisols	Central America
	(iii) Alfisol	Brazil, West Africa, China
Semi-humid and semi-arid	(i) Alfisols	West Africa, Central India
	(ii) Vertisols	East Africa, Central India, Sudan
Arid	(i) Aridisols	Sub-Saharan Africa, Northern Africa
	(ii) Psamments	West Africa, West Asia

A. Assessment of Soil Physical Indicators

Most soil physical attributes should either be measured *in situ* under field conditions, or on intact cores. Measurement of water retention, water transmission and structural properties are preferably done under field conditions. Because of high spatial variability (Cassel, 1983) and changing soil properties in the process of obtaining samples, it is important that correct procedures are followed for obtaining and preparing soil samples (Thomas, 1967; Soil Survey Staff, 1984). Particular care should be exercised to make appropriate corrections, where necessary, for gravel content and skeletal fraction (Lal, 1979a). Some important soil physical indicators and methods of their assessment are listed in Table 21.

1 Texture: Initial characterization of soil texture is important. Subsequent measurements can be done every 2 to 4 years because textural characteristics of the surface horizon are altered only if accelerated soil erosion is a predominant degradative process. Erosion is a selective process that preferentially removes clay and other fine particles leaving coarse fraction and skeletal material behind. Severe erosion can also expose subsoil of different textural composition. Measurements of soil texture should preferably be done by the pipet method (Gee and Bauder, 1986), with due consideration for prior removal of the cementing agents in strongly structured soils e.g., sesquioxides, organic matter, calciferous and siliceous materials, etc.

2 Soil tilth: Soil physical condition or tilth is often difficult to quantify (Karlen it al., 1990). Tilth can be quantified by assessment of tilth forming processes (Karlen et al., 1990) or by computing the tilth index (Singh et al., 1992). Tilth index is rated from scale of 0 (e.g., non-limiting or optimal rooting environment) to 1 (e.g., root-restrictive and unsuitable for plant growth).

3 Soil water reserves: The difference between field capacity and permanent wilting point is expressed on volume or depth basis (Ritchie, 1981; Gupta and Larson, 1979a; Bruce and Luxmoore, 1986; Cassel and Nielsen, 1986; Klute, 1986). The field capacity, upper limit of the available water content, should be determined *in situ* after a saturated soil has been allowed to drain under gravity without surface evaporation. If logistically unfeasible, field capacity can be determined in the laboratory on intact cores using pressure plate extractors. Soil moisture potential for determining field capacity may be 0.006 MPa to 0.01 MPa for coarse-textured soils and 0.03 to 0.05 MPa for heavy-textured soils. Permanent wilting point can be determined on disturbed and sieved soil sample at a moisture potential of 0.5 to 1.5 MPa depending on soil texture (Lal, 1979a). *In situ* measurement of soil moisture regime is a challenge in highly variable soils of the tropics. Neutron thermalization technique is not suitable for many soils e.g., soils with high concentration of Fe, B, and Mn; soils with gravel horizon, cracking clay soils (Lal, 1974; 1979b). Gypsum blocks have problems for use in acid soils. Accurate characterization of soil moisture regime remains to be a challenge. Although laborious and destructive, gravimetric method is the most reliable technique.

4 Soil structure: It is a complex attribute and is difficult to quantify. Lal (1991) proposed several indices of assessing soil structure, and several techniques and conceptual methods have been suggested and described by Blake and Hartge (1986) and Kay (1989). Morphological attributes of soil structure involve aggregation and aggregate size distribution. These attributes can be measured by wet or dry sieving techniques (Kemper and Rosenau, 1986), and results can be expressed as percent water stable aggregates (% WSA) greater than 0.5 mm or 1.0 mm size. The data can also be computed in terms of the mean weight diameter (MWD) or geometric mean diameter (GMD).

Table 21 Suggested methods for assessment of soil physical indicators

Indicator/Attribute	Method	Reference
Texture	International pipet or hydrometer method, correction for gravels	Gee and Bauder (1986), Lal (1979a)
Soil tilth	Tilth index, tilth farming process	Singh et al. (1992); Karlen et al. (1990)
Soil structure	(i) WSA > 1 mm and MWD	Kemper and Rosenau (1986); Edwards and Bremner (1967)
	(ii) Bulk density using intact cores	Blake and Hartge (1986); Manrique and Jones (1991)
	(iii) Non-limiting range of soil moisture	Letey (1985)
	(iv) Air permeability	Corey (1986)
	(v) Crust conductance	Falayi and Bauma (1976); Hanks and Thorp (1956)
	(vi) Structural indices	Lal (1991)
Available water capacity	(i) Field capacity *in-situ*	Klute (1986); Baver et al. (1972)
	(ii) Permanent wilting point	Bruce & Luxmoor (1986); Klute (1986)
Rooting depth	Core-break method	Bohm (1979)
Water transmission	(i) Saturated hydraulic conductivity on intact cores	Klute and Dirksen (1986)
	(ii) Infiltration rate (double ring)	Klute (1986)
Soil strength	(i) Penetration resistance at known moisture content	Blake and Hartge (1986); Bradford (1986)

Functional attributes of soil structure are better determined by evaluating total and macroporosity and the pore size distribution. Determining pore size distribution is an important aspect of structural characterization (Olson, 1985; 1987; Olson and Zobeck, 1989). Macroporosity or drainable porosity measured at 0.006 MPa suction or at 0.01 MPa suction is a measure of soils ability to transmit water or its susceptibility to anaerobiosis. Pore size distribution can be determined from soil moisture retention characteristic (Child and Collis-George, 1951).

5 Soil strength and rooting depth: Soil compaction is measured directly by assessment of soil bulk density (Blake and Hartge, 1986) or can be predicted from particle size distribution (Gupta and Larson, 1979b). Soil strength and densification affects root growth and development. Soil strength can be indirectly assessed by measurements of penetration resistance expressed as Kg/cm^2 or kPa (Bradford, 1986). Assessment of penetration resistance should

always be related to soil moisture content measured at the time. Crust strength can also be assessed by determining penetration resistance. Crust conductance is another useful indicator in relation to crop growth (Falayi and Bouma, 1975). Another indirect measure of soil strength and compaction in relation to root growth and development is soil bulk density or weight:volume relationship.

Effective rooting depth is an important indicator of soil productivity, and can be assessed from soil characteristic (Groenevelt et al., 1984). Rooting depth also varies among crop species and cultivars (Taylor and Terrel, 1982). Root-restrictive characteristics in soil may be related to physical, and chemical or nutritional attributes. Physically, soil layers of high strength or bulk density restrict or limit root growth. Depth to root penetration can be determined by several methods (Bohm, 1979). A commonly used, simple, and a practical method is based on obtaining soil cores and counting roots on the naturally broken edges. This method is called the "core break" method. The data is appropriately expressed as root length density.

6 Water transmission properties: Water transmission characteristics can also be determined by measuring saturated (K_s) or unsaturated (K_θ) hydraulic conductivity on intact cores in the laboratory. Hydraulic conductivity can also be determined under field conditions using an auger hole method either below or above the water table (Klute, 1986). There are also several models to predict permeability of soil (Child and Collis-George, 1950; Marshall, 1958; Millington and Quirk, 1961; Green and Corey, 1971; McKeague et al., 1982). An important integrative indicator of several soil physical attributes is the infiltration rate. Infiltrate rate, the equilibrium rate attained after a constant head of water is maintained on the soil surface for about 3 hours, is a measure of soils ability to receive water at the soil-air interface and transmit it through the profile. Infiltration rate can be flux controlled (depending on the rate of water application to the surface by rainfall or irrigation) or profile controlled. An appropriate indicator of water transmission characteristics is the profile-controlled infiltration rate determined in the field either by double-ring infiltrometer or rainfall simulator (Lal, 1979b). It is useful to analyze the infiltration data according to several models e.g., Philips, Kostiakov, Green-Ampt and Horton, etc. (Lal, 1979b).

B. Assessment of Soil Chemical and Nutritional Indicators

Commonly used methods of determining soil chemical and nutritional properties are described in Table 22. Relative importance of chemical and nutritional indicators varies among soils, ecoregion and objectives.

1 pH and acidity: Soil reaction, an important indicator of soil's chemical health, can be determined by measuring soil pH. Soil reaction also determines solubility and availability of some elements, and deficiency or

toxicity of others. Low pH of about 4.5 to 5.5 indicates a possibility of high concentrations of exchangeable Al. In contrast, high pH of 7.5 to 8.5 is indicative of the presence of free $CaCO_3$. Soil pH can be determined using pH meter either in 1:1 in water or soil:0.01 M Ca Cl_2 suspension (McLean, 1982).

Table 22 Methods of determining soil chemical and nutritional indicators

Indicator/Attribute	Method	References
pH	Glass electrode, calomel electrode, pH meter, potentiometer	McLean (1982)
Total organic carbon	Wet combustion method	Nelson and Sommers (1982)
Active organic carbon	Digestion with Kcl	Gianello and Bremner (1986)
ECEC	Summation of exchangeable cations	IITA, 1975; Page (1982)
Soil nitrogen	Chemical method	Gianello and Bremner (1986); Stanford (1982)
Plant available nutrients	Soil test	Engelsted, 1986; Thomas (1967)
Electrical conductivity and total soluble salts	Ohms meter	U.S. SLS (1954); Rhoades (1986)

2 Soil organic carbon: Amount and nature of soil organic carbon content play a key role in soil quality (Larson and Pierce, 1992; Parr et al., 1992). Although organic carbon is not a plant nutrient, low concentrations (0.5-1% by weight) can have serious deleterious effect on productivity (Stevenson, 1982; Allison, 1973). However, productivity effects of small changes in soil organic carbon content are relatively negligible in soils with high antecedent concentrations in excess of 5% e.g., Mollisols, Histosols, etc. Soil organic carbon affects productivity through its effect on soil structure, plant available water capacity, as a source or sink for plant nutrients, and as a buffer against sudden fluctuations in soil characteristics.

In addition to total soil organic carbon determined by wet or dry combustion methods (Gianello and Bremner, 1986), it is also important to determine active or biomass carbon. It is the biomass carbon which is more sensitive to differences in management and land use systems. Management and land use effects should be assessed in terms of quantity and composition of soil organic matter content. The active organic carbon fraction ranges from 10 to 20% of the total organic carbon content. Despite its widely known beneficial effects, it is difficult to increase soil organic carbon content especially in arid and semi-arid tropics. Large quantities and frequent applications of crop residues and biomass are needed to maintain or bring about slight increase in soil organic carbon content in these harsh ecoregions and ecologically-sensitive environments.

3 Nutrient capacity and intensity factors: Low soil fertility is a major factor responsible for low productivity of soils of the tropics. Total nutrient reserves (capacity) and the available nutrient (intensity) reserves are important indicators of soil quality and productivity. Intensity and capacity factors must be assessed for all essential nutrients e.g., macro (N, P, K, Ca, Mg) and micro-nutrients (Zn, S, Cu, B, etc.). Elemental toxicity (e.g., high concentrations of some elements) is an important aspect of soil quality and productivity in several soils of the humid and sub-humid tropics e.g., Oxisols and Ultisols. Nutrient supplying potential of the soil must be determined by standard soil-test procedures (Engelsted, 1985; Page, 1982). Validation of these procedures is essential for locale conditions relevant to soil, crop and other agro-ecological factors. Mineralization capacity for N and fixation capacity for P are important indicators of soil productivity. Low P availability and high P fixation capacity are severe limitations in several major soils of the tropics e.g., acid soils in Latin America.

4 Soluble salts and electrical conductivity: High salt concentration in the root zone is a severe limitation in many semi-arid and arid region soils. Therefore, knowledge of the salinity and alkalinity status of these soils is extremely relevant to soil quality and productivity. Electrical conductivity of saturated paste is a good measure of the total salt concentration (Rhoades, 1982). In addition to total salt, nature of salts (e.g., Na vs. Ca and Mg) is also important especially in relation to soil structure. Sodium absorption ratio (SAR) is a good indicator of soil's potential and actual alkalinity. There is a need to determine empirical and crop-specific critical limits for electrical conductivity and salt concentration (Gupta and Abrol, 1990). Growth and predominance halomorphic plant species can also be used as indicator of the salivity/alkalinity status.

C. Assessment of Soil Fauna

Soil fauna plays an important role in soil structure, nutrient recycling, and dynamics of soil organic matter content. Soil macrofauna, comprising activity and species diversity of earthworms and termites, is an important soil indicator for sustainable use of soil and water resources (Lal, 1987; Lavelle et al., 1992). Activity and population of macrofauna should be done by non-destructive method of sieving. Use of chemicals to expel these organisms from the soil, although quick and easy, is destructive and not an accurate technique.

D. Soil Erosion Assessment

Despite its importance or threat to sustainability and the voluminous literature available on the subject, soil erosion assessment remains to be an art rather than a science. The data reported in the literature are obtained by a wide range of unstandardized techniques. The data accuracy and reliability are major constraints to precise assessment of the magnitude of soil erosion problem. Despite attempts made towards standardization of erosion assessment techniques (Lal, 1994), however, data reliability remains to be a major challenge in characterizing potential and actual risks of soil erosion.

Appropriate field and laboratory techniques of measuring the magnitude and rate of soil erosion by wind and water are described in the manual by Lal (1994). Apparently, suitable techniques are those that can be used on several soils and across different temporal and spatial scales. Some common methods of erosion assessment at different spatial scales are described in Table 23. Field calibration of equipment and accurate assessment after every rainstorm are critical to obtaining reliable data. Sediment concentration in streams and rivers can also be determined by remote sensing techniques using satellite imagery. Proper calibration of this technique is essential to reliable assessment of the temporal and spatial variability in the sediment load. This technique may not be applicable, however, for measurement of bedload.

Soil erosion can also be assessed by several parametric and conceptual models (Table 24). Commonly used models of wind erosion include the Wind Erosion Equation (WEQ), The Revised Wind Erosion Equation (RWEQ), and the Wind Erosion Prediction System (WEPS) or the Wind Erosion Research Model (WERM). Pros and cons and methods for their use are described by Skidmore (1994) and Skidmore et al. (1994). The WEQ, although widely used, is an empirical and a black box model and may have limited applications. The dynamic aspects of wind erosion are assessed by process-based WEPS and WERM models. Nonetheless, soil and climatic indices and crop coefficients must be obtained for locale conditions.

Table 23 Techniques for assessment of erosion at different spatial scales

Scale	Size	Techniques
Small test plots	1-2 m^2	Rainfall simulation
Microplot	1-10 m^2	Runoff plot, buried nail technique
Field plots	10-100 m^2	Field runoff plot, flourescent dye, buried nail technique, multi-divisor system
Hillside	0.01-0.5 ha	Flume, water stage recorder, runoff samplers
Agricultural watershed	0.5-5 ha	Flumes, water stage recorder, runoff samplers
Large watersheds and river basins	> 100 ha	Weirs, stage height measurement, sediment sampler, remote sensing

Table 24 Predictive models for soil erosion assessment

Erosion Process	Model	Reference
Wind Erosion		
Average annual estimate of soil erosion	The Wind Erosion Equation	Woodruff and Siddoway (1965)
Process-oriented model	(i) Wind Erosion Prediction System (WEPS)	Skidmore (1994)
	(ii) Wind Erosion Research Model	Skidmore et al. (1994)
Water Erosion		
Parametric models	(i) The Universal Soil Loss Equation (USLE)	Wischmeier & Smith (1978)
	(ii) Revised Universal Soil Loss Equation (RUSLE)	Foster (1982); Renard et al. (1994)
	(iii) Modified Universal Soil Loss Equation (MUSLE)	Williams (1975)
Conceptual model	(i) Water Erosion Prediction Project (WEPP)	Nearing et al. (1994)
	(ii) Griffith model	Rose (1994)
Watershed management	(i) ANSWERS	Beasley et al. (1980)
Soil Erosion-Crop Productivity		
Parametric model	(i) The Productivity Index (PI)	Pierce et al. (1983)
	(ii) Theprom	Biot (1990)
Conceptual models	Erosion Productivity Impact Calculator (EPIC)	Williams et al. (1983; 1984)
Productivity and environment model	CREAMS	Knisel and Foster (1981)

The Universal Soil Loss Equation (USLE) is also an empirical and a black box model. This statistical model, developed for soil and agroecological environment of the midwestern USA, has limited application and has been grossly abused for situations where it is least applicable. The original model has been revised (RUSLE; Renard et al., 1994) and modified (MUSLE) to address some concerns. However, the conceptual approach of the Water Erosion Prediction Project (WEPP) makes it a process-based model and more relevant for diverse situations. Nevertheless, knowledge of locale soil and climatic parameters is critical to meaningful and legitimate use of any model.

Severity of soil erosion can only be assessed by evaluating on-site and off-site effects. Principal on-site effects of accelerated erosion are related to decline in crop productivity. However, quantitative information on crop productivity effects of erosion is not available for most soils, crops, and ecoregions of the tropics.

Several techniques are available to assess impact of soil erosion on crop yield (Lal, 1987; Pierce and Lal, 1994). Field techniques are based on experimental measurement of crop performance on erosion plots for which the exact amount of soil loss is known. Yield effects of erosion can also be assessed by estimating erosion on field plots by soil survey techniques and monitoring crop performance under recommended management systems. Varying levels of soil erosion can also be simulated by artificial soil removal and assessing its effects on crop growth and yield. Techniques based on simulated soil erosion often provide inaccurate and unnatural effects of erosion on productivity.

There are several models available to assess impact of erosion on productivity (Pierce and Lal, 1994). A commonly used model is the Productivity Index (PI) developed by Pierce et al. (1983). This parametric model is based on quantitative information on soil profile characteristics to at least 1 m depth. These characteristics include pH, rooting depth, soil organic carbon, available water capacity, etc. However, application of this relative and parametric technique may be questionable for several soils of the tropics. Several process oriented models (e.g. EPIC and CREAMS) require a large database on soil, climate and crop growth parameters. Therefore, field measurements of erosion effects on productivity are required for principal soils and crops of the tropics for different management systems and input levels. Use of simulation models is a viable shortcut only if appropriate parameters are known. Models are not intended to be substitute for experimental data from well designed field experiments.

XIII. SAMPLING DESIGN AND MONITORING FREQUENCY

Initial baseline characterization or assessment of antecedent conditions of the experimental site is crucial to objectively evaluate management-induced changes in soil indicators. In addition to soil conditions, it is also important to record land use history, and conduct a topographic survey at 0.5 m or 1 m contour interval. Detailed soil map should also be prepared at 1:1500 or 1:2500 scale.

A sampling grid should be established to assess soil properties at 25 m x 25 m grid. The grid size may be less for a highly variable site. A transact design can be used for an undulating terrain or site with steep slope gradient. Transact orientation is usually normal to the contour from hill crest to the valley bottom.

Soil sampling can also be done on a mapping unit basis. The latter is a discrete parcel of land of several hectares. A mapping unit, however, may contain several soil series with high spatial variability in soil properties (Cassel and Fryrear, 1990). The variability may be natural or introduced by management e.g., change in bulk density due to wheel tracks (Cassel, 1983). However, some properties are more variable than others. Wilding (1988) listed variability of several soil properties within a mapping unit (Table 25). Considering the magnitude of variability, Wilding grouped soil properties into 3 categories: (i) least variable properties have coefficient of variability (CV) of less than 15%, (ii) moderately variable have a CV of 16 to 35%, and (iii) highly variable properties have a CV of 36 to 70%.

Table 25 Relative variability of selected soil properties sampled within mapping units of soil series (Wilding, 1988)

Soil Property	Coefficient of Variability (%)	
	Mean	Range
Bulk density	7	5-13
pH	10	5-15
A horizon thickness (cm)	10	8-13
Water retention (33 kPa)	18	10-31
Total sand content (%)	25	8-46
Total clay content (%)	25	10-31
Organic-matter content	39	20-61
Soil thickness (cm)	43	25-58

Assessment of temporal changes in soil properties is preferably done at the pedon level. The objective is to sample exactly the same site over time so that management-induced changes in soil properties or sustainability indicators can be quantified and trends established.

Management treatments should be preferably imposed on the same soil series or association. Treatments may be implemented according to a randomized block design with 3 to 6 replications depending on the site variability in soil properties. Highly variable soils require more replications than relatively uniform soils. Split plot design can also be used, with more critical treatments imposed at split plot level. Strip designs are also used in implementing treatments that require large plot size. Such designs are, however, inefficient and do not lend themselves to an easy computation of the analysis of variance (ANOVA).

Monitoring frequency is important in establishing time trends of management-induced changes in soil indicators. Monitoring frequency depends on the nature of indicators. Some indicators are highly labile and undergo rapid changes while others are stable and change only slightly over years. The rate of change of various soil characteristics or indicators has been outlined by Arnold et al. (1990). Most soil physical indicators change in less than 0.1 year. Water retention and transmission and nutrient reserves change between 0.1 and 1 year. There are several properties which change over a geological time span. Monitoring frequency shown in Table 26 is based on this concept of the relative change in indicators. These indicators are grouped into 5 categories. Some soil physical indicators (e.g., soil moisture and temperature) may undergo diurnal changes, while others (e.g., bulk density and porosity) undergo seasonal changes. In contrast changes in soil structure are relatively slow and are measurable over time span of 1 to 2 years. Changes in soil texture are extremely slow and are usually caused by accelerated erosion of the soil surface. Textural changes are difficult to observe over less than 3 to 5 year period.

Table 26 Suggested frequency of monitoring soil indicators

Soil Indicator	Suggested Monitoring Frequency
Soil Physical Indicators	
Soil moisture	Every week
Bulk density and penetration resistance	Every season
Hydraulic conductivity	Yearly
Structure	1 to 2 years
Infiltration	1 to 2 years
Available water holding capacity	3 to 5 years
Texture	3 to 5 years
Soil Chemical Indicators	
pH	Seasonal
Total nitrogen	1 to 2 years
Available nutrients	1 to 2 years
CEC	1 to 2 years
Soil Biological Indicators	
Earthworm activity	Every season
Biomass carbon	1 to 2 years
Soil organic carbon	1 to 2 years
Crop Indicators	
Yield	Every season
Root growth	Every season
Nutrient Status	1 to 2 years
Micro-climate	
Soil temperature	Daily & seasonal
Air temperature	Daily
Evaporation	Daily
Rainfall amount	Seasonal
Rainfall intensity	Maximum over 5 to 10 minutes

For soils containing predominantly low-activity clays, there can be relatively rapid changes in soil pH and acidity. Therefore, changes in soil pH may be monitored every season. However, changes in concentration of total and plant-available nutrients are relatively slow and can be quantified once every 1 to 2 year period. Unless accelerated soil erosion is a predominant degradative process, changes in soil organic matter content are relatively slow and the monitoring frequency may also be 1 to 2 years. Biomass carbon changes drastically and may vary on seasonal basis. Changes in earthworm population are also highly seasonal.

Crop yield and yield parameters should be recorded for each cropping sequence. Crop nutrient status can also be assessed, usually during the flowering stage and on crop-specific tissue, once every season. Root growth is also assessed on seasonal basis usually at reproductive growth stage. Most climatic indicators are measured on daily or seasonal basis.

XIV. CONCEPTUAL BASIS OF DEFINING CRITICAL LEVELS OF SOIL AND WATER INDICATORS

Once a minimum set of standardized data base is developed, it is important to interpret the information in terms of potentials and constraints of the resource and evaluate appropriate land use and soil and crop management systems. The development and strengthening of the database are continuing and on-going processes. The available data base has to be interpreted in terms of intended land uses including production, environmental regulation, water quality, etc. Assessment of the potential and constraints of the resource for different land uses is based on the knowledge of critical level of soil and water indicators. The critical level of an indicator or an attribute is defined as the level beyond (below or above) which crop/animal production declines rapidly. The critical level can also be defined in terms of the severity of degradation. The lower limit of critical level is the one at which degradation rate is high but the trend can be reversed. Upper limit of the critical level refers to the point of no return or irreversible soil degradation. The schematics in Fig. 13 identifies three categories of critical levels. The critical level C, denotes soil condition at which production or other economic functions begin to lag behind and register a significant decline. At this level productivity begins to decline even with recommended management systems. However, production can be maintained with adoption and implementation of best management practices. At this level, change in land use or adoption of new crops or innovative techniques can drastically transform the production capability to another plane.

If best management techniques are not adopted at the critical level 1, soil degradative trends continue to the critical level 2 at which production reaches a sub-economic level. It is no longer economic to continue the same land use or farming system with traditional or recommended systems of management. However, adoption of improved management systems or change of land use can enhance production and even reverse the degradative trend. The new or alternative land use system, however, may not be socially or politically acceptable in meeting the economic and cultural needs. If the traditional or conventional land use is continued and soil degradation proceeds unabated, soil quality attains the critical level 3. This is the point of no return and soil is irreversibly degraded. Productive capacity and soil quality at this level cannot be enhanced even with adoption of improved management system and with additional inputs. There may, however, be other land uses that can produce some useful goods and services even at this level. Tree crops and shrubs have been successfully grown in regions of high demographic pressure even on severely eroded and shallow soils. Such undertakings require special management techniques e.g., digging deep pits and filling those with organic matter and compost prior to seedling establishment, and using supplemental irrigation at least during the initial stages. Land hunger and demographic pressure dictate these alternative land uses. However, the adverse environmental impact can be drastic even with alternate land use systems.

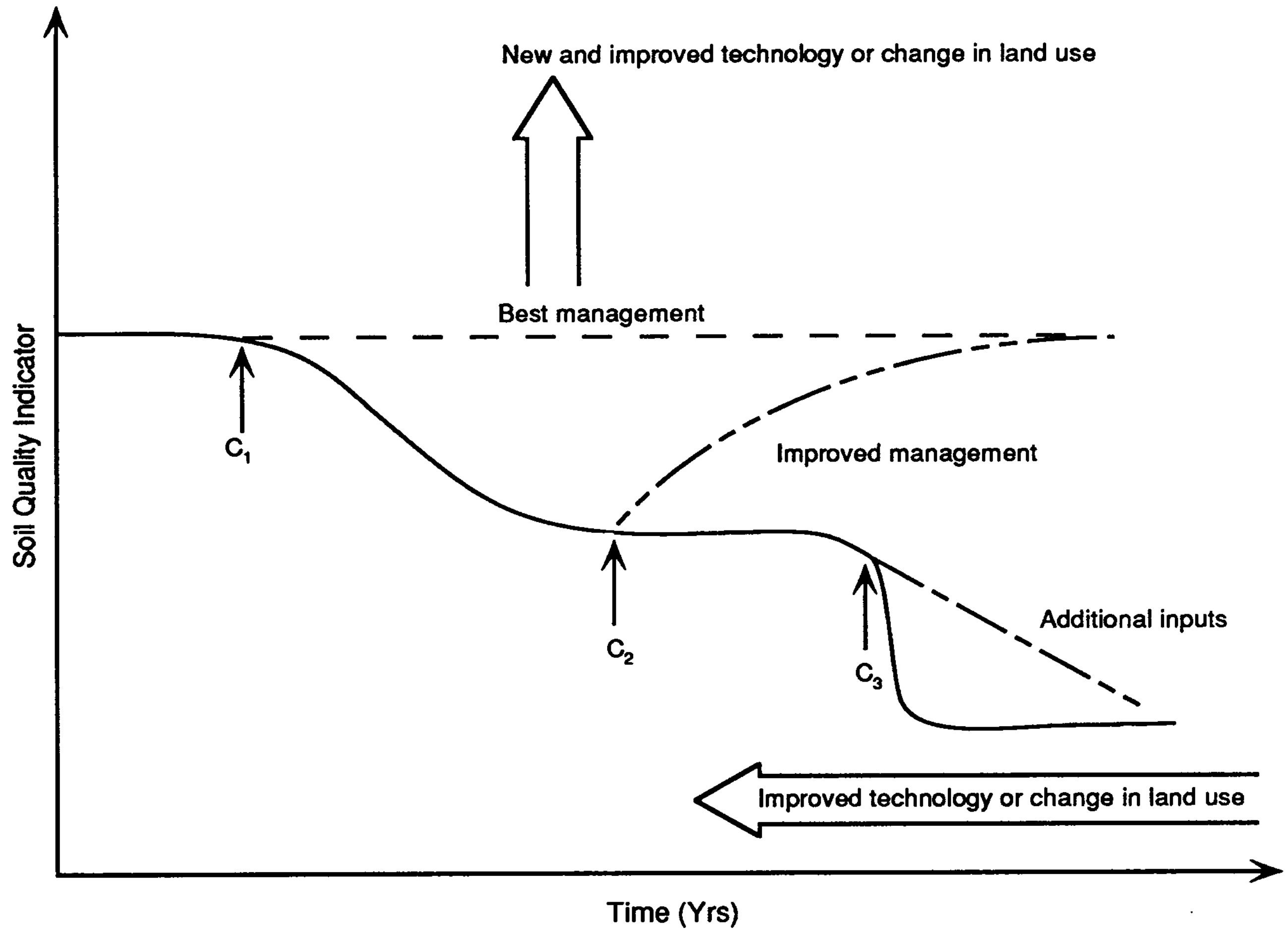

Fig. 13. Different types of critical levels in relation to land use and management systems.

These critical levels of soil indicators must be defined in terms of quantifiable returns of goods and services e.g., production, environmental regulation capacity. At present, however, these critical levels in relation to economic and environmental functions are not known for most soils and ecoregions of the tropics. It is justified to infer that these levels are not known even in technologically advanced nations of North America and Western Europe for several soils and ecoregions and for diverse land uses. Although some progress has been made in obtaining initial estimates of regional and global extent of soil degradation by different processes (Oldeman, 1991-92; WRI, 1992-93), these estimates are at best qualitative and educated guesses.

Critical levels should be defined in terms of loss in production or other economic and environmental functions of a soil. Furthermore, production and productivity are functions of land use, management, and intensity and types of inputs. Therefore, an objective evaluation of the severity of degradative process and soil quality can only be made on the basis of loss in economic goods and services. An example of such a matrix to assess severity of soil degradation is shown in Table 27. The suggested level of the productivity loss may differ among soils, ecoregions, and land use system. Nonetheless, the magnitude of loss must be quantified and standardized. An example of qualitative and subjective system of soil degradation assessment is shown by the matrix in Table 28. The quantitative assessment of soil erosion is often based on the use of empirical models (e.g., USLE or WEQ). These estimates are rarely if at all based on field measurements of erosion rates. Similarly, the extent and types of soil erosion are usually estimated by reconnaissance surveys at large scales of 1:1,000,000 or 1:5,000,000 if not more. Such estimates are useful for creating public awareness with regards to potential or perceived risks. However, these estimates have little use in land use planning and defining policy options for improved management or land restoration. These quantitative and subjective estimates can also be misleading and lead to erroneous conclusions and expensive and environmentally disastrous mistakes. Bad information is not a substitute for no information.

Table 27 An example of a matrix for quantitative and objective assessment of soil degradation in relation to productivity

Degradation Class	Loss in productivity at recommended and science-based management (%)		
	Agronomic Land Use 1	**Environmental Function**	**Cultural Use**
None	None		
Slight	0-10	**Quantitative**	
Moderate	10-25	**Indicators**	
Severe	20-50	**of Loss**	
Extremely severe	>50		

Table 28 An example of a matrix of qualitative and subjective assessment of soil degradation with disregard to productivity and environmental functions

Degradation Class	Magnitude of Soil Erosion	
	Qualitative (Mg/ha/yr)	Areal Extent (%)
None	0-5	0-5
Slight	5-10	5-10
Moderate	10-20	10-20
Severe	20-100	20-30
Extremely severe	>100	30-40

XV. SUGGESTED CRITICAL LEVELS OF KEY INDICATORS

It is extremely important to establish appropriate criteria for establishment of critical levels of soil and water indicators. Sustainable use of natural resources being the principal objective, critical levels should be related to productivity. Different critical levels should also be assigned rating or weighting factor. Weighting factor, the relative significance of that factor, is based on the productivity loss at that level of soil indicator.

Because of diverse soil orders, climates, ecoregions, and crops and cropping systems, it is extremely difficult to generalize or universalize the critical level of indicators. The critical level of indicators must be decided on the basis of locale-specific situations and by relating productivity to soil attributes. Nonetheless, some arbitrary guidelines and their rating factors for soil strength and structural properties are shown in Table 29, for soil mechanical properties in Table 30, for porosity and available water capacity in Table 31, and for water transmission characteristics in Table 32. Ranges of soil's indicators for none to severe limitations are tentatively fixed at 150 to 20 cm for effective rooting depth, and 1.3 to 1.6 Mg/m^3 for bulk density of light-textured soils and 1.2 to 1.5 Mg/m^3 for those of heavy-textured soils. Critical levels of soil structural indicators for none to severe limitations range from 75% to 5% for percent aggregation (based on wet or dry sieving) and 2.5 mm to 0.5 mm for the MWD. Some other soil physical indicators (e.g., stoniness, hydraulic conductivity, etc.) can also be appropriately rated. It is, however, difficult to develop a weighting factor for clay content. Both extremes, too much and too little, of clay or sand contents can have adverse effects on productivity and sustainability. Critical levels for soil texture should, therefore, be established in conjunction with other attributes e.g., available water capacity, infiltration rate, etc.

Table 29 Suggested critical levels of soil strength and structural indicator

Limitation	Relative Weighting Factor	Effective Rooting Depth (cm)	Penetration Resistance (mPa)	Soil Bulk Density(Mg/m3)		Soil Structure		
				Light Texture	Heavy Texture	Morphology	WSA %	MWD mm
None	1	>150	<1.0	<1.3	<1.2	Strong sub angular blocky to crumb	>75	>2.5
Slight	2	100-150	1.0-1.5	1.3-1.4	1.2-1.3	Sub-angular blocky	50-75	2-2.5
Moderate	3	50-100	1.5-2.0	1.4-1.5	1.3-1.6	Moderate sub-angular blocky	25-50	1.0-2.0
Severe	4	25-50	2.0-2.5	1.5-1.6	1.4-1.5	Weak sub angular blocky	5-25	0.5-1.0
Extreme	5	<25	>2.5	>1.6	>1.5	Massive or single grain	<5	<0.5

It is difficult to generalize critical levels of plant nutrients. Sufficiency levels of plant nutrients depend on crop species and expected yield. Critical levels of some soil chemical indicators are shown in Tables 33 and 34. Critical levels of soil pH depend on the pH scales. The optimum range of pH is in the vicinity of neutral soil reaction from 6.0 to 7.0. The pH is generally sub-optimal for plant growth on both ends of the pH scale. Ranges of soil pH for none to severe limitation on acid soils are >6.0 and <5.0. In alkaline and sodic soils, however, ranges of soil pH for none to severe limitations are 7 to 7.4 and >8.2 (Table 33).

Table 30 Critical limits for soil mechanical properties

Limitation	Weighting Factor	Consistency	Texture	Coarse Fragment in Surface (%)	Penetration Resistance (mPa)
None	1	Loose	Loam	<10	<1.0
Slight	2	Very friable	Silt loam, silt silty clay loam	10-20	1.0-1.5
Moderate	3	Friable	Clay loam, sandy loam	20-40	1.5-2.0
Severe	4	Hard	Silty clay, loamy sand	40-60	2.0-2.5
Extreme	5	Harsh or extremely hard	Clay, sand	>60	>2.5

Table 31 Critical limits for porosity and available water capacity

Limitation	Weighting Factor	Permeability	Drainable Porosity at 0.006 mPa (%)	Moisture Retention Porosity (%)	Residual Porosity	Available Water Capacity (cm)
None	1	Rapid	>20	>20	<15	>30
Slight	2	Moderately rapid	18-20	18-20	15-18	20-30
Moderate	3	Moderate	15-18	15-18	18-20	8-20
Severe	4	Slow	10-15	10-15	20-25	2-8
Extreme	5	Very rapid or very slow	<10	<10	>25	<2

Table 32 Critical limits for water transmission properties

Limitation	Relative Weighting Factor	Permeability	Infiltration Rate (cm/h)	Saturated Hydraulic Conductivity (cm/h)
None	1	Rapid	>5	>2
Slight	2	Moderately rapid	2-5	0.2-2
Moderate	3	Moderate	1-2	0.02-0.2
Severe	4	Slow	1-0.5	0.002-0.02
Extreme	5	Very slow or excessively rapid	<0.5	>0.002

Toxic concentrations of Al, Mn and other nutrients also vary among soils (depending on clay mineralogy, CEC, soil organic carbon content, etc.) and crop species. Some acid tolerant species can withstand high concentrations of Al, Mn and total acidity than others. Tolerance to high concentrations of Al and Mn also depend on the total and soluble contents of Ca. In many soils, crop respond more to the deficiency of Ca than to excess of Al and Mn. Some suggested critical levels shown in Table 34 indicate the Al concentration for none to severe limitation ranges from less than 20% of total CEC to more than 50%. Similarly, percent of Mn on the exchange complex ranges from <5% for no limitation to more than 20% for severe limitation.

Similar to pH, it is difficult to establish critical levels of soil organic carbon content. Organic carbon content is important only for those soils with low antecedent levels. In general, organic carbon content of mineral soils is considered sufficient if it is 5 to 10%. Soil organic carbon content can be a severe limitation if its concentration is less than 0.5%. In that case, soil structure is rapidly deteriorated, and water and nutrient retention capacities are at sub-optimal level. Rather than total organic carbon, it is the biomass carbon or active fraction of soil organic carbon which plays an important role in regulating soil properties and underlying processes. Critical levels of biomass carbon are also shown in Table 35. Under favorable conditions, the biomass carbon should be at least 25% of the total soil carbon content.

Table 33 Suggested critical levels of soil chemical indicators

Limitation	Weighting Factor	pH (1:1 in H_2O)	SAR*	Electrical Conductivity (ds/m)
None	1	6.0-7.0	<10	<3
Slight	2	5.8 to 6.0 and 7.0-7.4	10-12	3-5
Moderate	3	5.4 to 5.8 and 7.4-7.8	12-15	5-7
Severe	4	5.0-5.4 and 7.8-8.2	15-20	7-10
Extreme	5	<5.0 and >8.2	>20	>10

*Sodium absorption ratio

Table 34 Critical levels of toxic concentrations of Al and Mn in acid tropical soils

Limitation	Weighting Factor	Exchangeable Cations (% of CEC)	
		Al	Mn
None	1	<20	<5
Slight	2	20-35	5-10
Moderate	3	35-40	10-15
Severe	4	40-50	15-20
Extreme	5	>50	>20

Table 35 Critical levels of soil organic carbon content

Limitation	Weighting Factor	Soil Organic Carbon Content of the Surface Horizon (%)	Biomass Carbon (% of Total)
None	1	5-10	>25
Slight	2	3-5	20-25
Moderate	3	1-3	10-20
Severe	4	0.5-1	5-10
Extreme	5	<0.5	<5

XVI. DATA ANALYSIS AND INTERPRETATION

The data base obtained on critical levels of soil indicators has to be combined into an index or several indices to assess sustainable use of soil and water resources. Some possible options for data analysis are outlined in Fig. 14.

The conference on soil quality held at the Rodale Institute (J. Alternative Agric., Vol. 7, 1992) proposed a method or procedure for integrating the interactions of the physical, chemical and biological soil indicators into an index in relation to productivity, environmental and health components. USDA (1992) developed another method to provide soil quality ratings for crop management. The approach was to develop a soil quality rating model that relates the combined effect of three variables on trends in soil quality. The model proposed in relation to soil organic matter management is shown in Eq. 11:

$$SQR = OM + TP + ER \quad \text{------------------------------- (Eq. 11)}$$

where SQR is soil quality rating, OM is the amount of soil organic matter that must be returned to the soil to maintain or increase soil organic matter content, TP is the subfactor related to all field operations which break down residues and aerate the soil e.g., tillage, sowing, intercultivation, fertilizer application, etc. The variable ER is the erosion subfactor which relates productivity decline to soil erosion as predicted by the USLE or; WEQ. The SQR index monitors the magnitude and trend in soil quality change.

Smith et al (1993) proposed another model called Multiple Variable Indicator Kriging (MVIK) that integrates a set of continuous variables into a single index that can be used to map soil quality on a landscape basis. This process involves an independent assessment of threshold values of all soil indicators for different crops. These values are given a rating from 0 to 1. The Kriging procedure integrates several soil indicators into a single new indicator data set which is then used to develop a variogram. The variogram is used to estimate indicator values at other unsampled locations. These indicator values are used to develop soil quality rating maps on a landscape basis. This technique can be applied on a field, farm, watershed or regional basis.

Larson and Pierce (1991) proposed another technique called "Pedotransfer functions" (PTF). These PTF's are mathematical functions that relate soil indicators and properties with one another for use in the evaluation of soil quality (Bouma, 1989). Larson and Pierce (1991) conducted a literature survey to collate several such functions (Table 36). Many of these PTF's are statistical or empirical in nature, and can therefore be used only for the same soil type or region. These functions need to be validated for application to another or ecoregion.

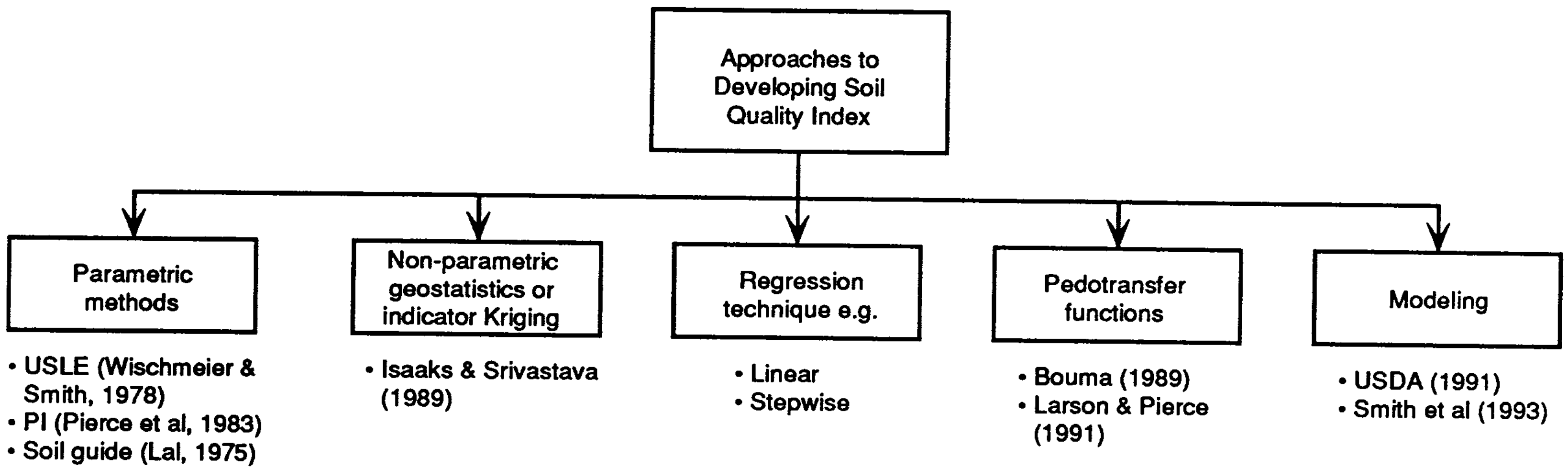

Fig. 14. Possible options for data analyses and synthesis into an operational index.

Table 36 Some examples of Pedotransfer functions (or PTF) (Larson and Pierce, 1991)

PTF	Relationship
Chemical	
Phosphate-sorption capacity (PSC)	$PSC = 0.4\ (Al_{ox} + FE_{ox})$
Cation-exchange capacity (CEC)	$CEC = a\ OC + b\ C$
Change in organic matter	$\Delta C = a + b\ OR$
Physical	
Bulk density	$D_B = b_0 + b_1\ OC + b_2\ S_i + b_3\ M$
Bulk density	Random packing model using particle size distribution
Bulk density	$D_B = f\ (OC, clay)$
Water retention	$q_{10} = b_0 + b_1\ C + b_2\ Sy$
Water retention	$q = b_1\ (\%Sa) + b_2\ (\%Si) + b_3\ (\%Cl) + b_4\ (\%OC)$
Randon roughness from mouldboard ploughing	RR = f(soil morphology)
Porosity increase	P = f(*MR*, *IP*, clay, *Si*, OC)
Hydraulic	
Hydraulic conductivity	$K^s = f$(texture)
Seal conductivity	SC = f(texture)
Saturated hydraulic conductivity	$D_s = f$(soil morphology)
Productivity	
Soil productivity	*PI* = f(D_B, AWHC, pH, Ec, *ARE*)
Rooting depth	*RD* = f(D_B, WHC, pH)

DB=bulk density; Si=percent silt; M=median sand fraction; OC=organic carbon; C=clay; Sy=1/DB; PSC=phosphate sorption capacity; Alox=oxalate extractable Al; Feox=oxalate extractable Fe; OM=organic matter; Sa=sand; Mr=moisture ratio; IP=initial porosity; ARE=aeration.

A commonly used approach is to combine data into a cumulative rating index. This analytical approach was followed by Mansfield (1975), Muchena (1979) and Lal (1985). Weighting factors for ten relevant indicators can be combined into a cumulative index. As was discussed in the section on "critical indicators", relevant indicators may differ among soil types, crops, cropping systems, and land uses. Once the relevant indicators for a soil or land use have been chosen, laboratory or field analysis is done to assign an appropriate weighting factor, and obtain a cumulative rating index (Table 37). The maximum value of the cumulative index based on 10 factors is 50. The next step is to establish relationship between sustainability and the cumulative index. An example of a rating scheme is shown in Table 38. This rating scheme suggests that weighting factor for soil indicators for a sustainable land use or farming system is about 2. However, site-specific empirical relationships should be established between cumulative rating index and one or several indices of sustainability discussed in another section of this report.

Table 37 An example of summation of weighting factors for 10 relevant critical indicators

Soil Indicator	Weighting Factor	Limitation
Rooting depth	3	Moderate
Acidity	5	Extremely low
Al toxicity	4	Severe
Available water capacity	2	Slight
Texture	1	None
Bulk density	2	Slight
Nutrient stratus	5	Extremely low
Soil organic carbon	3	Moderate
Percent aggregation	1	None
Soil erosion	3	Moderate
Cumulative Rating Index	**29**	

Table 38 Sustainability of a land use in relation to the cumulative rating index based on 10 soil indicators

Sustainability	Cumulative Rating Index
Highly sustainable	<20
Sustainable	20-25
Sustainable with high input	25-30
Sustainable with another land use	30-40
Unsustainable	>40

Contrary to the rating scheme suggested in Table 38, it is likely that the relationship between cumulative rating index and sustainability computed from experimental data is not linear. Five among several possible relations are shown in Fig. 15. The rating scheme presented in Table 38 can be improved on the basis of empirical data of the type presented in Fig. 15. These empirical relationships may also differ among soil types, ecoregions, and land uses. The curve A depicts a gradual decline in sustainability until the cumulative rating index is 30. Curve B shows no change in sustainability until the cumulative index of 25 beyond which there occurs a sharp decline in sustainability. Curve C is most likely an atypical or an unusual scenario in which sustainability declines linearly with increase in cumulative index. Curve D exhibits a composite function with linear decline in sustainability until the rating index of 25 followed by a rapid decline from 25 to 30. Curve E is an example of a logarithmic decline in sustainability. The schematic in Fig. 15 shows that sustainable systems have cumulative rating index of <30.

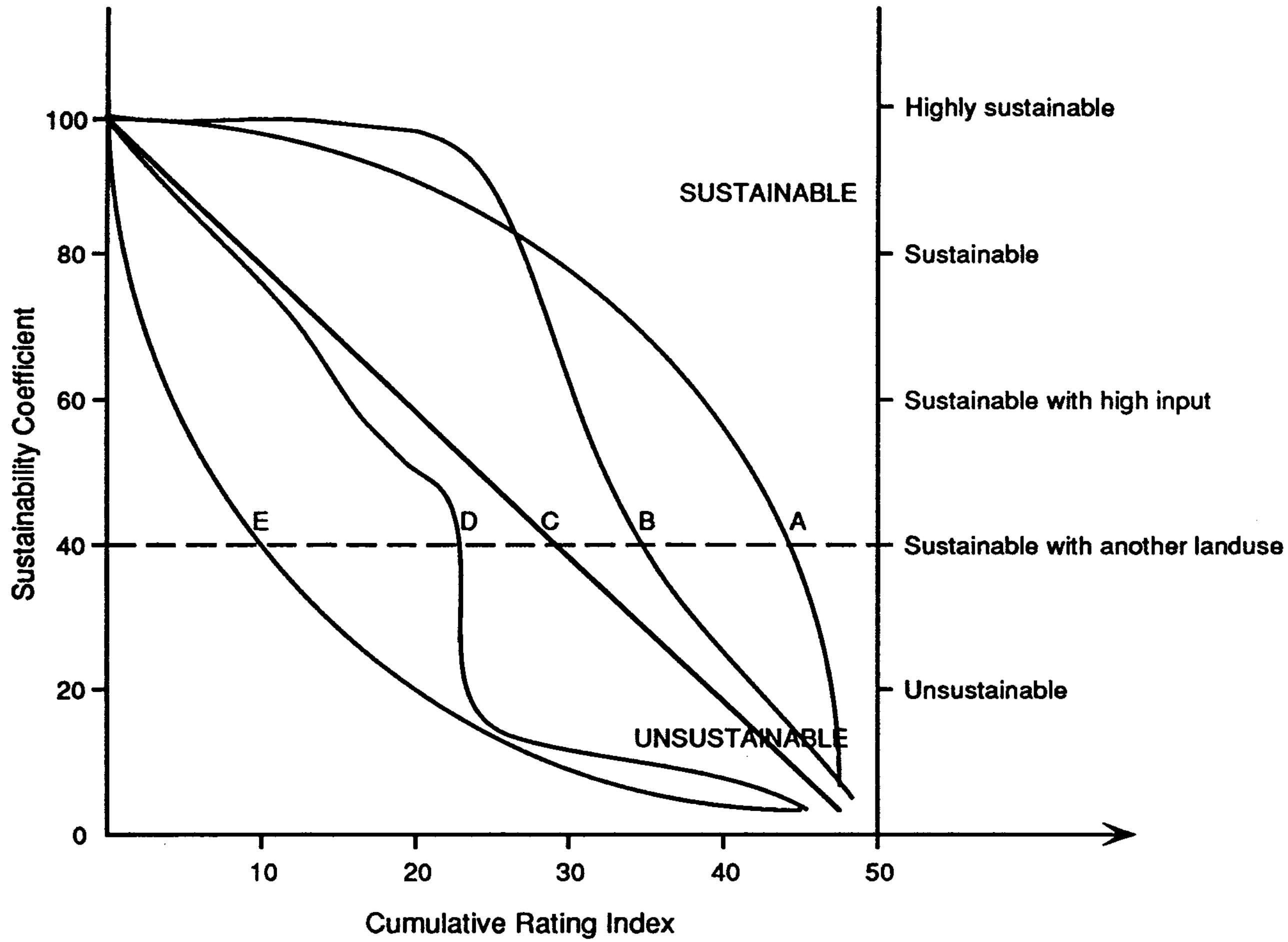

Fig. 15. Schematic of possible relationships between cumulative rating index and sustainability indices.

XVII. CHECKLIST AND SEQUENCE OF STEPS IN SUSTAINABILITY ASSESSMENT

The checklist consists of detailed assessment of all physical and socio-economic factors of the study site at farm, landscape or watershed level. Factor analysis also comprises anthropogenic parameters and institutional variables. Once the routine survey has been completed, assessment of sustainability of soil and water resources requires a sequence of steps to be followed. These steps are outlined in (Fig. 16).

1 The first step in sustainability assessment is program planning and defining objectives by identifying the most critical or limiting factors in achieving the goals envisioned. Most critical or limiting factors are decided through a very detailed resource survey to assess the potential and constraints of soil and water resources. The detailed resource assessment survey, based on soil and hydrological factors along with relevant climatic and vegetational characteristics, would provide the needed information on inherent quality of the soil. The choice of scale (temporal, system and spatial) is also made at this step.

2 The second step is to conduct an objective constraint analysis and identify potential or actual soil degradative processes and the properties which may be altered by those processes. Principal among soil modifying processes are accelerated erosion, compaction and hard setting, chemical degradation and decline in soil fertility, acidification, salinization, biological degradation, etc. Soil indicators affected by these processes are listed in Table 39.

3 The third step is to reevaluate soil indicators affected by predominant soil modifying processes in relation to land use and management systems. Type and rate of degradative processes are determined by land use and management system. Therefore, reevaluation of indicators of sustainability should be done in view of these factors.

4 From the knowledge of critical limits of soil indicators and functional relationship between soil indicators and productivity obtained by a set of supportive experiments or literature survey, assess loss in actual and potential productivity due to change in soil quality indicators.

5 If the adverse impact of change in soil indicators on productivity and environmental quality is drastic, it calls for a change in land use and management. An appropriate land use should be selected on the basis of soil and environmental factors. Subsequently, steps one to four should be repeated to reevaluate objectives, and perform constraint analysis, etc.

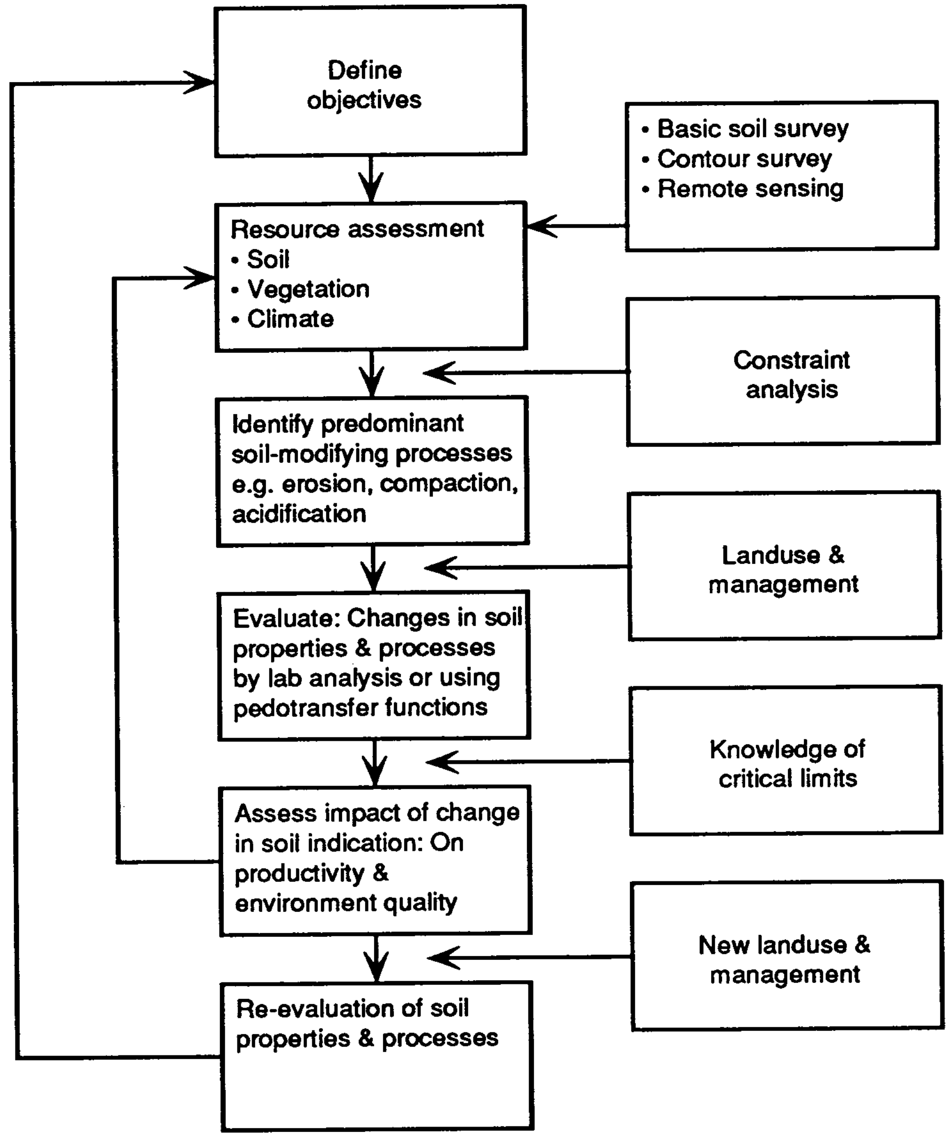

Fig. 16. Sequence of steps in sustainability assessment of soil and water resources.

6 In view of the new land use and management, reevaluate predominant degradative processes and soil and water indicators modified by them. This step should involve reevaluation of the potentials and constraints of the soil and water resources.

Sustainability of soil and water resources should be computed, using coefficients and indicators, outlined in section II of this report, at step 5. The choice of index and appropriate scale of computation is important and should be considered during step 1. Knowledge of temporal changes in soil indicators and productivity, and relationship between soil indicators and productivity are essential to sustainability evaluation.

Table 39 Some sustainability indicators influenced by soil modifying degradative processes

Processes	Soil Indicators Affected
Accelerated erosion	Soil organic carbon, soil depth, available water capacity, soil texture, nutrient capacity
Compaction and hard setting	Soil bulk density, porosity and pore size distribution, soil strength, infiltration rate, hydraulic conductivity
Chemical degradation	Nutrient depletion, reduction in CEC
Acidification	Decline in pH, decrease in base saturation, increase in total acidity and Al concentration
Salinization	Increase in electrical conductivity, and total soluble salts, change in soil color
Alkalization	Increase in SAR, change in soil color due to solublization of carbon, decrease in infiltration
Biological degradation	Reduction in soil organic matter content, decrease in soil biodiversity e.g., population of earthworms, etc., decline in biomass carbon

XVIII. IMPROVING SUSTAINABILITY OF SOIL AND WATER RESOURCES

Improving sustainability of soil and water resources implies enhancing soil structure, nutrient capacity and cycling mechanisms, available water capacity and cycling mechanisms, and soil's life support processes. Maintenance and enhancement of soil organic matter content are crucial to improvement of soil physical, chemical and biological properties. In this regard important management practices are mulch farming techniques, conservation tillage, cover crops and green manuring, strengthening nutrient cycling mechanisms, diversified cropping systems, and frequent and liberal application of organic amendments. These generic technologies need to be adapted and fine-tuned under locale and site-specific conditions (Table 40).

There are two basic strategies to enhance sustainable use of soil and water resources. One is to prevent degradation and the other is to enhance soil quality.

Management options for degradation preventive and soil enhancing measures may be similar. Degradation preventive measures include appropriate land use, suitable crop rotations and combinations, and fertility maintenance through appropriate type and rate of fertilizer and lime applications, low cropping intensity and low stocking rate. Land capability assessment and choice of appropriate land use are crucial to prevention of soil degradation. Measures to enhance soil quality include restorative fallowing, and soil-test based application of fertilizers and organic amendments. For several soils of the tropics in harsh climate, yield expectations should be comparatively low. It is the intensive land use, none or low levels of off-farm inputs, and neglect and misuse of resources over a long period that reduce soil resilience, accentuate degradation, jeopardize soil quality, and decrease sustainability of soil and water resources.

Table 40 Basic principles and technological options for enhancing sustainable use of soil and water resources

Strategy	Technological Options
Enhance soil structure	Mulch farming, conservation tillage, cover crops
Improve soil organic matter content	Application of organic waste, green manuring, conservation tillage
Reduce compaction	Conservation tillage, paraplow or sub-soiling, guided traffic
Improve nutrient cycling	Agroforestry, conservation tillage, multiple cropping, organic matter application
Enhance soil fertility	Balance nutrient application, apply nutrients according to expected yields, recycle organic wastes
Manage soil acidity	Liming, application of appropriate types of fertilizer, use acid tolerant varieties and crops
Salinity and alkalinity management	Appropriate cropping systems e.g., rice based rotation to enhance leaching, gypsum application for alkaline soils, soil amendments

XIX. RESEARCH AND DEVELOPMENT PRIORITIES

The need to develop sustainable systems of soil and water management is more now than ever before. Although some information is available on basic principles of soil and crop management, less is known about quantitative relationships between soil indicators and productivity. The data base to improve our understanding of the quantitative magnitude or the extent of soil degradation and the cause-effect relationship is rather narrow, especially with regards to soil physical and hydrological indicators and underlying processes. Consequently, there are several researchable issues:

1 Analytical procedures: Simple and reliable methods are needed for quantification of soil physical and hydrological indicators with relevance to highly variable soils in harsh and extreme tropical environment. These analytical techniques should be field-oriented, based on mechanical rather

than electronic devices, and have special relevance to agronomic productivity as measured by crop and animal production, and environmental regulatory capacity for filtering and detoxifying pollutants and wastes applied to the soil, soil's capacity to retain and recycle nutrients, and soil's ability to regulate water supply.

2 Limiting properties and processes: It is important to identify properties and processes that limit productivity and accentuate degradative processes. Such information is fundamental for identification of appropriate land use and choice of suitable soil and crop management systems. Limiting properties and processes are different for different land uses. Is soil depth or pH more important than CEC and organic matter content?

3 Interactive processes: Both degradative and restorative processes are often inter-related. Decline in soil structure can cause compaction, increase in compaction accelerates runoff, high runoff accentuates erosion and aggravates drought. It is particularly important to determine inter-relationship between soil physical and biological processes, soil biological and chemical or nutritional processes, and soil physical and nutritional processes. Similar interactive relationships should also be established among soil physical, chemical, and biological properties that regulate these processes.

4 Critical limits: A little is known about critical limits of soil indicators with regard to productivity and environmental regulatory functions. These limits differ among soil types, land use, crops, and management. It is important to recognize that management has an important impact on critical limits, the limits being more extreme for science-based compared with resource-based or low input systems. Critical limits may also be different for different objectives or strategies. These limits need to be identified with regard to: (i) choice of land use, (ii) deciding inputs for maintaining an expected level of productivity, (iii) preventing or minimizing degradation risks, and (iv) reversing degradative trends. For example, it is important to determine: (i) quantity and quality of soil organic matter content for maintaining soil structure, (ii) available water capacity to minimize risks of drought, (iii) toxic levels of Al or Mn in relation to root growth, (iv) tolerable level of soil loss, (v) threshold level of soil temperature for seed germination and seedling establishment, (vi) oxygen diffusion rate for adequate aeration, (vii) bulk density and soil strength that limit root growth of different crops, (viii) mean weight diameter and strength of aggregates to minimize slaking and crusting, (ix) crust strength that limit seedling emergence, and (x) soil biodiversity and activity of earthworms that regulate macroporosity and mineralize organic wastes.

Understanding critical limits is also essential to choosing an appropriate strategy for soil restoration. What are the critical limits of essential soil properties and processes beyond which the soil is irreversibly degraded? Such information is extremely important to land use planning and for taking land out of the degradative use before it reaches the point of no return.

5 Soil resilience: Quantifying soil resilience, along with underlying properties and processes and methods of their determination, is important to developing sustainable use of soil and water resources. Resilient soils can withstand intensive and somewhat excessive or inappropriate land use better than non-resilient soils. Processes and properties that govern soil resilience should be identified and their critical limits established.

6 Coefficient of sustainability: Sustainability quantification is important with reference to the most limiting soil property or the non-renewable resource e.g., non-rechargeable ground water, shallow top soil depth, etc. Although basic principles may be known, suitable coefficient of sustainability and underlying critical or limiting soil properties and processes differ among soils and agroecological regions. Development, validation and adaptation of these coefficients is important to transfer qualitative and vague concepts of sustainability into objective, quantitative and measurable entities.

7 Soil quality indicators: Similar to coefficients of sustainability, there is also a need to develop soil quality indicators. Soil indicators and their critical limits differ among soils, land uses and management systems. Soil quality indicators may also depend on the type of soil quality. MacDonald et al. (1993) identified two types of soil quality:

(a) Inherent soil quality is related to the capacity of the soil to perform critical functions which do not change with time. Indicators of inherent soil quality may be parent material, total elemental composition, etc.

(b) Labile or dynamic soil quality is related to soil functions which are time-dependent. Dynamic soil quality can change with time especially due to management. The change may be due to: (i) biological factors or (ii) land use or management factors.

These indicators, related to objective and environmental factors, should be developed and adopted under site-specific situations in relation to the type of soil quality.

8 Minimum data set: The minimum data set for soil sustainability indicator is also different depending on objectives, soil characteristics, land use, management systems, and the scale of assessment. With reference to spatial scale, the minimum data set and intensity of measurement depends on the areal extent e.g., watershed, region, political or national boundaries. These data sets must be established.

9 Quality control standards: Data accuracy and reliability should be checked against reference standards established for field and laboratory techniques, for biological and physical parameters, for properties and processes, and for indices of soil quality and sustainability. Such standards should be generalized and preferably developed by professional societies e.g., International Society of Soil Science, Soil Science Society of America, etc.

10 Modeling: Models, although no substitute for good quality experimental data, are useful tools to identify knowledge gaps and extrapolate information to similar soils and environmental conditions elsewhere. There is a need to develop process-based or conceptual models to assess sustainability of soil and water resources for different land use and management systems. Conceptual modes are also needed to develop soil quality indicators with reference to productivity, and environmental regulatory functions. It will be useful to develop predictive ability to forecast rate of soil degradation or rate of soil restoration in relation to land use, management, soil properties, and predominant processes.

XX. CONCLUSIONS

Sustainable use of soil and water resources is more important in the tropics now than ever before because of: (i) land hunger and shortage of prime agricultural land, (ii) low productivity of resource-based and predominantly subsistence agriculture practiced in the tropics, (iii) susceptibility of soils to degradative processes prevalent in harsh environment and perpetuated by low-input agricultural systems, (iv) ecological sensitivity of some tropical regions in terms of global impact e.g., the greenhouse effect, (v) widespread poverty, malnutrition, drudgery and sub-standard living of majority of agricultural population, and (vi) lack of institutional support in these regions to effectively address the issues of resource management.

The concept of sustainability has received an enthusiastic and a widespread response from scientists and policy makers. Despite the urgent need for developing and adopting systems for sustainable use of soil and water resources in the tropics, the concept remains to be vague, subjective, qualitative and merely an emotional rhetoric. It is important, therefore, that objective and science-based criteria are developed and standardized for quantitative assessment of sustainability especially in relation to soil and water resources.

Indices or coefficients of sustainability can be defined in terms of productivity trends over time per unit input or use of the most limiting or critical resource. Relevant indices of sustainability are those that provide a quantitative measure of trends in productivity and soil quality indicators over time.

Choice of an appropriate index of sustainability depends on several factors including objectives of assessment, land use, management, and scale of measurement. There are 3 types of operational scales e.g., temporal, spatial and system. With reference to tropical ecosystems, it is appropriate to assess productivity for cropping system over a farm level for about 10 years.

Inherent soil quality and its productivity depend on some key properties. A set of key properties or soil indicators differ among soil types, land use, management and agroecological factors. The choice of key properties also depend on predominant soil-modifying processes. Indicators of soil physical and hydrological properties include texture, structure, effective rooting depth, plant available water capacity, and infiltration rate. Important processes modifying soil physical indicators are accelerated soil erosion and desertification, compaction and hard-setting, leaching, anaerobiosis and drought. Relevant soil chemical indicators are pH, CEC, nutrient reserves, and concentration of toxic elements. Modifiers of soil chemical indicators are acidification, leaching, volatilization, and nutrient depletion. Important soil biological indicators are total and bioreactive soil organic carbon content, and soil biodiversity. Activity and species diversity of soil fauna are important biological indicators. Modifiers of soil biological indicators are erosion, anaerobiosis, compaction, etc.

In addition to soil and water characteristics, crop productivity is an important indicator of sustainability. Productivity can be measured in terms of land use intensity (e.g., land use factor, LER, ATER, etc.), biomass production, or harvest index. Productivity can also be estimated by several models e.g., PI, EPIC, etc.

Assessment of soil indicators should be done by standard methods so that results are comparable. These measurements should be made on a series of long-term experiments established in benchmark soils in representative ecoregions. Sustainability of soil and water resources in these long-term experiments should be assessed for traditional systems of land use and management or control in comparison with several new and innovative systems embodying science-based concepts and best management practices.

There is a need to develop scientific data base for developing quantitative and objective systems of sustainability assessment. Research is needed for developing analytical procedures, identifying productivity limiting processes and properties, delineating critical limits of soil and water indicators, quantifying soil resilience, and developing indices of sustainability and soil quality. It is also important to define the minimum data set needed for sustainability assessment, and to develop quality control standards. Development of predictive models can be useful for extrapolating results to similar soils and ecoregions.

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