AGL/MISC/36/2004

GUIDING PRINCIPLES FOR THE QUANTITATIVE ASSESSMENT OF SOIL DEGRADATION

With a focus on salinization, nutrient decline and soil pollution

AGL/MISC/36/2004

GUIDING PRINCIPLES FOR THE QUANTITATIVE ASSESSMENT OF SOIL DEGRADATION

With a focus on salinization, nutrient decline and soil pollution

by

G.W.J. van Lynden (Ed.)
S. Mantel
A. van Oostrum
International Soil Reference and Information Centre

FOOD AND AGRICULTURE ORGANIZATION OF THE UNITED NATIONS
Rome, 2004

Contents

List of tables	v
List of figures	v
Acknowlegements	vi
Preface	vii
1. Introduction	1
Soil and land degradation	1
Qualitative soil degradation assessments	1
Advantages and disadvantages of qualitative assessments	4
2. Land quality indicators and monitoring soil quality and productivity	7
Human impacts on land	7
Land quality indicators	8
Land quality indicators: definitions and relationships	9
Typology and selection of indicators	10
Indicators of soil and land conditions	14
Threshold and background values	14
Stratification by soil type	16
Monitoring land quality changes	16
Monitoring soil nutrient status and erosion at selected sites	17
False-time-series sampling	17
Benchmark sites for monitoring	17
Monitoring benchmark sites and statistical procedures	19
Scales of data and information for local assessment of soil degradation	21
3. Threshold values and estimation methods for selected types of degradation	23
Threshold values	23
Saline and sodic soils	23
Occurrence	23
Chemical and physical characteristics	25
Potential responses	25
Threshold values for salt-affected soils	26
Soil fertility	27
Selection of sites for fertilizer experiments	31
Assessment of soil nutrient status	32
Threshold values for soil nutrients	34
Soil pollution	34
Occurrence and effects of toxic elements	34
Thresholds	36

4. Quantitative determinations: approaches, procedures and quality management 39
Approaches 39
Sampling 40
Laboratory and field procedures 40
Method description 41
Quality management 42
Proficiency testing 42
Method selection on the basis of quantitative performance characteristics 43

5. Use of crop growth models to generate indicators of land productivity change 45
Introduction 45
An example: the Uruguay case study 46

6. Case studies 51
Monitoring changes of forest soils in Indonesia1 51
Logging-induced disturbance of the forest ecosystem 51
Indicators for change 51
Conclusions 54
Evaluation and monitoring of soil and water quality in Morocco1 55

References 57

List of tables

1. Degree of present degradation due to water erosion 2
2. Degree of present degradation due to salinization 2
3. Degree of present degradation due to nutrient depletion 2
4. Comparison of qualitative soil degradation assessment methodologies 3
5. Typology of environmental indicators 10
6. Common (generic) indicators for monitoring and evaluating sustainable land 11
7. Internationally accepted core (generic) land quality indicators 11
8. Examples of representative environmental performance indicators 13
9. Minimum data set for benchmark site characterization 14
10. Extent (000 ha) of global soil groupings by climatic zones 15
11. Parameters for degradation assessment and monitoring in the European Union 16
12. Soil properties (chemical, physical, biological, and mineralogical) measured at benchmark sites 19
13. Summary of results of comparison of analytical results on 20 soil samples 20
14. Classification of saline and sodic soils 24
15. Characterization of water based on its potential to degrade soil properties 26
16. General interpretation of ECse 27
17. USDA ratings of relative crop tolerance to salinity 28
18. Crop salt tolerance levels (surface irrigation) 29
19. Elements required for plant growth 30
20. Input and output factors governing nutrient flows in the soil (in kg/ha per year) 32
21. Attributes of Land use Systems and their specification 33
22. Concentration (ppm) of trace elements in various soil-forming rocks and other natural materials 35
23. Dutch target and intervention values for total concentration of heavy metals in a standard soil (with 25 percent clay and 10 percent organic matter) 38
24. Element related constants for metals in soils 38
25. Trends in wheat yield gaps for different production situations (relative to constraint-free yields) expressed as percentage of total area suitable for mechanized, low-input wheat 47
26. Soil variables that may serve as indicators for logging-induced changes 52
27. Properties for description of current erosion damage 52
28. Summary of recommendations for an EMS 56

List of figures

1. Pressure-state-response framework 9
2. Scatterplot of P-Bray analysis on identical samples in two laboratories 20
3. Scatterplot of P-Olsen analysis on identical samples in two laboratories 20
4. Crop responses to soil salinity (ECse) and sodicity 24
5. Relative crop yield in relation to soil salinity (ECse) for plant salt tolerance groupings 27
6. Flow chart of modelling process to generate indicators of land change 47
7. Water-limited yield for wheat in Uruguay 48
8. Suitability map for low-input wheat in Uruguay 48
9. Erosion risk map for wheat in Uruguay 48
10. Water-limited yield decline after 20 years erosion scenario in Uruguay 49
11. Experimental layout of monitoring erosion status using toposequences 53

List of boxes

1. Issue: resources availability 12
2. Issue: soil management strategies 12
3. Cluster of LQIs 13

Preface

There are areas with degraded soils in most if not all countries, and soil degradation is a serious and widespread process in various countries. Global maps of the extent and severity of several types of soil degradation are available, and some countries have more detailed information for their territories. To date, most of this information is qualitative, but quantitative data and assessments are still lacking and if undertaken would be very useful for planning and prioritizing restoration or remediation activities.

To date there is no single set of guidelines and procedures for the quantitative assessment of the different kinds of land degradation, but several countries and institutes have been developing methods and standards and have tested and applied them to specific sites.

This document is intended for government institutes and others concerned with the quantitative assessment of soil degradation. These guiding principles would be also useful in the implementation of the Land Degradation Assessment in Drylands (LADA) project, which FAO in collaboration with other institutions is currently piloting in selected countries. It discusses principles and provides examples of experimental, preliminary as well as locally or nationally tested and applied procedures and standards from different countries, with a focus on salinization, fertility decline and soil pollution.

The users of this document are encouraged to communicate their views and experiences to the Land and Plant Nutrition Management Service (AGLL) of FAO, with a view to its modification and updating.

It is hoped that this document will stimulate bilateral contacts and information exchange, as well as promote steps towards harmonization of quantitative approaches and procedures of soil degradation assessment.

Acknowlegements

This publication was jointly prepared by the Land and Plant Nutrition Management Service (AGLL) of the Land and Water Development Division (AGL) of FAO and the International Soil Reference and Information Centre (ISRIC) of the Netherlands.

Special thanks are given to H. Nabhan and P. Koohafkan (AGLL) for conceptualization and initiation of this document, technical guidance, inputs and reviews. The contribution of G. van Lynden, S. Mantel and A. van Oostrum (ISRIC) in the preparation of these guiding principles is highly acknowledged. Technical editing and review by R. Brinkman, R. Tassone and I. Verbeke are highly appreciated.

Chapter 1
Introduction[1]

This document discusses guiding principles, rather than a comprehensive set of guidelines for quantitative soil degradation assessment, since these are different for each type of soil degradation, current or intended land use, and site characteristics. Each kind of soil degradation needs a distinct assessment method, in terms of analytical or field data needed as well as of model formulation. For example, the effects of water erosion on soil properties are totally different from those of pollution. The impact of soil fertility decline may be serious on agricultural land, but is generally irrelevant for an envisaged construction site or other non-agricultural land uses. This document highlights issues and factors that should be considered when embarking on a quantitative soil degradation assessment. Strong points and disadvantages, data requirements and appropriateness at different scales of quantitative approaches are analysed in comparison with qualitative assessments.

Soil and land degradation

In order to avoid misunderstanding it is necessary to define what is meant by soil and land degradation respectively.

Soil degradation, as defined for the GLASOD map, is "a process that describes human-induced phenomena which lower the current or future capacity of the soil to support human life" (Oldeman *et al.* 1991). In a general sense, soil degradation could be described as the deterioration of soil quality, or the partial or entire loss of one or more functions of the soil (Blum 1988).

Land degradation is the reduction in the capability of the land to produce benefits from a particular land use under a specified form of land management (after Blaikie and Brookfield 1987). Soil degradation is one aspect of land degradation; others are degradation of vegetation or water resources.

Not all problem soils are degraded soils. Degraded soils have properties that have recently been altered in a negative sense through human intervention or by natural processes with immediate effect, such as extreme rainfall events. They should not be confused with *problem* soils, which have unfavourable characteristics created by natural, long-term soil-forming processes: for example rocky soils in mountainous areas, desert soils or saline soils.

Qualitative soil degradation assessments

Qualitative assessments of soil degradation have been used for some global or (sub)continental studies, such as the Global Assessment of Human-induced Soil Degradation (GLASOD; Oldeman *et al.* 1991), the Assessment of Soil Degradation in South and Southeast Asia (ASSOD; van Lynden and Oldeman 1997) or in the context of the Soil Vulnerability Assessment in Central and Eastern Europe (SOVEUR; van Lynden 2000). These were potentially subjective, being based on the perception by experts of the intensity of the degradation process and the impact

[1] G.W.J. van Lynden

TABLE 1
Degree of present degradation due to water erosion

Slight:	- in deep soils (rooting depth more than 50 cm): part of the topsoil removed, or with shallow rills 20–50 m apart, or both.
	- in shallow soils (rooting depth less than 50 cm): some shallow rills at least 50 m apart.
	- in pastoral country the ground cover of perennials of the original or optimal vegetation is in excess of 70%.
Moderate:	- in deep soils: all topsoil removed, shallow rills less than 20 m. apart or moderately deep gullies 20–50 m apart or a combination.
	- in shallow soils: part of topsoil removed, shallow rills 20-50 m apart, or both.
	- in pastoral country: ground cover of perennials of the original or optimal vegetation ranges from 30 to 70%.
Severe:	- in deep soils: all topsoil and part of subsoil removed, moderately deep gullies less than 20 m. apart, or both.
	- in shallow soils: all topsoil removed: lithic or leptic phases or with exposed hardpan.
	- in pastoral country: ground cover of perennials of the original or optimal vegetation is less than 30%.

Source, Oldeman 1988

TABLE 2
Degree of present degradation due to salinization

Salinization should be considered as the relative change over the past 50 years in salinity status of the soil, the latter being defined as follows:

Non-saline:	- electrical conductivity less than 5 dS/m; E.S.P.< 15%; pH < 8.5
Slightly saline:	- electrical conductivity 5-8 dS/m; E.S.P. < 15%; pH < 8.5
Moderately saline:	- electrical conductivity 9-16 dS/m; E.S.P. < 15%; pH < 8.5
Severely saline:	- electrical conductivity more than 16 dS/m; E.S.P. < 15%; pH < 8.5

The present degree of human-induced salinization can be identified as a change in salinity status as follows:

Slight:	- from non-saline to slightly saline; from slightly to moderately saline, or from moderately saline to severely saline.
Moderate:	- from non-saline to moderately saline, or from slightly saline to severely saline.
Severe:	- from non-saline to severely saline.

Source, Oldeman 1988

TABLE 3
Degree of present degradation due to nutrient depletion

Criteria to assess the degree of present degradation are the organic matter content; the parent material; climatic conditions. The nutrient depletion by leaching or by extraction by plant roots without adequate replacement is identified by a decline in organic matter, P, CEC (Ca, Mg, K).

Slight:	- Cleared and cultivated grassland or savannas on inherently poor soils in tropical regions.
	- Cleared or cultivated formerly forested land in temperate regions on sandy soils, or in tropical (humid) regions on soils with rich parent materials.
Moderate:	- Cleared and cultivated grassland or savannas in temperate regions, on soils high in inherent organic matter, when organic matter has declined markedly by mineralization (oxidation).
	- Cleared and cultivated formerly forested land on soils with moderately rich parent materials in humid tropical regions, where subsequent annual cropping is not being sustained by adequate fertilization.
Severe:	- Cleared and cultivated formerly forested land in humid tropical regions on soils with inherently poor parent materials (soils with low CEC), where all above-ground biomass is removed during clearing and where subsequent crop growth is poor or non-existent and cannot be improved by N fertilizer alone.
Extreme:	- Cleared formerly forested land with all above-ground biomass removed during clearing, on soils with inherently poor parent materials, where no crop growth occurs and forest regeneration is not possible.

Source, Oldeman 1988

on agricultural suitability, biotic function or decline in productivity. Semi-quantitative sets of criteria were suggested for water and wind erosion in relation to soil depth and for salinization, and qualitative criteria for other kinds of degradation, such as nutrient depletion; Tables 1–3, from the GLASOD guidelines, (Oldeman 1988). So far there are no quantitative assessments of soil degradation at small (e.g., continental) scales.

In the ASSOD assessment, the seriousness of degradation was expressed in terms of the impact of degradation on productivity for three management levels, rather than its degree of severity.

For SOVEUR, both degree (as in GLASOD) and impact (as in ASSOD) were assessed, the degree reflecting the intensity of the process, such as tonnes of soil lost by erosion, the impact reflecting the inferred change in productivity. The impact on productivity was assessed for all types of degradation, but additional impact classes were applied for pollution, in view of its importance for human and animal health and the entire ecosystems. A comparison of these methodologies is given in Table 4.

Based on the experiences with GLASOD, ASSOD and SOVEUR, general guidelines have been developed for the qualitative assessment of soil degradation (FAO 2001). Degradation is

Table 4
Comparison of qualitative soil degradation assessment methodologies

	GLASOD	ASSOD	SOVEUR	GENERAL
Coverage	Olobal	South and Southeast Asia (17 countries)	Central and Eastern Europe (13 countries)	General
Scale	1:10M (average)	1:5M	1:2.5M	Variable
Base map	Units loosely defined (physiography, land use, etc.)	Physiography, according to standard SOTER methodology	Physiography and soils, according to standard SOTER methodology	SOTER maps or other as appropriate
Status assessment	Degree of degradation + extent classes (severity)	Impact on productivity (for three levels of management) + extent percentages	Degree and impact + extent percentages	Degree and impact + extent percentages far major land use types
Rate of degradation	Limited data	More importance	As for ASSOD	As for ASSOD
Conservation	No conservation data	Some conservation data	No conservation data	No conservation data, but close link with WOCAT
Detail	Data not on country basis	Data available per country	Data available per country	Depends on scale
Cartographic possibilities	Maximum 2 degradation types per map unit	More degradation types defined, no restrictions for number of types per map unit	As for ASSOD, but special emphasis on pollution	As for ASSOD
End product	One map showing four main types with severity	Variety of thematic maps with degree and extent shown separately	As for ASSOD	As for ASSOD
Databasse/ GIS	Digital information derived from conventional map	Data stored in database and GIS before map production	As for ASSOD	As for ASSOD
Source	Individual experts I	National institutions	National institutions	Regional, national or local institutions

assessed for the major land use types occurring within a delineated unit on a soil and terrain map, specifying the extent, degree, impact, rate and causative factors of various degradation types for each land use type. This degradation assessment has now been integrated as one component of the WOCAT mapping methodology (World Overview of Conservation Approaches and Technologies, Liniger *et al.* 2002), the other components being assessments of soil and water conservation technologies and the effects on productivity.

At detailed scales, for example in local assessments, a far wider range of soil and terrain features lends itself to field observation and interpretation, and a participative approach is appropriate, jointly with the land users. Detailed guidelines and examples are given in the Handbook for the field assessment of land degradation (Stocking and Murnaghan 2001).

Advantages and disadvantages of qualitative assessments

Some advantages of qualitative assessments are:

- a wide range of different degradation types can be addressed simultaneously, at multiple scales;
- they can provide a relatively quick overview for national and regional planning;
- they enable identification of hot spots and bright spots (problem areas and examples of effective responses) for further study;
- they constitute a good tool for awareness raising;
- the data requirements are limited: adequate expert knowledge, though preferably supported by hard data, is sufficient.

Some disadvantages are:

- a general lack of hard supporting data;
- the potentially subjective character;
- the information being based on expert knowledge and existing data, may not always be up to date;
- temporal or spatial comparisons are more difficult;

It can be argued that by its very nature, degradation assessment is qualitative, since "Degradation implies a loss of value. In this sense, the assessment of degradation is a value judgement…." (López-Bermúdez et al.). Perception of that value is also depending on the user of the land: the land qualities important for a farmer are very different from those of importance for a construction engineer.

> "Qualitative indicators have the advantage of providing richness and intuitive understanding that numerical data cannot convey. But [their] assessment may be even more demanding than the assessment of quantitative indicators. In addition they are more difficult to present and appear therefore less accurate than quantitative data" (SRDIS and CIESIN 2001).

The accuracy of quantitative assessment should be judged with care and caution, however. "Quantitative indicators are preferred as they are perceived to be simple, clear, accurate and valid. However, reliable quantitative data are rare in most developing countries. Sampling, handling, analysing and interpreting may be biased, due to inexperienced or poorly trained personal and lack of appropriate equipment and materials. Data collection only makes sense if a certain quality is guaranteed." (SRDIS & CIESIN 2001). So-called objective, quantitative measurements may also have an element of subjectivity that is caused by the choice of measurement method, the selection of variables to be measured, and the interpretation of the measured data.

Chapter 2
Land quality indicators and monitoring soil quality and productivity[1]

HUMAN IMPACTS ON LAND

There is an increase in concern in society about the state of the environment. Along with air and water, soil is increasingly recognized as a vital part of the human environment. Soil has different functions in our ecosystem. For each of these functions qualities may be defined and monitored (White 1997). Concerns with pollution and sinks in the ecosystem (air, water and soil pollution, greenhouse gases, etc.), have a high political profile in industrialized countries, while developing countries often face direct problems with maintenance of the basic resources of the economic system and the environment, such as soil productivity and biodiversity (Herweg *et al.* 1998). A range of qualities and functions of land needs to be considered when assessing the impact of land use and management on the environment. Waste disposal sites, for example, are being developed as recreational parks or golf courses in Western Europe, adding to the quality of the land of the site (provided that proper measures will have been taken to control the harmful processes in the waste, such as leaching of toxins to the groundwater). Such sites have limited potential for other functions, such as agriculture, construction or nature development. On the other hand, existing natural or agricultural systems may be degrading in terms of qualities that are not reflected in the actual land uses.

Achieving sustainability is a problem of equilibrium, which applies at all scales and to all aspects of land use (Driessen 1997). Increased food production to meet the nutritional needs of an increasing population can only be expected from intensification and modification of existing cropping systems, as expansion of arable land in most countries implies taking marginal lands into use. Often farmers are using technologies suited to high-potential regions that are not adapted to ecologically fragile areas (Ndegwa 1997). The extent of land available for expansion of agriculture is generally overestimated, and population increase will augment problems of landlessness, land degradation, and food security (Young 1998).

Herweg et al (1998) argue that there is no standard definition of sustainability, because it incorporates several, sometimes even conflicting issues, requiring reconciliation at the local and policy level. These include:

- *Individual perceptions*: farmers, pastoralists, forest dwellers, fishermen, policymakers, scientists, even men and women within the same family may define sustainability differently, according to their own attitudes and economic, social and ecological interests, which often vary widely and are not easily harmonized.
- *Spatial considerations*: water use in tropical highlands, for example, may be sustainable for the people in the highlands, but unsustainable in less humid lowlands downstream, where it can lead to water shortage; or unsustainable land use practices by farmers in the upper part of a catchment may contribute to flash floods or a decline in the quality of drinking water for urban dwellers far downstream.

[1] S. Mantel

- *Temporal scales and perspectives*: it is not possible –and probably not desirable– to define sustainability today on behalf of the next generation. But it is possible to maintain the potential of land resources so that future generations can develop their own values, priorities and possibilities to satisfy their needs.

Land quality indicators

Indicators describe the rate, intensity or magnitude of complex processes. Indicators are statistics or measures that relate to a condition, change of quality, or change in state of something valued. They provide information and describe the state of the phenomena of interest, but with a significance beyond that directly associated with an individual parameter (OECD 1993). Indicators should be developed in accordance with their intended applications, and this requires reliable statistics and other data. Because of regional requirements and priorities, achieving global agreement on a single set of indicators would be difficult and unnecessary for many issues. However, a common aggregate of key indicators could be used as a basis for international comparison (Dumanski 1994; Bakkes *et al.* 1994). Such indicators may used to monitor land changes and to determine whether the quality of land remains stable, or is declining or improving. They are criteria by which the sustainability of land use systems or the environmental impact of land management can be judged.

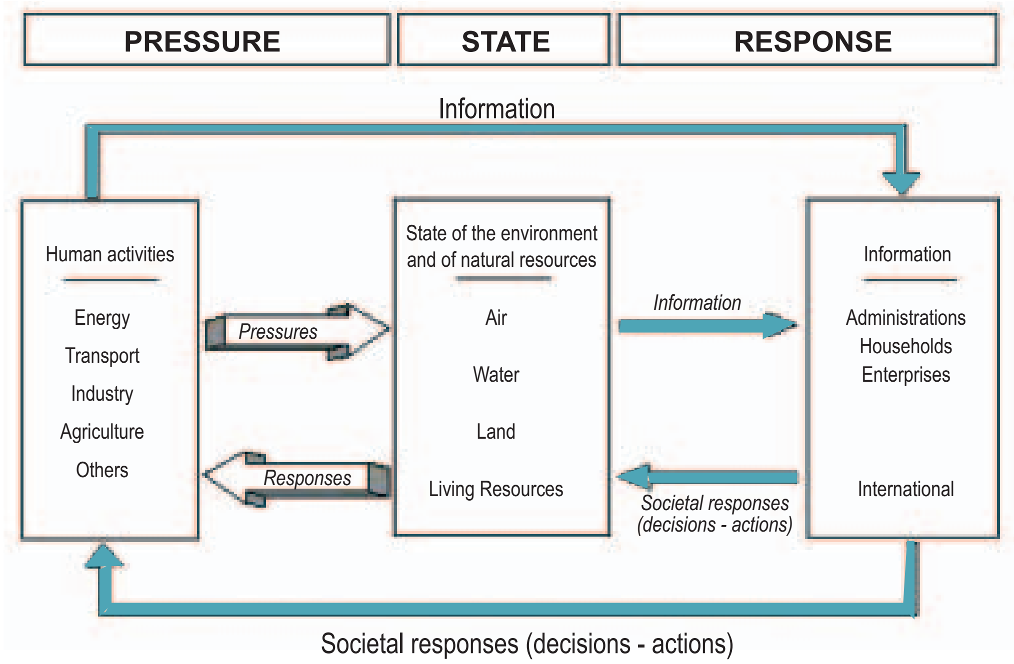
The World Bank developed a programme in cooperation with FAO, UNEP and other institutions to develop land quality indicators using a common framework. The indicators developed under this LQI initiative should support policy and programme formulation for district, national and global assessment and environmental impact monitoring; promote technologies, policies and programmes; and ensure better use of natural resources and sustainable land management (Land Quality Indicators program, World Bank *et al.* 2001).

The term land quality indicator has gained recognition under its own meaning and is distinct from the term land quality used in the Framework for Land Evaluation. Indicators of pressure show the pressure on land from human activities. Indicators of state describe the land resource conditions, and changes in this condition over time. Response indicators reflect the action taken by society, in the form of governments, organizations and individuals, in reaction to pressures or changes in the state of a resource.

The (earlier) definition of a land quality (LQ) in the FAO framework for land evaluation (FAO 1976) is very different. In that framework a land quality is a set of interacting land characteristics, each of which acts in a distinct manner in its influence on the suitability of land for a specified use. Examples of land qualities are availability of nutrients, resistance to erosion and water availability to a crop (influenced by land characteristics –properties of the land that can be measured or estimated– such as available water capacity, rainfall, soil depth, hydraulic conductivity).

The LQI initiative is based on the pressure-state-response framework. The pressure-state-response model was developed in the 1970s by the Canadian statistician Anthony Friend, and subsequently adopted by the State of the Environment (SOE) group of the Organisation for Economic Cooperation and Development (OECD). This framework places land resources in the context of society and the interaction among policies, the economy and management measures (Figure 1).

Figure 1
Pressure-state-response framework.



Source: Dumanski 1998; OECD 1993.

An extension of this causal framework (DPSIR: Driving forces, Pressures, States, Impacts, Responses) has been developed by the European Environment Agency (Gobin *et al.* 2001). This has also been adopted in the LADA project (Land Degradation Assessment in Drylands).

Land quality indicators: definitions and relationships

Different concepts and definitions have emerged that describe land and soil conditions and change. The definition of some land change concepts are summarized below, to the extent that there is a degree of consensus on how these should be applied.

Soil quality is the capacity of a specific soil to function within natural or managed ecosystem boundaries to sustain plant and animal production, maintain or enhance water quality, and support human health and habitation (SSSA 1994).

Land quality in the LQI framework is the condition, state or health of the land relative to human requirements, including agricultural production, forestry, conservation, and environmental management (Pieri *et al.* 1995).

Sustainable land management combines technologies, policies and activities aimed at integrating socio-economic principles with environmental concerns so as to simultaneously maintain or enhance production, reduce the level of production risk, protect the potential of natural resources and prevent (buffer against) soil and water degradation, be economically viable, and be socially acceptable (Smyth and Dumanski 1993).

These are more than simple differences in semantics; the concepts differ in the kinds and scales of the processes being described, the data used for input, and the amount and kinds of integration with other disciplines (SRDIS and CIESIN 2001).

These concepts span the scales of detail, application, and levels of integration with socio-economic data. Soil quality is the most restrictive, followed by land quality and then sustainable land management. Soil quality is effectively a condition of a site, and it can be studied using soil data alone. Land quality requires integration of soil data with other biophysical information, such as climate, geology and land use. Land quality is a condition of the landscape, i.e. it is a biophysical property, but includes the impacts of human interventions (land use) on the landscape. Sustainable land management requires the integration of these biophysical conditions, i.e. land quality, with economic and social demands. However, the concepts form a continuum over the landscape, and they are useful for different types and scales of land use (SRDIS and CIESIN 2001).

The definitions sometimes overlap, and the terms are often used interchangeably. To avoid (further) confusion or misinterpretation it is important that definitions are strictly applied and explained when used.

Typology and selection of indicators

For the identification of policy-relevant indicators on soil issues, the European Environment Agency has defined a typology of environmental indicators (Table 5).

The first type of indicators is descriptive (Type A). These indicators give information on what is happening to the environment, and provoking the question 'Does it matter?' The second type (B) comprises performance indicators, and 'It matters' can be the reply, depending on the value of these indicators with respect to the relevant reference value or threshold. If performance indicators show that there is a problem (or in the absence of a standard reference value or a policy target value, if a type A indicator shows that there could be a problem), improvement can be estimated through the efficiency indicators (type C), which measure the eco-efficiency of production and consumption processes. They can often be compiled merging two type A indicators. Finally, the indicators relevant to total welfare (type D) answer the question 'Are we better off on the whole?' (Gobin *et al.* 2001).

Generic indicators, or at least common indicator themes, are essential as national and international standards for purposes of comparison, for monitoring and evaluating sustainable land management, and in order to focus research on those indicators that are strategically the most important. Examples are listed in Table 6 (SRDIS and CIESIN 2001).

International agreement has been achieved on the Core LQIs recommended for Stream 1 research. Stream 1, or Core LQIs, are those where sufficient research has already been conducted

Table 5
Typology of environmental indicators

Type A :	*'What is happening?'* — For example vehicle kilometres driven, emissions to soil, soil losses, environmental expenditures for air pollution abatement ('descriptive indicators').
Type B :	*'Does it matter? '*— Indicators linked with some kind of reference value, such as the critical load or carrying capacity, health standards, or policy targets ('performance indicators').
Type C :	*'Are we improving?'* — The eco-efficiency of production and consumption processes, e.g. energy use per unit of GDP, use of fertilizers in agriculture production ('efficiency indicators').
Type D :	*'Are we on the whole better off?'* Environmental sustainability, e.g. Green GDP, etc. ('total welfare indicators').

Source: EEA 2001.

TABLE 6
Common (generic) indicators for monitoring and evaluating sustainable land

Productivity	Security	Protection	Viability	Acceptability
Crop yield	Soil cover Yield variability Climate	Soil quality, quantity Water quality, quantity Biological diversity	Net farm profitability Input use efficiency - pesticides - fertilizers - nutrients Off-farm income Return to labour	Use of conservation practices Farm decision-making criteria

Source: SRDIS 2001.

TABLE 7
Internationally accepted core (generic) land quality indicators

Indicators to be developed in the near term	Indicators requiring longer term research	Indicators being developed by other networks
Nutrient balance (multi-scale) Yield gap Land use intensity (RS, census) Land use diversity (RS, census) Land cover (RS, ground-truthing)	Soil quality Land degradation Agro-biodiversity	Water quality Forest land quality Rangeland quality Soil pollution

Source: SRDIS and CIESIN 2001; World Bank *et al.* 2001.

to establish a sound theoretical base, where sufficient data are already available, or where procedures for development, such as remote sensing, have been tested and are available. These LQIs are ready for immediate development, testing and implementation (Table 7).

The second stream research will test the LQIs identified in the first stream, but it should also promote new research and in particular, identify new LQIs related to impacts of land management on the landscape. It will often involve data analyses, but also field studies, modelling, and model calibration in selected Agro-Ecological Zones. The basis of this research is that robust LQIs can only be developed through thorough analyses and understanding of the cause-effect relationships that explain the impacts of human interventions; a priori selection of LQIs is not recommended, although some brainstorming is essential at the outset to develop a short list of potential LQIs for testing, and to better design the research programme. Consequently, research in the second stream will be longer term and more detailed and structured, so as to ensure the scientific rigour to produce robust indicators that will stand up under scientific scrutiny.

LQIs recommended for Stream 2 research are those requiring further development of their theoretical basis or lacking adequate data for development. Those identified so far are:

- Soil quality: likely to be based on soil organic matter turnover, particularly the dynamic (microbiological) carbon pool most affected by environmental conditions and land use change.
- Land degradation (erosion, salinization, compaction, organic matter loss, etc.): these processes have been much researched and have a strong scientific base, but reliable data on extent and impacts are often lacking.
- Agro-biodiversity: involves dual objectives of managing natural habitats and the co-existence of native species in agricultural areas, as well as managing the gene pools utilized in crop and animal production.

Sets of selected indicators identified during a recent international workshop (World Bank/ICRAF 1994) for resource availability and for soil management strategies are shown in Boxes 1 and 2, respectively.

Box 1

ISSUE: RESOURCE AVAILABILITY

Pressure Indicators

- productivity of arable land
- increased use of marginal lands
- increased cropping intensity.

State Indicators

- change in erosion
- change in productivity (yield/ha)
- change in water quality.

Response Indicators

- change in out-migration
- shift to more tolerant crops
- change in rate of land abandonment
- change in capital investment
- change in input use efficiency
- change in production systems
- any positive response action by government or institutions.

Box 2

ISSUE: SOIL MANAGEMENT STRATEGIES

Pressure Indicators

- technologies imported from other dissimilar environments
- technologies unrelated to range of natural variability or risk.

State Indicators

- gaining or declining in nutrient status
- gain or decline in organic matter
- gain or decline in yield per unit area or yield per unit input
- increase or reduction in wind or water erosion
- increase or reduction in runoff or storm events
- increase or reduction in acidification
- increase or reduction in variability.

Response Indicators

- increased use of manure and residues
- change to more tolerant crops, or to crop to livestock mix
- expansion of cultivated area or farm
- increase in abandoned or degraded land
- formation of farmer support groups or conservation clubs.

The following paragraph and Box 3 are taken from Benites (1998), where the use of LQIs for monitoring purposes was discussed. He states that in each situation there will be a different range of land factors for which changes could be observed, and from which indicators of change could be derived. Not everything that happens can or should be monitored. Land change indicators must be representative, indicative or a proxy for the factor considered important (such as production potential). Complex changes may be highlighted by a limited number of suitable indicators that are regularly monitored and compared with previous readings back to the baseline for each. Special studies might then be undertaken to characterize more details, for instance in agricultural development projects.

To measure changes, it is essential that the baseline conditions be established at the very outset for people's attitudes (both farmers and advisory staff) and for socio-economic and biophysical conditions. This agrees with what was stressed by Driessen (1984): "If the seriousness of erosion, and therewith the need for conservation measures or alternative land uses is to be made explicit, the initial productive capacity must be known as well as the effect of erosion on this productive capacity". To determine the nature, direction and rate of changes, assessments need to be made on a recurring basis and compared with baseline data. Land managers therefore require *land change indicators* to monitor and evaluate *what* is changing, the *processes* by which change is occurring, and the *sustainability* of beneficial changes. With carefully chosen key indicators, which may be direct or proxy, the work involved in monitoring the change is kept to a minimum. It is important that those making the measurements and observations make unbiased reports based on them, without favouring one interpretation or another: that is done during the periodic evaluations. Both farmers and researchers need to be involved in monitoring and subsequent evaluations.

Box 3

Clusters of LQIs

Pressure (or driving force) indicators

Estimates of the intensity of production, as well as the range of production systems used, number and types of products, and features describing the complexity of systems used, such as proportions of crop, pasture or grazing land; potentially arable and pasture lands; proportion of monoculture or mixed farming.

State (or condition) indicators

Measurements that express current quality of the land, as well as estimates of future land quality as reflected through land management practices such as estimates of actual to potential biological productivity; extent and severity of major soil constraints.

Response (from society) indicators

a. Automatic effect of the changes, if no positive response from society is made.

b. Measures employed through policies and programmes to create awareness of the problem, improve land management technologies, and counter or ameliorate the impacts of land degradation, such as the number and kinds of soil conservation awareness and education programmes or special credit programmes for soil conservation.

Source: Benites 1998.

Table 8 provides some examples of indicators for the Pressure-State-Response framework used in the major categories of environmental problems. It is not meant to be exhaustive. Impact or state indicators can be linked to more than one pressure and process, but are only mentioned once in this table.

Table 8
Examples of representative environmental performance indicators

Process	Outcome or Pressure	Impact or State	Comments
Soil fertility decline	• Nutrient removal in excess of fertilizer applications and natural regeneration	• Nutrient level (of N, P, K, and of other nutrients depending on the specific crops being grown); • Organic matter content; • Soil pH	Appropriate indicators are very site-specific.
Soil erosion	• Erosion rates	• Soil depth; • River sediment load; • Extent and severity of visible signs; • Total Factor Productivity (TFP); • Yield gap	
Soil pollution	• Heavy metals concentration	• Heavy metals concentration	The same indicators can serve as measures of *pressure* or *state*, depending on where they are measured.
Salinization	• Rainfall deficit, lack of drainage, lack of (good quality) irrigation water	• Concentration of salts in the soil (measured by electrical conductivity, sodium)	Appropriate indicators are very site-specific.

Source: World Bank 1996; Young 1998.

Indicators of soil and land conditions

Table 9
Minimum data set for benchmark site characterization

Properties	Parameters
Site characteristics	Elevation Slope Meteorological
Soil type	Classification Soil profile
Nutrients	Macronutrients (total and available)
Organic carbon	Total
Soil chemistry	pH CEC, exchangeable cations
Soil structure	Bulk density
Soil biology	Key species (earthworms)
Contamination	Selected heavy metals, e.g. Pb

Source: Huber *et al.* 2001.

For adequate assessment of land and soil conditions in relation to degradation, an understanding of the process of each degradation type is important. The measured parameters should adequately describe those land conditions that are the resultant of the degradation process. The selection of the measurement or observation method is critical and depends on the selected indicators and parameters for the degradation type. The measured or observed values must be judged against target values, threshold values or background or reference values that describe the natural condition (Huber *et al.* 2001). Reference values should be established for specific soils. Qualitative and quantitative descriptions and normal ranges for each of the properties should be available to facilitate the identification of anomalies in soil conditions. Table 9 provides an example of a minimum data set for the characterization of benchmark sites.

Threshold and background values

The threshold value can be related to a clear decline in land quality (status) or to a significant impact of degradation on land productivity or environmental functions. The background values reflect values and processes that occur in natural or "accepted" conditions. Soil is continuously variable in space and, being a complex, dynamic biological system, variable in time as well. The rate of change of individual soil properties itself is very variable. A first indication of background values can be obtained from the world soil distribution over climatic zones. Table 10 shows that certain soil forming processes and degradation processes are restricted to specific climate zones. It sets a very broad standard for land-ecoregions. Highly weathered soils are mostly found in the tropical and subtropical areas that have high temperatures and rainfall (leaching conditions). The parent rock that is the substrate on which such soils often have developed is another contributing factor in the process (e.g. old, pre-weathered parent rock on the African shield). Dominant soils in the temperate and cold zones are characterized by accumulation of organic matter. Inland salinization (i.e. not including intrusion of seawater) is restricted to the arid and seasonally dry tropics and subtropics. Wind erosion is dominant in arid and seasonally dry areas. Water erosion, though common in most climate zones, is widespread particularly in the seasonally dry tropics and subtropics.

Each of these degradation types can be defined by the conditions in which they occur, the processes of their formation, the main drivers of these processes, the variables by which they can be measured, and the threshold values of these variables, which depend on the land use, vegetation, land unit and climate.

The occurrence or intensity of degradation processes is linked to specific parts of the landscape, to certain climatic zones, and to specific kinds of land use and management. Threshold values

TABLE 10
Extent (000 ha) of global soil groupings by climatic zones (based on FAO 1993)

FAO Major soil group	Description	Mediterranean	Temperate	Cold	Boreal	Mountainous	Arid	Seasonally dry (sub)tropics	Humid (sub)tropics	Total area
Organic soils										
Histosols	Soils rich in partly decomposed organic materials	1 823	10 070	86 599	125 873	792	3 410	12 232	32 449	273 248
Soils conditioned by parent material										
Andosols	Soils derived from volcanic glass	1 795	7 874	13 640	14 582	20 683	9 418	18 379	20 674	107 045
Arenosols	Weakly developed and coarse textured soils	23 176	16 694	11 669	0	6 980	395 942	320 140	127 284	901 885
Vertisols	Swelling and shrinking heavy clays	14 982	15 282	0	0	3 820	51 243	222 983	29 012	337 322
Soils conditioned by topography or physiography										
Fluvisols	Alluvial soils	14 430	28 777	30 318	29 668	4 401	90 074	84 360	66 207	348 235
Leptosols	Weakly developed shallow soils	30 441	28 705	22 935	344 382	544 330	419 462	198 332	66 731	1 655 318
Gleysols	(Grey) Soils under excess of water	4 925	59 388	30 749	298 904	11 002	34 492	111 543	167 704	718 707
Regosols	Loose mantle overlying a hard rock core	18 203	1 473	13 606	278 190	35 916	170 083	52 109	9391	578 971
Soils conditioned by their limited age										
Cambisols	Young soil showing signs of development	68 434	163 362	58 821	337 989	153 299	503 586	192 294	95 617	1 573 402
Soils conditioned by a wet (sub)tropical climate										
Plinthosols	Soils with mottled clays that harden when dry	0	2 816	0	0	255	53	15 657	42 354	61 135
Ferralsols	Chemically poor soils high in sesquioxides	0	0	0	0	4 036	0	231 347	507 217	742 600
Nitisols	Physically stable moderately fertile soils	647	3 010	0	0	9 996	2 792	101 782	87 291	205 518
Acrisols	Physically unstable acid soils, aluminium toxic	11 461	142 297	0	0	13 581	1 067	238 808	589 386	996 600
Lixisols	Strongly weathered soils, low fertility	0	174	0	0	11 390	26 397	366 862	31 697	436 520
Soils conditioned by a (semi-)arid climate										
Solonchaks	Saline soils	10 981	6 122	1 051	0	3608	140 324	20 824	4 415	187 325
Solonetz	Sodium saturated soils	8 139	5 687	21 748	0	5367	57 037	36 771	518	135 267
Gypsisols	Soils high in calcium sulphate (gypsum)	1 586	0	0	0	1666	86 711	54	0	90 017
Calsisols	Soils high in calcium carbonate	85 876	42 693	15 258	1 753	44 857	552 765	47 267	5 430	795 899
Soils conditioned by a steppic climate										
Kastanozems	Brown or chestnut soils rich in organic matter	27 584	131 298	92 851	9 754	17 569	143 513	44 729	459	467 757
Chernozems	Black soils rich in organic matter	377	65 097	140 867	9 281	1 802	11 794	0	0	229 218
Phaeozems	Dark-coloured soils rich in organic matter	9141	99 064	11 831	5 441	8 721	2 089	15 249	2 703	154 239
Greyzems	Org.matter-rich soils w.uncoated silt and sand	0	1998	19 556	5 089	5 010	2 230	0	0	33 883
Soils conditioned by a (sub)humid temperate climate										
Luvisols	Moderately weathered, fertile soils	65 878	187 615	111 213	20 930	13 541	165 499	62 002	21 827	648 505
Podzoluvisols	Intermediate soil between Luvisol and Podzol	0	43 282	153 253	107 172	17 358	0	0	0	321 065
Planosols	Seasonally waterlogged soils in level land	15598	25 842	1057	678	2 609	3 762	74 083	6 267	129 896
Podzols	Coarse soils with strongly bleached horizons	6837	58 752	213 362	179 157	3 221	1 366	13 475	11 343	487 513
Total area		422 314	1 147 372	1 050 384	1 768 843	945 810	2 875 109	2 481 282	1 925 976	12 617 090

Note: The grey areas of the table represent the climatic zones in which the soils have their lagest global extent.

Table 11
Parameters for degradation assessment and monitoring in the European Union

Degradation type or process	Parameter
Desertification	• Rain aggressiveness • Evapotranspiration • Vegetation cover or biomass • Specific key species.
Acidification	• Acid deposition (wet and dry) • Exchangeable and solution Al • pH • Soil water chemistry • Specific key species.
Salinization	• Irrigation • Evapotranspiration • Salinity or sodicity • Water retention • Conductivity.
Eutrophication	• N deposition • 'Available' soil N • Soil water chemistry • Specific key species.

Source: Huber *et al.* 2001.

depend on the impact of degradation and the impact in turn depends on the land unit and land use management (input level). For example, acidification and fertility decline can be corrected by application of lime and fertilizer, but in land use systems with low or zero external inputs a decline in fertility is more serious and the threshold will be different. Therefore, generic threshold values have limited value and benchmark sites need to be properly characterized. Table 11 shows selected parameters for description of degradation processes as proposed for soil monitoring in the European Union.

Stratification by soil type

Background values with regard to soils can be estimated by taxonomic unit. However, soil classification systems are often based on (surmised) genetic history and processes, and do not necessarily reflect functional properties of direct use to the evaluator. One pragmatic system that classifies soils on their actual and potential nutrient capacity is the Fertility Capability Classification (Buol *et al.* 1975 and Sanchez *et al.* 1982), or FCC. The FCC criteria were linked with the mapping units of the Soil Map of the World by taxonomic transfer functions, algorithms based on statistical analysis of soil profiles belonging to each soil unit (Batjes 1997). For example the indicator hydromorphy (wet conditions) in the FCC is applied to all soil mapping units belonging to the classes of Fluvisols, Gleysols and Histosols and to gleyic units in other soil groups. The FCCC is discussed in the next chapter, section soil fertility.

Monitoring land quality changes

Monitoring is the repeated assessment of land condition over time so that inferences can be made on stability or changes in land conditions. Monitoring can assess the impact of land management practices. It is expensive and difficult to measure land quality changes. The selection of relevant indicators is a crucial step in provision of measurable criteria for monitoring, management and policy support. As indicators are simplified representations of a complex reality, their use always carries the risk of over-simplification. This would result in irrelevant or even wrong indicators (Herweg *et al.* 1998). The adequacy of indicators depends on several factors, such as the desired accuracy and quality, the complexity of the underlying process, cost and ease of measurement, and their temporal and spatial variability.

Herweg *et al* (1998) mention that only the involvement of all major stakeholders can make long-term monitoring practical. They defined a seven-step procedure for sustainable land management impact monitoring for projects and the identification of indicators:

1. ***Identification of stakeholders.*** Who can carry out impact monitoring and who will benefit from it?

2. ***Identification of core issues.*** What is essential to make land management more sustainable? Which aspects to be monitored are most important?
3. ***Formulation of impact hypotheses.*** Which impacts of project activities are desirable and expected? Can impacts other than the desired ones be expected?
4. ***Identification and selection of indicator sets.*** How can indicators be identified? What indicates the sustainability of land management? How to proceed from measurement to assessment?
5. ***Selection and development of methods to monitor chosen indicators.*** How can changes in land management be observed and measured? How can sustainable land management and impact monitoring methods be developed?
6. ***Data analysis and assessment of sustainable land management.*** Which principles need to be considered in analysing data? How can results be assessed in view of a contribution towards sustainable land management?
7. ***Information management.*** How can information be presented and disseminated in a user-friendly manner? How can information be stored accessibly for all stakeholders?

Monitoring soil nutrient status and erosion at selected sites

There are several approaches to monitoring for evaluation of the sustainability of land management practices. Measurements repeated over time to record possible changes of soil properties meet with the practical difficulty that it often takes several years before significant differences are detected. Then there is the spatial problem. A soil can never be re-sampled at exactly the same location (soil is removed). Many soil properties vary over short distances. This spatial variation introduces (random) differences between successive measurements, which can be confused with time-induced changes. The same holds for systematic analytical or sampling differences or errors.

False-time-series sampling

Sometimes land changes are evaluated based on measurements at only one point in time, using so-called backtrack monitoring or false-time-series sampling (Bruijnzeel 1990). This is a method where measurements are made at different locations that have the same conditions with respect to land and vegetation but which have been exposed to different circumstances or management. These may be conditions such as logging, increased exposure to rain and radiation (due to removal of vegetation) compared with a control where no interference has taken place. With backtrack monitoring spatial background variation can be minimized by choosing locations with similar soil and vegetation conditions, but it is inherently included in the changes found. Also, the assumptions made about the history are based on the current land (management) status and may be erroneous. One example is an experiment that studied the effects of logging of natural forest on physical properties of profondic Acrisols (Typic Paleudults) overlying sedimentary rocks (Baharuddin *et al.* 1996). Observations were done in undisturbed forest and were assumed to be representative of the conditions in logged-over forest *before* logging.

Benchmark sites for monitoring

Changes in the quality of land and soils are natural phenomena. Natural events or human activity may cause processes of change to be accelerated in a positive (improvement or reclamation) or negative (degradation) sense. Land changes under natural conditions, different land uses and management practices may be monitored at benchmark sites. A benchmark site reflects environmental and management conditions that are representative for a larger area. It may also be a site that is not representative for large areas, but has conditions that are distinct from other environments (and therefore processes and changes may be different). At benchmark sites certain soil and environmental characteristics should be measured in a standard way at regular intervals, so that changes can be observed over time. The changes measured over time can be related to the land use and management practices and the climate. A set of baseline and re-sampling data are obtained at benchmark sites with repeated measurement of land properties that reflect the inherent quality and changes of the land. With such data the sustainability of land use systems may be assessed. Monitoring of benchmark sites provides a basis for validation of simulation models for land degradation. Benchmark site characterization and monitoring is also valuable for verification of remotely sensed information. A monitoring site provides an opportunity for government and non-governmental organizations to conduct cooperative research.

Benchmark sites may be selected on the basis of the following criteria (Acton and Gregorich 1995).

Benchmark sites are to represent:

- a major soil zone, land use region, or both;
- a typical landform or a broad textural grouping of soils, or both;
- an important farm production system within a region (in case of monitoring agricultural land).

They should also:

- fit well with provincial agricultural concerns;
- show signs of soil degradation or the potential for soil degradation;
- cover about 5 to 10 hectares (a small watershed in some cases).

Emphasis should be placed on the first four points, so that monitoring results can be used to evaluate as many landforms and farming systems as possible over as broad an area as possible within each agricultural region.

The benchmark site and the area around it should be properly described. Collection of baseline information is the first step in a monitoring programme. It forms the reference with which future observations will be compared. The history of the site should be known, including: past land uses and management; acquisition; first cultivation; land management in the early years; major changes in farming practices; crop rotations; tillage system; crop yields and quality; use of commercial fertilizers, organic fertilizers and soil conditioners, and chemical pesticides or herbicides; any drainage or other improvement; any degradation problems; current natural vegetation types or cropping and tillage practices, including crop rotation system; tillage, crop management, and harvesting methods; and an inventory of farm machinery (Acton and Gregorich 1995).

A number of chemical, physical, biological and mineralogical properties of soil can be identified as key elements of a baseline data set. These properties are classified into the following categories (Table 12): *sensitive* properties, which could change significantly in less than 10 years; *moderately sensitive* properties, which are likely to change over decades; *non-sensitive* properties, which are not expected to change significantly in 100 years. The non-sensitive

TABLE 12
Soil properties (chemical, physical, biological, and mineralogical) measured at benchmark sites

Sensitive properties[1]	Nonsensitive properties[4, 6]
Soil reaction (pH)	Soil taxonomic class
Available phosphorus and potassium	Functional soil properties, such as rootable depth, gravel content, soil structure, porosity
Organic carbon	Particle-size distribution
Total nitrogen	Clay mineralogy[5]
Exchangeable cations	Total surface area
Bulk density	Total elements (aluminum, calcium, cobalt, chromium, copper, iron, potassium, lithium, magnesium, sodium, nickel, lead, zinc)
Dry-aggregate size distribution	Saturated hydraulic conductivity
^{137}Cesium distribution	Near-saturated hydraulic conductivity
Extractable iron and aluminum[2]	Penetrometer reading and soil moisture
Erosion class and status	Electromagnetic ground conductivity[7]
Depth to groundwater	Biopore and root counts
	Earthworm counts[8]
	Crop yields.
Moderately sensitive properties[3]	**Site properties[6]**
Cation exchange capacity	Landform & Landscape position (land element)
Carbonates	Coordinates
Soil moisture retention	Parent material
Soil drainage	Slope
	Land use & management
	Natural vegetation
	Flooding hazard.

[1] Measured every 5 years.
[2] For Podzolic soils only.
[3] Measured every 10 years.
[4] Measured only at the beginning of the observation period to establish baseline data.
[5] Heavy applications of nitrogen and potassium fertilizers may alter some silicate clays and special studies may be needed.
[6] See Guidelines for soil description (FAO 1990).
[7] Only in areas with potential salinity problems.
[8] Where these occur.
Source: Modified after Acton and Gregorich, 1995.

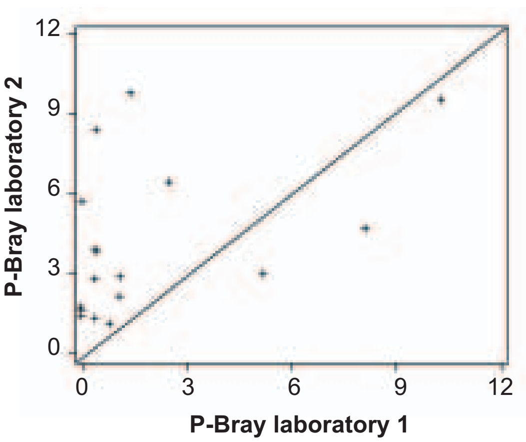
properties, although not expected to change much over the duration of this study, are important for assessment of the overall soil health of the benchmark sites.

Soil physical properties related to the rootability (soil strength) and water movement and storage capacity (soil porosity, hydraulic conductivity) have an important bearing on the vegetation and crop yield. Compaction and a decline in organic matter and soil biological life may degrade these properties. Biological life (estimated by, e.g., earthworm counts) is an important indicator for soil health.

Monitoring benchmark sites and statistical procedures

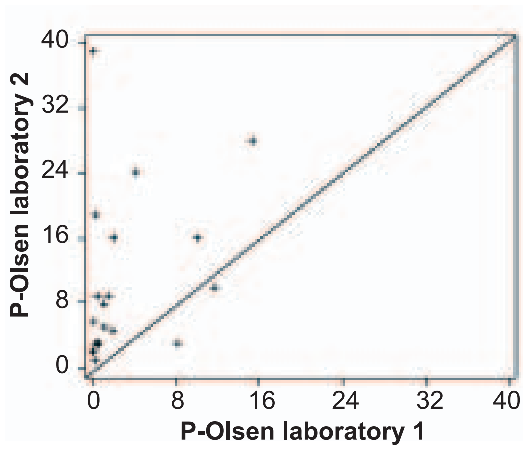
For the purpose of monitoring, permanent sampling plots may be located in different units of the landscape and areas with different management type and history. These sites should be re-sampled at intervals of several years to track possible changes caused by management differences. One plot should be located at an undisturbed site for reference – to be able to estimate natural rates of change. Since repetitive samples cannot be taken at exactly the same place, the studied temporal change of land properties may become obscured by spatial variation. Sampling strategies may be followed that allow for quantification of the spatial variability, using geostatistical techniques. However, these methods have a high data requirement: a minimum of 50-60 observations (Wopereis *et al.* 1994) or even 150 to 300 (Webster in Shulin *et al.* 1993) for calculating semivariance (a statistical tool for quantifying spatial variability). In cases where

Figure 2
Scatterplot of P-Bray analysis on identical samples in two laboratories



Source: Mantel, 1999.

Figure 3
Scatterplot of P-Olsen analysis on identical samples in two laboratories



Source: Mantel, 1999.

the variability is small, a classical statistical approach can be applied: sequential t-testing. With this sampling method, reliable average values are obtained with the minimum number of observations (Stein *et al.* 1989; Finke 1991). A practical problem may be the quality of the laboratory analyses. Differences between laboratories are unacceptably high for some properties (Breimer *et al.* 1986; Van Reeuwijk 1984), as illustrated in Figures 2 and 3.

Table 13
Summary of results of comparison of analytical results on 20 soil samples

Analysis	Significance of difference[#]	Acceptability[*]
PH-H_2O	+	L
PH-KCl	-	H
Texture – sand	+	H
Silt	-	H
Clay	+	H
EC_e	+	L
Exch. Bases	-	M
Exch. Acidity	-	M
CEC_{pH7}	+	L
Org. C%	-	H
Org. N%	-	H
P-Olsen	+	L
P-Bray-I	+	L

[#] (+) = differences are significant, (-) = differences are not significant.
[*]H = high acceptability, M = medium acceptability, L = low acceptability.
Source: Mantel, 1999.

The summary of results for all soil properties from that study is presented in Table 13. The first column supplies information on the *t*-test result, whether differences are significant (+) or not (-). The second column states whether the range of differences found are acceptable in relation to the required accuracy of the data for the specific use(s), whereby H (high), M (medium) and L (low) represent degrees of acceptability of the differences in view of the envisaged use of the data.

A general conclusion is that the two data sets are reasonably compatible, but that for some properties disturbingly large variation between the data sets exists.

Any variation within a given laboratory will be attributed to the change with time in the plots. This can only be overcome if the laboratory can supply the customer with quantitative data on the quality of the analyses, e.g. standard deviations of each analysis, value of control sample for the relevant batch compared with the control for other batches, as discussed in chapter 4.

Spatial variation obscuring temporal changes cannot be avoided even with large investments in time, labour and sample analysis. If applied properly, the plot method draws heavily on the budget. Implementing the plot method requires a large sampling programme to cover the different terrain conditions. To account for spatial variation within plots, samples from several points should be taken and analysed for each property. Even then, problems of variation of a property at one point in time have not been overcome completely. Within-laboratory variation, if not quantified, obscures time-dependent observations. An alternative method is to record field observations along mini-transects, as discussed in the case study on monitoring changes in forest soils in Indonesia (chapter 6).

Scales of data and information for local assessment of soil degradation

Quantitative assessment of soil degradation can be approached in different ways. A quantitative assessment of the status of soil degradation involves continuous monitoring of (changes in) the relevant soil properties, which are different for every degradation type. A standardized soil database structure (such as developed for SOTER, van Engelen and Wen 1995) is a good basis for storing data from such a monitoring activity, but a database alone does not suffice for an assessment of the degradation status. Both appropriately scaled models and auxiliary databases of the main driving processes and controlling factors will be needed, for each degradation (sub)type under consideration.

The question should be raised whether the emphasis of an assessment should be on the *intensity of the degradation process* (degree of degradation as defined above; i.e. measuring changes in soil properties) or rather on the *impact* of degradation on specific soil functions. However, it is evident that a good understanding of the degradation process is essential for good information on its impact and for the identification of possible responses.

Quantitative risk assessment methods are available for several degradation types, generally in the form of models, e.g. USLE and similar models for erosion, and contaminant transport models (available for homogenous soils) for assessment of vulnerability to pollution. Most of these models have been developed and tested for use at local scales.

Scale is an important aspect in the sense that the necessary generalization associated with smaller scales is likely to have more impact on quantitative indicators than on qualitative ones. For quantitative assessments as well as for modelling more specific and detailed data are required; these are more generally available at larger (local) scales than at smaller (e.g., national) scales. Quantitative data related to soil degradation are very limited or non-existent at the scale of entire countries, regions or continents. As stated in the findings of a recent FAO workshop for the Maghreb countries in Algiers: “the lack or weakness of monitoring and evaluation systems of irrigated land in certain countries does not allow a proper quantification of soil degradation phenomena. … The flow and exchange of information and experience in these fields are virtually absent in the region”.

Besides direct mapping of degradation from satellite images, remote sensing can play a role in collecting certain data (e.g. topography, vegetation cover) at small scales, but it should not be considered a panacea in areas lacking basic data. Besides biophysical aspects such as soil, climate, topography and land use, socio-economic factors have a significant influence on the occurrence or prevention of degradation (van Lynden and Mantel 2001)

Data requirements for modelling, and for process-based models in particular, are usually high in terms of both quantity and quality. While these requirements can be met for an experimental plot, the scanty data availability at smaller scales explains why few models are being applied at country or regional level.

Quantitative assessments therefore are generally less appropriate for small-scale monitoring than qualitative assessments. These can be used at regional or country level to identify hot spots (problem areas). Their problems can then be studied in detail with quantitative approaches at more detailed scales, necessitating increasingly mechanistic or statistical modelling approaches.

Soils vary spatially over distances of as little as a few metres, and many soil properties have strongly non-linear relationships to the analytical data from which they are predicted. Therefore great care needs to be taken when scaling soil properties.

Chapter 3
Threshold values and estimation methods for selected types of degradation[1]

THRESHOLD VALUES

Depending on the required scale and accuracy, threshold values for soil degradation can be derived with help of existing and new data collections. This study does not deal with the identification of existing collections in any region, but concentrates on methodologies. It is anticipated that only limited information will be available, and possibly not always of the required quality to be entered into a combined database.

To arrive at an adequate assessment of threshold values, information from several sources should be combined. In relation with information on soil, climate, land use and expected degradation types a monitoring and control programme should be developed that may cover wide areas. Models may be used to find out the most sensitive soil parameter for the particular soil degradation type, and to estimate sampling time and sampling intervals. Existing data should be checked for the intended use and laboratories involved should meet the minimal quality requirements set by the monitoring and control programmes. It is strongly recommended to start with pilots and aim for efficient use of existing laboratory capacity.

The next three sections of this chapter present theoretical and practical background information for the establishment of threshold values for soil degradation in salt affected soils, nutrient depletion and toxic elements. The required soil tests and analyses are also used to define land and soil quality as described in chapter 2, and most of them are standard for soil characterization. References to compilations of analytical and testing methods are cited in the next chapter.

SALINE AND SODIC SOILS

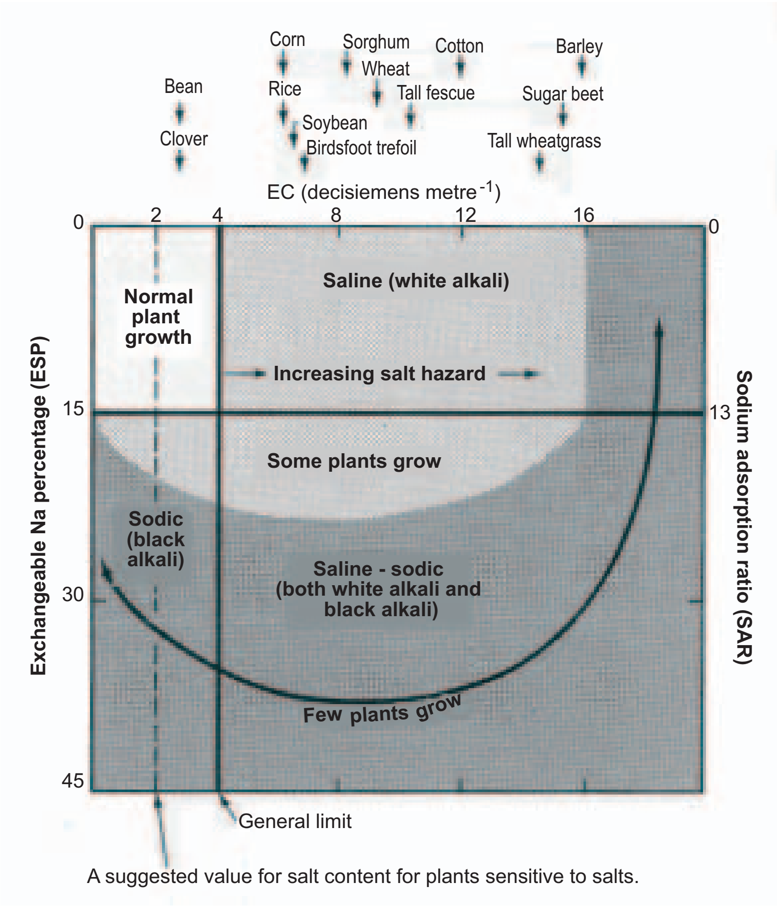
Occurrence

Saline and sodic soils develop in arid regions where the precipitation is less than 500 mm annually and in semi-arid regions with poor drainage. Under such conditions evaporation and evapotranspiration are not compensated by precipitation and irrigation. Salts, weathered from rocks and minerals, deposited by rainfall and wind, ground water and irrigation, are insufficiently washed from the upper soil layers. With evaporation these accumulated salts precipitate from upward-moving water on or near the surface. Most common salts are NaCl, Na_2SO_4, $CaCO_3$, and $MgCO_3$. Excessive salts hinder crop growth by toxic effects, reduce water availability through the action of osmotic pressure, and may result in unbalanced nutrient uptake. General responses of several crops to soil salinity (EC_{se}) and sodicity are shown in Figure 4.

Saline and sodic soils are identified by the salt content and by the proportion of exchangeable sodium respectively (Table 14).

---
[1] A. van Oostrum

FIGURE 4
Crop responses to soil salinity (EC_{se}) and sodicity



Diagrammatic representation of salt-affected soils, their defined salt and exchangeable sodium levels, and the likely growth of plants on those soils. Each crop listed above the graph is placed with its first letter at about the EC value at which 10 percent yield reduction occurs. A 50 percent yield reduction occurs at an increase of about 3.0 to 6.0 dS m^{-1} to the right of the 10 percent reduction line. (*Information source for plant salt tolerance*: Leon Bernstein, "Salt tolerance of plants". *USDA Information Bulletin 283*, 1964; courtesy of Raymond W. Miller).

TABLE 14
Classification of saline and sodic soils

	EC (dS/m)	ESP (%)	Typical pH	Structure	Description
Saline	>4	<15	<8.5	Good	Non-sodic soils containing sufficient soluble salts to interfere with the growth of most crops
Sodic	<4	>15	>9.0	Poor	Soils with sufficient exchangeable sodium to interfere with the growth of most crops, but without appreciable quantities of soluble salts
Saline-Sodic	>4	>15	<8.5	Fair to good	Soils with appreciable exchangeable sodium and sufficient soluble salts to interfere with the growth of most crops

ESP: Exchangeable Sodium Percentage (ESP in %) = (Exch. Na/ CEC) * 100
CEC: Cation Exchange Capacity ($cmol_c$/kg soil or alternatively me/100 g or $mmol_c$/100g)
Sources: McBride 1994 and Landon 1984

Most salt-affected soils can be identified in the field. With decreased soil permeability, small wet spots are visible. With higher evaporation white salt covers the soil surface, starting on the high spots. Under high soil pH, puddles of surface water are coloured black by dispersed organic colloids. Upon drying, black crusts are formed on the soil surface.

Chemical and physical characteristics

Salt accumulation causes characteristic physical and chemical changes in soils. Salt-affected soils are classified on the basis of their total soluble salt content and exchangeable sodium percentage. Total salt content can be estimated by the electrical conductivity of soil extracts. Individual cations in these extracts usually are determined by flame atomic absorption and flame emission spectrometry (AAS and AES respectively).

In sodic soils, sodium is the dominant cation. Many sodic soils have a pH of 9 or above, which is due to hydrolysis of Na_2CO_3 or exchangeable Na.

High salt and sodium concentrations in the soil water affect water and nutrient uptake processes in plants. A high salt content in the soil solution severely inhibits plant growth by reducing water uptake by plant roots (Tan 1982).

With a high proportion of Na^+ cations in the soil solution, the proportion of Na at the cation exchange sites of the soil is high as well, and the soil may become dispersed; clay and silt particles may be washed into pores and seal them. Low soil porosity and poor aeration limits the yield.

The tendency for sodium to increase its proportion on the cation exchange sites at the expense of other types of cations is estimated by the ratio of sodium concentration to the square root of the concentration of calcium plus magnesium ($mmol^+/l$) in the water: the Sodium Adsorption Ratio (SAR).

$$SAR = \frac{Na^+}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$$

A low SAR value indicates a low proportion of exchangeable sodium. Higher SAR values imply higher exchangeable sodium percentages and a likelihood of low soil permeability (Richards 1953; Miller and Donahue 1990). At high soil pH also several micronutrients (Fe, Cu, Zn, or Mn) may become deficient.

As evaporation of water from soils proceeds, Ca^{2+} and Mg^{2+} are precipitated as insoluble and relatively innocuous carbonates. Any excess of carbonate or bicarbonate remaining in solution poses an alkalinity hazard. The alkalinity of water is measured as the residual sodium carbonate (RSC) value given by:

$$RSC = [HCO_3^- + CO_3^{2-}] – [Ca^{2+} + Mg^{2+}]$$

in millimoles of charge ($mmol^+$ or $mmol_c$) per liter. The RSC is equal to the quantity of acidity that is needed to neutralize the solution alkalinity in excess of the alkalinity associated with Ca^{2+} and Mg^{2+} (McBride 1994).

Potential responses

With continued accumulation of salts soil productivity is decreasing. Reclamation then requires special techniques based on limitation of the evaporation and replacement of Na by the divalent calcium cation in case of sodic soils. To identify and prevent further degradation, the salt content in the irrigation water and in the soil water, as well as the proportion of exchangeable Na, should be regularly determined. In problem soils, especially in semiarid zones, the groundwater table should be kept below the level at which capillary rise to the soil surface could take place, and agricultural practices may have to be adjusted.

Farmers attempt to reduce the negative effects of salinity and sodicity, by irrigation techniques and gypsum ($CaSO_4$) application or by growing salt-tolerant crops (Miller and Donahue 1990). However, scarcity of high-quality irrigation water often limits the possibility to leach out or dilute the salts in the degraded soil.

Threshold values for salt-affected soils

Common techniques to monitor the salt and sodium status of water and soil are based on the determination of the electrical conductivity (EC) of a soil/water extract. The cation concentrations in the extract can be determined by flame atomic emission and absorption spectrometry (AES and AAS). Compilations of analytical methods are cited in chapter 4.Usually a 1:5 (weight) soil/water extract is prepared (EC_5). Saturation extracts (EC_{se}) would more closely approximate field conditions, but their preparation is generally more difficult, and impossible in some cases. A conversion factor or method to estimate EC_{se} from EC_5 developed for a specific area cannot be used elsewhere without local validation: usually it only holds for data from samples comparable with the set used for the development of the conversion factor or method.

The effects of the accumulated salts are influenced by the quality of the irrigation water, the kinds of salt present, soil texture, drainability, crop species and varieties, stage of crop growth and climate. Management and irrigation practices also affect the yields.

An important factor is the control of the irrigation water quality. A classification of irrigation water on the basis of the EC, SAR and RSC is presented in Table 15.

A classification of salt-affected soils based on the electrical conductivity in the saturation extract (EC_{se}) in fine and medium textured soils is given in Table 16. For coarse textured soils with larger pores the limits may be somewhat higher.

This classification of soils, based on the research at the US Soil Salinity laboratory, is widely adopted and is a basis for adaptation to local conditions. Advanced interpretations of salt effects on soils and plant growth in Australia are summarized in chapters 8 and 9 of Peverill *et al.* (1999).

The salt tolerance of field, fruit, vegetable and forage crops for EC values is indicated in Table 17. The general relation of crop yield decreases with the EC of the soil solution is

Table 15
Characterization of water based on its potential to degrade soil properties

	Salinity hazard (EC)	Sodicity hazard (SAR)	Alkalinity hazard (RSC)
Low (safe)	< 0.25	< 7	< 1.25
Medium (marginal)	0.25 – 0.75	7 – 13	1.25 – 2.5
High (unsuitable)	0.75 – 2.25	13 – 20	> 2.5
Very high	> 2.25	> 20	–-

Source: McBride 1994

Table 16
General interpretation of EC_{se}

USDA soil class	Designation	EC_{se} (dS/m)	Total salt content (%)	Crop reaction
0	Salt-free	0 - 2	< 0.15	Salinity effects are negligible, except for the most sensitive plants
1	Slightly saline	4 - 8	0.15 – 0.35	Yields of many crops are restricted
2	Moderately saline	8 - 15	0.35 – 0.65	Only tolerant crops yield satisfactorily
3	Strongly saline	> 15	> 0.65	Only very tolerant crops yield satisfactorily

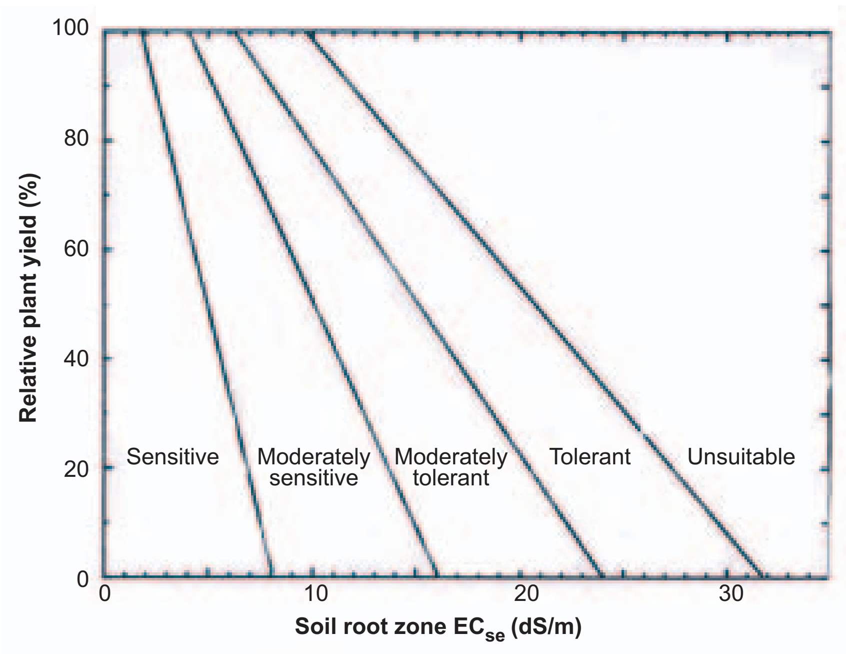
Source: Landon 1984

presented in Figure 5. Table 18 shows the relation between relative yield potential and electrical conductivity of irrigation water and of the saturated soil extract for a wide range of crops. These tables are copied from Landon 1984. They are a first approach to arrive at threshold values but still need adjustments to regional and local situations.

Soil fertility

Chemical and physical properties of the soil affect the availability of nutrients to plants. At least 16 elements can be regarded as essential nutrients for plant growth. Not all elements are

Figure 5
Relative crop yield in relation to soil salinity (EC_{se}) for plant salt tolerance groupings



Relative crop yield in relation to soil salinity (EC_{se}) for plant salt tolerance groupings redrawn from Maas and Hoffman (1977).
Source: Peverill et al. 1997

TABLE 17
USDA ratings of relative crop tolerance to salinity

Plant grouping	High salt tolerance	Medium salt tolerance	Low salt tolerance
Fruit crops	Date palm	Pomegranate Fig Olive Grape Cantaloupe	Pear Apple Orange Grapefruit Prune Plum Almond Apricot Peach Strawberry Lemon Avocado
Vegetable crops	EC_e = 12 Garden beets Kale Asparagus EC_e = 10	EC_e = 10 Tomato Broccoli Cabbage Bell pepper Cauliflower Lettuce Sweet corn Potatoes (White rose) Carrot Onion Peas Squash Cucumber EC_e = 4	EC_e = 4 Radish Celery Green beans EC_e = 3
Forage crops	EC_e = 18 Alkali sacaton Salt grass Nuttall alkali grass Bermuda grass Rhodes grass Fescue grass Canada wild rye Western wheat grass Barley (hay) Bird's-foot trefoil EC_e = 12	EC_e = 12 White sweet clover Yellow sweet clover Perennial rye grass Mountain brome Strawberry clover Dallis grass Sudan grass Huban clover Alfalfa(California common) Tall fescue Rye (hay) Wheat (hay) Oats (hay) Orchard grass Blue grama Meadow fescue Reed` canary Big trefoil Smooth brome Tall meadow oat grass Cicer milk-vetch Sour clover Sickle milk-vetch EC_e = 4	EC_e = 2
Field crops	EC_e = 16 Barley (grain) Sugarbeet Rape EC_e = 10	EC_e = 10 Rye (grain) Wheat (grain) oats (grain) Rice sorghum (grain) Sugarcane Corn (field) Sunflower Castor beans EC_e = 4	EC_e = 4 Field beans Flax EC_e = 3

Plants are listed within groups in order of decreasing tolerance to salinity. EC_e values (dS/m) correspond to 50% decrease in yield.
Source: Richards, 1954

TABLE 18
Crop salt tolerance levels (surface irrigation)

Crops		Yield potential for EC values shown								
		100%		90%		75%		50%		No yield
		EC_e	EC_w (1)	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e
Field crops										
Barley (2)	Hordeum vulgare	8.0	5.3	10.0	6.7	13.0	8.7	18.0	12.0	28
Cotton	Gossypium hirsutum	7.7	5.1	9.6	6.4	13.0	8.4	17.0	12.0	27
Sugarbeet(3)	Beta vulgaris	7.0	4.7	8.7	5.8	11.0	7.5	15.0	10.0	24
Wheat(2), (4)	Triticum aestivum	6.0	4.0	7.4	4.9	9.5	6.4	13.0	8.7	20
Safflower	Carthamus tinctorius	5.3	3.5	6.2	4.1	7.6	5.0	9.9	6.6	14.5
Soyabean	Glycine max	5.0	3.3	5.5	3.7	6.2	4.2	7.5	5.0	10
Sorghum	Sorghum bicolor	4.0	2.7	5.1	3.4	7.2	4.8	11.0	7.2	18
Groundnut	Arachis hypogaea	3.2	2.1	3.5	2.4	4.1	2.7	4.9	3.3	6.5
Rice (paddy)	Oryza sativa	3.0	2.0	3.8	2.6	5.1	3.4	7.2	4.8	11.5
Sesbania	Sesbania exaltata	2.3	1.5	3.7	2.5	5.9	3.9	9.4	6.3	16.5
Corn	Zea mays	1.7	1.1	2.5	1.7	3.8	2.5'	5.9	3.9	10
Flax	Linum usitatissimum	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Broadbean	Vicia faba	1.6	1.1	2.6	1.8	4.2	2.0	6.8	4.5	12
Cowpea	Vigna unguiculata	1.3	0.9	2.0	1.3	3.1	2.1	4.9	3.2	8.5
Beans	Phaseolus vulgaris	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.5
Fruit crops										
Date palm	Phoenix dactylifera	4.0	2.7	6.8	4.5	10.9	7.3	17.9	12.0	32
Fig	Ficus carica	2.7	1.8	3.8	2.6	5.5	3.7	8.4	5.6	14
0live	Olea europaea	2.7	1.8	3.8	2.6	5.5	3.7	8.4	5.6	14
Pomegranate	Punica granatum	2.7	1.8	3.8	2.6	5:5	3.7	8.4	5.6	14
Grapefruit	Citrus paracisi	1.8	1.2	2.4	1.6	3.4	2.2	4.9	3.3	8
Orange	Citrus sinensis	1.7	1.1	2.3	1.6	3.2	2.2	4.8	3.2	8
Lemon	Citrus limon	1.7	1.1	2.3	1.6	3.3	2.2	4'.8	3.2	8
Apple	Malus sylvestris	1.7	1.0	2.3	1.6	3.3	2.2'	4.8	3.2	8
Pear	Pyrus communis	1.7	1.0	2.3	1.6	3.3	2.2	4.8	3.2	8
Walnut	Juglans regia	1.7	1.1	2.3	1.6	3.3	2.2	4.8	3.2	8
Peach	Prunus persica	1.7	1.1	2.2	1.4	2.9	1.9	4.1	2.7	6.5
Apricot	Prunus armeniaca	1.6	1.1	2.0	1.3	2.6	1.8	3.7	2.5	6
Grape	Vitis spp	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12
Almond	Prunus dulcis	1.5	1.0	2.0	1.4	2.8	1.9	4.1	2.7	7
Plum	Prunus domestica	1.5	1.0	2.1	1.4	2.9	1.9	4.3	2.8	7
Blackberry	Rubus spp	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6
Boysenberry	Rubus ursinus	1.5	1.0	2.0	1.3	2.6	1.8	3.8	2.5	6
Avocado	Persea americana	1.3	0.9	1.8	1.2	2.5	1.7	3.7	2.4	6
Raspberry	Rubus idaeus	1.0	0.7	1.4	1.0	2.1	1.4	3.2	2.1	5.5
Strawberry	Fragaria spp	1.0	0.7	1.3	0.9	1.8	1.2	2.5	1.7	4
Vegetable crops										
Beets3	Beta vulgaris	4.0	2.7	5.1	3.4	6.8	4.5	9.6	6.4	15
Broccoli	Brassica oleracea italica	2.8	1.9	3.9	2.6	5.5	3.7	8.2	5.5	13.5
Tomato	Lycopersicon esculentum	2.5	1.7`	3.5	2.3	5.0	3.4	7.6	5.0	12.5
Cucumber	Cucumis sativus	2.5	1.7	3.3	2.2	4.4	2.9	6.3	4.2	10
Cantaloup	Cucumis melo	2.2	1.5	3.6	2.4	5.7	3.8	9.1	6.1	16
Spinach	Spinacia oleracea	2.0	1.3	3.3	2.2	5.3	3.5	8.6	5.7	15
Cabbage	Brassica oleracea capitata	1.8	1.2	2.8	1.9	4.4	2.9	7.0	4.6	12
Potato	Solanum tuberosum	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3.9	10
Sweet corn	Zea mat's	1.7	1.1	2.5	1.7	3.8	2.5	5.9	3,9	10
Sweet potato	Ipomea batatas	1.5	1.0	2.4	1.5	3.8	2.5	6.0	4.0	10.5
Pepper	Capsicum annuum	1.5	1.0	2.2	1.5	3.3	2.2	5.1	3,4	8.5
Lettuce	Lactuca sativa	1.3	0,9	2.1	1.4	3.2	2.1	5.2	3.4	9
Radish	Raphanus sativus	1.2	0.8	2.0	1.3	3.1	2.1	5.0	3.4	9
Onion	Allium cepa	1.2	0.8	1.8	1.2	2.8	1.8	4.3	2.9	7.5
Carrot	Daucus carota	1.0	0.7	1.7	1.1	2.8	1.9	4.6	3.1	8
Beans	Phaseolus vulgaris	1.0	0.7	1.5	1.0	2.3	1.5	3.6	2.4	6.5

(1) EC_w means electrical conductivity of the irrigation water in dS/m at 25°C. This assumes about a 15 to 20% leaching fraction (LF) and an average salinity of soil water taken up by the crop about three times that of the irrigation water applied ($EC_{sw} = 3EC_w$) and about twice that of the soil saturation extract ($EC_{sw} = 2\ EC_e$). From the above $EC_e = 3/2\ EC_w$. New crop tolerance tables for EC_w can be prepared for conditions which differ greatly form those assumed. The following are estimated relationships between EC_e and EC_w for various leaching fractions:
LF = 10% ($EC_e = 2\ EC_w$), LF = 30% ($EC_e = 1.1\ EC_w$) and LF = 40% ($ECe = 0.9\ EC_w$).

(2) Barley and wheat are less tolerant during germination and seedling stage. EC_e should not exceed 4 or 5mS/cm.

(3) Sensitive during germination. EC_e should not exceed 3 dS/m for garden beets and sugarbeets.

(4) Tolerance data may not apply to new semi-dwarf varieties of wheat.

(5) An average for Bermuda grass varieties. Swannee and Coastal are about 20% more tolerant; Common and Greenfield are about 20% less tolerant.

TABLE 18 – Crop salt tolerance levels (surface irrigation) (Continued)

Crops		Yield potential for EC values shown								
		100%		90%		75%		50%		no yield
		EC_e	EC_w(1)	EC_e	EC_w	EC_e	EC_w	EC_e	EC_w	EC_e
Forage crops										
Tall wheat grass	Agropyron elongatum	7.5	5.0	9.9	6.6	13.3	9.0	19.4	13.0	31.5
Wheat grass	Agropyron cristatum	7.5	5.0	9.0	6.0	11.0	7.4	15.0	9.8	22
Bermuda grass(5)	Cynodon dactylon	6.9	4.6	8.5	5.7	10.8	7.2	14.7	9.8	22.5
Barley (hay)	Hordeum vulgare	6.0	4.0	7.4	4.9	9.5	6.3	13.0	8.7	20
Perennial rye grass	Lolium perenne	5.6	3.7	6.9	4.6	8.9	5.9	12.2	8.1	19
Trefoil, bird's-narrow-leaf(6)	Lotus corniculatus tenuifolius	5.0	3.3	6.0	4.0	7.5	5.0	10.0	6.7	15
Harding grass	Phalaris tuberosa	4.6	3.1	5.9	3.9	7.9	5.3	1.1	7.4	18
Tall fescue	Festuca elatior	3.9	2.6	5.8	3.9	8.6	5.7	13.3	8,9	23
Crested wheat grass	Agropyron desertorum	3.5	2.3	6.0	4.0	9.8	6.5	16.0	11.0	28.5
Vetch	Vicia sativa	3.0	2.0	3.9	2.6	5.3	3.5	7.6	5.0	12
Sudan grass	Sorghum sudanense	2.8	1.9	5.1	3.4	8.6	5.7	14.4	9.6	26
Wild rye, beardless	Elymus triticoides	2.7	1.8	4.4	2.9	6.9	4,6	11.0	7.4	19.5
Trefoil, big	Lotus uliginosus	2.3	1.5	2.8	1.9	3.6	2.4	4.9	3.3	7.5
Alfalfa	Medicago sativa	2.0	1.3	3.4	2.2	5.4	3.6	8.8	5.9	15.5
Lovegrass	Eragrostis spp	2.0	1.3	3.2	2.1	5.0	3.3	8.0	5.3	14
Corn (forage)	Zea Mays	1.8	1.2	3.2	2.1	5.2	3.5	8.6	5.7	15.5
Clover, berseem	Trifolium alexandrinum	1.5	1.0	3.2	2.1	5.9	3.9	10.3	6.8	19
Orchard grass	Dactylis glomerata	1.5	1.0	3.1	2.1	5.5	3.7	9.6	6.4	17.5
Meadow foxtail	Alopecurus pratensis	1.5	1.0	2.5	1.7	4.1	2.7	6.7	4.5	12
Clover, ladino red, alsike, strawberry	Trifolium spp	1.5	1.0	2.3	1.6	3.6	2.4	5.7	3.8	10

(6) Broad-leaf bird's-foot trefoil appears to be less tolerant than narrow-leaf.
Source: FAO, 1979; Ayers and Westcot, 1976.

required to the same extent by plants and crops. Some of them are only required in such small concentrations that they are called micronutrients or trace elements. Other elements may be present in larger amounts and are called macronutrients. Micronutrients present in larger amounts may be harmful. The fertility status of the soil is largely determined by nitrogen, phosphorus and potassium. A subdivision of the essential nutrients is presented in Table 19.

Twelve of these essential elements are naturally derived from weathering of rocks and minerals. Nutrients also are released by the decay of organic matter. Soils differ in their ability to release these nutrients. Different processes and pathways may convert nutrients (e.g nitrogen, sulphur and phosphorus) into a form usable for plants.

TABLE 19
Elements required for plant growth

Basic elements	Macronutrients		Micronutrients
	Absorbed in ionic form from the soil		
Supplied by carbon dioxide and water	Converted from the atmosphere	Originate from weathering rocks and minerals	
carbon (C)	nitrogen (N)	phosphorus (P)	iron (Fe)
hydrogen (H)		potassium (K)	zinc (Zn)
oxygen (O)		sulphur (S)	manganese (Mn)
		calcium (Ca)	copper (Cu)
		magnesium (Mg)	boron (B)
			molybdenum (Mo)
			chlorine (Cl)

Extended from Harpstead and Bennett, 1997

For successful crop production an external supply of nutrients may be required. Not only the quantity but also the form in which nutrients are (made) available is important for plant uptake. Nutrients in the soil may be present in the soil solution or at the exchange sites of clay or humus, or be part of a chemical compound (formed in the soil). The availability of different nutrients tends to decrease towards high and low soil pH.

Soil structure, porosity and root development are also favoured by higher contents of organic matter, especially in case of dense or clayey soils. Without the presence of water in sufficient amounts, nutrient release from the soil and uptake by the roots is impossible. For plant growth, water-holding capacity and infiltration rate are important physical soil characteristics.

Good soil management is a powerful tool to increase yields but may differ even between farms on the same soil. The farming system depends also on the crop grown, applied amendments, labour and machinery, erosion hazards, and whether irrigation is an option. In extreme cases such as greenhouses even climate is controlled. Nutrient mining or excessive additions may disturb the soil nutrient balance.

Management practices to raise crop production often include use of fertilizers, manure and other amendments to improve pH conditions and physical soil properties. A wide range of methods and practices is used to determine whether a nutrient is deficient and which quantity is needed to relieve the deficiency. They include chemical analyses of the soil and the plant, observation of nutrient deficiency symptoms and growth tests. Recommendations can be based on fertilizer experiments and controlled additions of micronutrients and measured plant responses.

Selection of sites for fertilizer experiments

Fertilizer recommendations based on average conditions still may need to be fine-tuned to soil type and farm management. The recommendations cannot be extended too far from the tested conditions, however. Soil and climate may differ at relatively short distances. To assess the nutrient status over larger areas stratification is necessary. Two methods for the selection of sites for fertilizer experiments are summarized below, as applied in Kenya and Mozambique respectively. Either approach may be used to identify areas with a similar nutrient status.

In Kenya, data sets and maps on climate, landform, geology and soils were used for the selection of sites for fertility trials (Smaling. and van de Weg 1990). From these sets a limited number of soil and climatic properties relevant to crop production were entered in a database. The soil status for crop production is characterized by effective soil depth, moisture storage capacity, drainage, nutrient availability and base saturation, among others. Existing land mapping units were re-described to reflect the soil status for crop production on the basis of such key variables. The new descriptions were combined whenever possible with soil and agro-climate maps. By overlaying the respective maps new land units were delimited, called Agro-Ecological Units (AEUs), each characterized by a specific set of biophysical conditions. Trial sites were chosen in these AEUs. Fertilizer recommendations based on these trials are both crop- and AEU-specific.

In Mozambique, areas sufficiently homogeneous to be served by the same fertilizer recommendations were identified on the basis of an agro-ecological zonation (Geurts and van den Berg 1998). This tested and validated zonation is based on FAO major soil groupings, altitude and mean annual rainfall. It was shown that FAO major soil groupings explain a significant part of the total variation in N, organic C, Olsen P, exchangeable K, pH and CEC.

The climatic factors temperature, radiation and rainfall as well as maize growth cycle relate significantly with altitude.

Assessment of soil nutrient status

Sustainable agriculture requires a proper balance in chemical, physical and biological condition of the soil. Fertilizers are used to improve the concentrations of available nutrients for plants. In many places, there are no funds or facilities for quantification of the nutrient status in plant and soil samples. Information on climate, soil, crop and management then should be combined with a view to improving fertilizer recommendations on larger areas. Three programmes or methods that have addressed aspects of this issue are summarized below: a study assessing soil nutrient depletion in Sub-Saharan Africa; the Fertility Capability Classification system; and a sequence of international studies on relations between macro- and micronutrients in soils.

Nutrient depletion in sub-Saharan Africa

With depletion the potential natural availability of nutrients decreases. The plant uptake and losses are not in equilibrium with inputs from fertilizers and weathering. To assess the risk of depletion, nutrient inputs and outputs of the prevailing agricultural systems need to be studied.

Table 20
Input and output factors governing nutrient flows in the soil (in kg/ha per year)

Input		Output	
IN 1	Mineral fertilizer	OUT 1	Harvested product
IN 2	Manure	OUT 2	Crop residues
IN 3	Deposition	OUT 3	Leaching
IN 4	Biological N fixation	OUT 4	Gaseous losses
IN 5	Sedimentation	OUT 5	Erosion

To assess soil nutrient depletion and future needs for fertilization in sub-Saharan Africa, Stoorvogel and Smaling (1990) concentrated on the rootable soil layer and the macronutrients N, P, K. Factors determining the input and output of these elements were defined and quantified (Table 20) for a number of specific Land Use Systems (LUS). A LUS is defined as a well-defined tract of land with its pertinent Land Utilization Type. A LUS is considered as a homogeneous entity and forms the basis for calculating the nutrient balance. The LUS attributes are rainfall, soil fertility, cropping pattern, farm management level, fertilizer and manure application, crop residue management, and rate of erosion (Table 21). Soil fertility dynamics in a LUS are governed by five input and five output factors. Information was made available by governments and by FAO from its databases.

In a similar way, the risk of soil nutrient depletion may be estimated for other regions with data from representative experimental stations and management systems, and data from (regional) economic institutions. However, some scientists have expressed concern about the approach used, as it is based on approximation and aggregation at country level – which may mask the bright spots –where agriculture is sustainable– and the hot spots –where urgent nutrient replenishment is needed. Assessment of fertility decline at micro-watershed or community scale would be more appropriate as a basis for action, but would be costly and time-consuming.

Fertility Capability Classification

Another simple way of soil stratification for the assessment of the nutrient status over large areas is the Fertility Capability Classification system (FCC, Sanchez *et al*. 1982). Here soils

TABLE 21
Attributes of Land use Systems and their specification

Attribute	Specification
Rainfall	Average, in mm/yr
Soil fertility	Classes: low, moderate, high
Management level	Differentiated in low and high
Fertilizer use	Weighting factor 0.0 – 3.0, related to regional distribution of total national consumption
Manure application	0, 500, 1000, 1500 kg/ha per year or 'during grazing'
Residue removal	Percentage of crop residues removed from the field or çrop residues burned
Erosion	Soil loss in t/ha per year
Crops	35 crops representative for sub-Saharan Africa

Source: Stoorvogel and Smaling, 1990

are grouped according to their inherent fertility constraints in a qualitative manner. The soils are classified by the presence or absence of specific fertility limitations. In this assessment of the nutrient status agricultural management practices are not included.

The system consists of three categorical levels: type (topsoil texture), substratum type (subsoil texture) and 15 modifiers. Each categorical level is subdivided into classes represented by simple codes. Class designations from the three categorical levels are combined to form an FCC unit. The codes indicate major fertility limitations important to crop production, such as Al content and toxicity, P fixing potential, low K reserve and salinity.

The absence of modifiers would indicate the absence of major fertility limitations other than nitrogen deficiency. An FCC unit may be characterized by one or more modifiers. The fertility limitations may require inputs and management in addition to those normally employed in profitable crop production (McQuaid et al. 1995).

FCC can be linked with the FAO Framework for Land Evaluation (FAO 1976). This framework lists seventeen land qualities related to productivity or plant growth. Seven of these are related to FCC codes: nutrient availability, salinity and alkalinity, soil toxicities, oxygen availability to the root zone, moisture availability, adequacy of foothold for roots (physical support), and resistance to soil erosion.

International assessment of soil nutrient status

These studies cover thirty countries and present laboratory data on soil, maize and wheat samples from fertilizer experiments.

A sequence of international studies (Sillanp*ää* 1972; 1982; 1990 and Sillanp*ää* and Jansson 1992) focussed on the uptake of micronutrients from different soils and the effects on yields of different crops. The reports document materials and methods and instructions for field trials, and summarize the results by country and soil type. Laboratory analyses on macronutrients and micronutrients are reported, together with soil characteristics such as pH and electrical conductivity, texture, organic matter content, cation exchange capacity and $CaCO_3$ equivalent, and with data on fertilizer use. All the analytical results for both topsoil samples and indicator plants (wheat and maize) originate from a single laboratory. The sampling sites cover thirty countries.

The samples and the original data may be of continuing value in an extended study on the assessment of threshold values for soil parameters. Re-sampling at selected sites and analysis of the old and new samples may be needed before the original data can be incorporated in monitoring programmes, because some of the methods used are not easily comparable with current laboratory methods.

Threshold values for soil nutrients

To quantitatively estimate the nutrient status and to arrive at threshold values for macro- and micro- nutrients, soil testing and fertilizer experiments are essential. However, differences in laboratory and field methodologies introduce both random and systematic errors in the data These seriously hinder the effective use of data from, for example, fertilizer experiments for regional assessments of the fertility status. They hamper the identification of representative areas for soil testing and the development of models for the assessment of the nutrient depletion risk. Changes in fertilizer recommendation schemes are projects of several years. In a first approach, stratification methods such as those described above could be combined with basic data from fertilizer experiments on the main crops on representative soils within each stratum.

Soil pollution

Soil pollution is a major factor of soil degradation. Pollution affects the soil by different pathways –airborne, terrestrial or by water. The pollutants in the soil in turn may follow different pathways or exposure routes to human beings, and in some cases combine with contaminants from other sources. Pollution limits the ecological function of the soil and may reduce yields or food quality or safety.

It is important to distinguish between the mere presence of a contaminating substance in the soil and its role as a pollutant because of its location, concentration and adverse biological or toxic effects. Nitrate and phosphate, for example, are essential nutrients to plants but may become pollutants if present in excessive quantities (van Lynden 1995).

Table 19 lists the elements required for plant growth. Elements present in small amounts are referred to as trace elements. Several are micronutrients, required by plants. Cadmium, lead and mercury belong to the group of heavy metals. The trace elements mercury (Hg), lead, (Pb), cadmium (Cd), nickel (Ni), and cobalt (Co) show toxic effects if present in higher concentrations, as does the micronutrient copper (Cu).

Occurrence and effects of toxic elements

Sources of toxic elements present in the environment are both natural and due to human activities. The content of these elements in the natural soil is largely dependent on that of the rocks from which the soil parent material was derived and on the process of weathering to which the material has been subjected. Table 22 shows the highly variable nature of trace element concentrations in various soil-forming rocks. Other primary sources of trace elements in agro-ecosystems are commercial fertilizers, liming materials, sewage sludge, animal wastes, pesticides and irrigation water. These sources also have impacts on natural ecosystems, as well as on rural and urban areas.

Trace elements are held in different forms in the soil-plant-animal system. An element introduced into the soil may be dissolved in the soil solution, held on exchange sites of organic

Table 22
Concentration (ppm) of trace elements in various soil-forming rocks and other natural materials

Element	Ultramafic igneous	Basaltic igneous	Granitic igneous	Shales and clays	Black shales	Deep-sea clays	Limestones	Sandstones
Arsenic	0.3-16	0.2-10	0.2-13.8	-	-	-	0.1-8.1	0.6-9.7
	3.0	2.0	2.0	10		13	1.7	2
Barium	0.2-40	20-400	300-1800	460-1700	70-1000	-	10	-
	1	300	700	700	300	2300	-	20
Beryllium	-	1.0	2-3	3	-	2.6	-	-
Cadmium	0-0.2	0.006-0.6	0.003-0.18	0-11	<0.3-8.4	0.1-1		
	0.05	0.2	0.15	1.4	1.0	0.5	0.05	0.05
Chromium	1000-3400	40-600	2-90	30-590	26-1000	-	-	-
	1800	220	20	120	100	90	10	35
Cobalt	90-270	24-90	1-15	5-25	7-100	-	-	-
	150	50	5	20	10	74	0.1	0.3
Copper	2-100	30-160	4-30	18-120	20-200	-	-	-
	15	90	15	50	70	250	4	2
Fluorine	-	20-1060	20-2700	10-7600	-	-	0-1200	10-880
		360	870	800		1300	220	180
Iron	94 000	86 500	14 000 – 30 000	47 200	20 000	65 000	3 800	9 800
Lead	-	2-18	6-30	16-50	7-150	-	-	<1-31
	1	6	18	20	30	80	9	12
Mercury	0.004-0.5	0.002-0.5	0.005-0.4	0.005-0.51	0.03-2.8	0.02-2.0	0.01-0.22	0.001-0.3
	0.1?	0.05	0.06	0.09	0.5	0.4	0.04	0.05
Molybdenum	-	0.9-7	1-6	-	1-300	-	-	-
	0.3	1.5	1.4	2.5	10	27	0.4	0.2
Nickel	270-3600	45-410	2-20	20-250	10-500	-	-	-
	2000	140	8	68	50	225	20	2
Selenium	0.05	0.05	0.05	0.6		0.17	0.08	0.05
Vanadium	17-300	50-360	9-90	30-200	50-1000	-	-	-
	40	250	60	130	150	120	20	20
Zinc	-	48-240	5-140	18-180	34-1500	-	-	2-41
	40	110	40	90	100?	165	20	16

The upper values are the usually reported range, the lower values the average
Source: Adriano 1986, p. 24

solids or inorganic constituents, occluded or fixed into soil minerals, precipitated with other compounds in soils, or incorporated into biological material. The capacity of soil to hold trace elements largely depends on the pH, cation exchange capacity, clay type, organic matter and redox potential. Approaching or exceeding the capacity of a soil to held these trace elements results in toxicity.

The fixing capacity of a soil for most trace elements increases with increasing pH from acid to a maximum under neutral and slightly alkaline conditions. Whether the soil has the capacity to neutralize pollution in particular by acidic inputs depends on the parent material and the weathering rate, on the clay and organic matter content as well as lime ($CaCO_3$) content. When this so-called buffer capacity is depleted, the pH will start to drop. With increasing acidity, aluminium ions in the soil are mobilized, which are toxic to most plants and have harmful effects on aquatic environments. A decrease of soil pH, as an effect of acid rain, results in a mobilization and depletion of trace elements.

The cation exchange capacity of a soil mainly depends on type and amount of clay and organic matter. Soil organic matter may be present naturally and added in animal manures, sewage sludge, compost, peat, and plant residues. Organic matter may also bind trace elements in a stable form by chelation. Trace elements present in anionic form, such as arsenic, are often held by free iron, manganese and aluminium oxides in the soil. Hydrous oxides of Fe and Mn may be most important in the fixation of trace elements in soils and freshwater sediments (Adriano 1986)

As the amounts and types of soil components differ, so does the capacity to hold trace elements. Within. paddy soils in tropical Asia, for example, minimum and maximum concentrations for trace elements may differ by more than 100 ppm. The various forms in which trace elements may be present in soil react differently to chemical treatments. Therefore, soil tests to simulate nutrient availability or toxicity remain empirical.

Extensive research on the assessment of levels of available nutrients in soils is reported by Sillanpää, 1990. The status of cadmium, lead, cobalt and selenium in soils and plants of thirty countries is documented by Sillanpää and Jansson, 1992. These two reports cover the most important micronutrients for the growth of plants or the nutrition of animals and humans, or both. Cadmium and lead, two heavy metals, were included in the study because of their environmentally harmful and toxic effects.

Thresholds

Different soils and soil components have widely different affinities for trace elements. The release of these elements also depends on soil management and environmental conditions. Trace elements have different toxic effects. A soil contaminant might enter the food chain through a crop, or might cause reduced yields, for example. Threshold values for the remediation of contaminated land may be derived through epidemiological techniques in human health and eco-toxicological risk assessment.

The amount of a trace element in soils that would be dangerous cannot be determined easily. This so-called critical load has been defined as the highest load that will not cause chemical changes leading to long-term harmful effects in the most sensitive ecological systems. A critical load is a maximum tolerable value rather than a target value. Amounts of pollutants released from the soil or taken up by rooting systems may vary widely and not only by the prevailing pH. Other important factors are the crop, the growth stage and concentration of the specific element in the soil solution.

Toxic elements originating from soil and water may enter the food chain by different pathways. European countries (www.caracas.at; Ferguson, 1999) focussed on topics for human health risk assessment and eco-toxicological risk assessment. It is usually assumed that adverse effects of exposure to soil contaminants are comparable to those resulting from exposure to the same substances in food. Because models on bioavailability of contaminants to be used at different risk levels are lacking, models have been developed to predict exposure on the basis of chemical analyses of soil and groundwater. However, these models are still abstract representations of complex systems and are based on numerous assumptions and approximations. Therefore it is important that models and sub-models be validated and tested in real-world situations, either as part of contaminated land risk assessments or in research projects. To run a model properly, adequate site-specific information should be available. This may also include expert knowledge.

Even with dedicated programmes, international organizations such as WHO and FAO have not yet been able to assemble all the data needed for running the models. At a national level, the United States Environmental Protection Agency developed media-specific contaminant concentrations for those chemicals commonly found in surface water and sediment at polluted sites. These values are intended for screening purposes only. Where measured concentrations exceed these values there is sufficient concern about adverse ecological effects to warrant further investigation. With a software program site-specific adjustments are made on the basis of pH, Ca and Mg in surface water and total organic carbon in sediment. Currently no data are available for soils.

A major issue for all industrialized countries is how to reduce the cost of dealing with land contamination without compromising public health and water quality, or business confidence in the benefits of land regeneration and sustainable use of soil. Cleaning up all contaminated sites to background concentrations or to levels suitable for the most sensitive land use is neither technically nor economically feasible. To arrive at sustainable solutions that will restore the usability and social and economic value of the contaminated land, land use-related requirements, spatial planning requirements and management requirements need to be integrated.

The Netherlands and the USA have adopted an approach of multifunctionality, i.e. improvement to a standard suitable for any possible use. In part, this approach is determined by the geology of the Netherlands (granular sands and soils with a high water table, permitting easy groundwater movement). The geology of the UK, for example, permits a more pragmatic approach, as overlying glacial clays tend to lock the potential pollutants in place. In Britain, the underlying philosophy is one of fitness for use; i.e. contaminated land should be restored according to the planned use. Hence the requirements and costs of reclaiming a site that will become a light industrial redevelopment will be different from those of a site that is to be used for agricultural purposes.

The Dutch decision-support system for the assessment and remediation of contaminated land has been very influential internationally. In the Dutch policy, emissions and the resulting soil pollution can be tolerated so long as the soil quality does not decline (standstill principle) and the multi-functionality of the soil is not endangered. In this risk-based soil quality policy, especially in relation to the clean-up of contaminated soils, target and intervention values are important instruments. These values have been established for about one hundred substances for soil and groundwater, and are related to the percentages of organic matter and clay in the soil. If target values are met, the soil is considered clean or multifunctional. If the average contaminant concentration in a minimum soil volume of $25m^3$ exceeds the intervention value, the contamination is classified as serious and remediation is required.

These target and intervention values reflect the potential for risk with full exposure. However, in practice, exposure will generally be less, and local circumstances are taken into account. Procedures for estimating actual risk are being developed (Ferguson 1999). The issue of multi-functionality has been given a more pragmatic interpretation in the past decade.

The Dutch standards for assessing soil contamination on the basis of the total concentration of heavy metals in soils (Ministry Environment 2000) are listed in Tables 23 and 24.

In their guidelines on the handling of contaminated sites (http://www.mst.dk/affald/02070000.htm in Danish), the Danish Environmental Protection Agency (EPA) published a PC-based spreadsheet to facilitate the risk assessment of soil pollution in relation to land use, ground water and evaporation. It is described (http://www.mst.dk/project/NyViden/1999/04070000.htm) as a user-friendly tool that requires a minimum of computing know-how. The spreadsheet lists physicochemical data and threshold values for soil, ground water and evaporation to the air for a large number of pollutants. Users may add their own data to the various selection tables. It presents the results of the assessment also in graphic form. It should be noted that threshold

TABLE 23
Dutch target and intervention values for total concentration of heavy metals in a standard soil (with 25 percent clay and 10 percent organic matter)

Elements	**Target value** (mg/kg soil)	**Intervention value** (mg/kg soil)
As	29	55
Ba	160	625
Cd	0.8	12
Cr	100	380
Co	9	240
Cu	36	190
Hg	0.3	10
Pb	85	530
Mo	3	200
Ni	35	210
Zn	140	720

1. Target values indicate desirable maximum levels of elements in uncontaminated soils.
2. Intervention values identify serious contamination of soils and indicate that remedial action is necessary.
3. The target and intervention values for heavy metals are dependent on clay and organic matter contents. The standard soil values must be modified for soils with different clay and organic matter contents by the formula:

$$SAR = \frac{Na^{+}}{\sqrt{(Ca^{2+} + Mg^{2+})/2}}$$

V_b is the target or intervention value for a specific soil and V_s is the target or intervention value for the standard soil. A, B and C are element-dependent constants; the values are listed in Table 24.
Source: Ministry Environment 2000

TABLE 24
Element related constants for metals in soils

Elements	A value	B value	C value
As	15	0.4	0.4
Ba	30	5	0
Cd	0.4	0.007	0.021
Cr	50	2	0
Co	2	0.28	0
Cu	15	0.6	0.6
Hg	0.2	0.0034	0.0017
Pb	50	1	1
Mo	1	0	0
Ni	10	1	0
Zn	50	3	1.5

Source: Ministry Environment 2000.

values have to be known before this tool can be used for risk assessment.

Chapter 4
Quantitative determinations: approaches, procedures and quality management[1]

Approaches

To obtain analytical information that meets the quality requirements for a soil degradation study several choices have to be made. If the information is already needed in the field, for instance for an efficient continuation of the field observations, a simple and quick method is required, and a (portable) field laboratory may be useful. Accurate and precise analytical results, however, often can only be produced in a reasonable time span by a well-equipped, staffed and housed laboratory organization. Urgency makes analytical information more costly.

The analytical performance of a method used on the site or in a laboratory not only determines the costs of the investigations but also the sampling scheme. A possible lack of precision may be compensated by higher sampling densities, but at increasing sampling costs. With limited available laboratory capacity and budgets sub-optimal schemes have to be developed and unacceptable uncertainties may be introduced in the study. Unfortunately laboratory and soil databases often have no (detailed) information on the quality or history of the respective data, which limits the use of existing information for planning sample schemes. For the identification of representative areas and sampling sites these data may not met the quality requirements.

Sometimes adequate correlation studies between methods are available. Pedo-transfer functions derived in well-described correlation studies may be used if direct measurement of the soil parameter is time-consuming or expensive.

A laboratory may have clients with different requirements with respect to the amount and quality of analytical information to be produced. This, too, makes the laboratory management complex. Larger institutions often have units for each sample type (soil, water, plant) or group of clients (soil characterization, soil fertility).

Institutions cannot simply change their soil testing schemes or other decision-support systems. This often implies that relations should be calculated between plant responses and variables already being analysed. Moreover, adoption of new laboratory methods may require expensive upgrading of the laboratory housing, equipment and staff. Nevertheless, introduction of standardized or internationally agreed methods is highly recommended. It facilitates the transfer of data outside the own organization and for other purposes. Therefore, harmonization of methods to quantitatively assess soil degradation over larger areas might be very difficult and costly and should not be extended too far.

As information requirements may change with time, the demands on laboratory capacity may be kept within limits by prioritising and selection of samples and analyses. Detailed analysis of irrigation water for monitoring purposes, for instance, may be postponed as long as the electrical conductivity is below a pre-determined threshold value.

---

[1] A. van Oostrum

Sampling

It is important to reconsider threshold values for degradation sampling as more information becomes available. An ongoing sampling and analysis programme may provide missing information, quality checks, and correlation studies between methods and soil parameters.

Sampling may be part of a (new) field survey that also includes other topics. The sampling areas will be selected on information abstracted from studies covering diverse aspects of the study area. Field and laboratory methods may be used for the analysis of these additional samples for complementary information. Incorporation of ancillary data such as related imagery, historic knowledge and expert knowledge will improve the assessment of areas with a low probability of being polluted with a contaminant (Groenigen 1999). Domburg (1994) developed a knowledge-based system to assist in the design of efficient and cost-effective soil survey schemes. In cases where data from different sampling and analytical methods are combined in a database, a specification of the method used should be linked with each analytical result (see for example WISE, Batjes 1997).

For saline and sodic soils the quality of the irrigation water is important. Quality checks of the water shortly before intended use and at water inlet times might be needed. The sampling time then is determined by actual climatic conditions and may be guided by a model for the particular catchment and land use type.

To compare actual values for soil parameters with target and intervention values for clean-up, the data quality should be similar. This also holds where data are used in decision-support systems for soil fertility. In these two cases an interval of days or a few weeks between sampling and analysis and use of the data may be acceptable. Moameni (1994) developed a control chart methodology to detect changes in soil parameters within one land use type. No degradation is identified as long as the actual value is between the upper and lower limits of the control chart. The advantages of the use of statistical quality control principles for the evaluation of the dynamics of soil quality and of the sustainability of land management are described by Larson and Pierce (in Doran *et al.* 1994).

Many other aspects have to be considered in monitoring changes in the soil, water or leaf parameters over longer periods within a defined land use: the location and number of sampling sites and the sampling time and interval largely determine the scheme and the required budget. The cost of the information and the management of a laboratory also depend on the period allowed between sampling and interpretation.

Laboratory and field procedures

Because of soil heterogeneity and inherent variability in chemical, mineralogical, and physical properties of the soil, it is extremely difficult to predict the fate and behaviour of trace elements in soil. Therefore, the selection of chemical treatment to simulate plant availability or toxicity is also complex. The result is a variety in soil, water and leaf analyses.

Current soil testing procedures all originate from attempts to simulate the root environment or the plant availability. The extractability of different elements depends on their properties, such as the tendency to be complexed with organic matter or chemisorbed on minerals, precipitated as insoluble sulphides, carbonates, phosphates or oxides, or co-precipitated in other minerals. Extractants used may be complexing, acidifying or reducing chemicals. Concentrations of elements in these extracts may be correlated with crop yields and often used as inputs in fertilizer recommendation schemes. The complexing agent AAAc-EDTA is widely used as an extractant for the assessment of micronutrients (Sillanpää 1982, 1990).

In most tests for fertilizer recommendations the nutrient is detected after it has been brought into solution. Phosphorus for instance first has to be extracted before detection by a colorimetric method is possible. Each extractant solubilizes different proportions of the fractions in which the nutrient is present at the time. Ideally the extractant resembles the soil solution or simulates the root action, and is selective for the directly available fractions of the nutrient. The choice of an extractant is also limited by the chemistry of the conditions for the detection method. For fertilizer recommendations, it is an advantage if the test is sensitive to small changes in the nutrient status. Research in soil testing has led to a wide range of extractants, even for one nutrient. Total contents in soil are generally used only for nitrogen and carbon. A decrease in total element content may reflect a lowering of buffer capacity. A decrease in content of extractable element is indicative for lower availability to plants.

Because of the wide variety in laboratory and field procedures for soil testing, data quality and specifications of the analytical method should be thoroughly checked and recorded with the analytical results before combination in one database or use with a model. Important criteria are the extractant used, details of the pre-treatment and detection method, the units in which the results are presented, and their accuracy and reliability. Data reported with a similar title or brief description may still be different.

METHOD DESCRIPTION

Measurements and observations provide a characterization of the site at a specific point in time. For existing databases the data are often collected in support of a decision step in soil and land management systems. This implies that the chosen sampling and analytical methods should be well described and appropriate for the local soil conditions, and should fit in the respective local decision system. For available phosphorus, methods with different extractants are applicable to different soils. The selection of a method, particularly the extractant and pretreatment steps before the actual measurement, also depend on the species (compound) of the nutrient relevant in the study.

The title of procedures used is not sufficient for comparison of quality of data. The International Organization for Standardization (ISO, http://www.iso.ch/iso/en/iso9000-14000/index.html) has specified accreditation requirements and outlines for adequate description of procedures and methods.

In Soil Taxonomy, methods and soil variables are linked in operational definitions. Other international and national soil classification systems also have their own specified procedures. The procedures for the Legend of the FAO–Unesco Soil Map of the World and the World Reference Base for Soil Resources are described in Van Reeuwijk (2002). In other cases ISO standardized methods may have been used (key words soil anal*, soil quality, chemical characteristics of soils, technical committee or subcommittee, e.g. ISO TC 190/SC3). In spite of initiatives such as those of ISRIC and FAO (Labex programme), the Wageningen Evaluating Programmes for Analytical Laboratories (WEPAL), and ISO, there is not yet a full international standardization of soil analytical methods.

Important elements for the judgment of analytical procedures are the scope, principle, instrumentation, validation parameters (bias, within-laboratory reproducibility, method detection limit), and test reports and references. The Standard Operating Procedures in the

Quality Handbooks of ISO certified laboratories, or Laboratories working with Good Laboratory Practices, include specifications of these items.

Quality management

The maximum tolerable standard deviation and bias are also part of the quality requirements and should be defined. These quality characteristics differ between laboratories and methods and in time. They should be controlled during the experiments and presented with the results. To guarantee the stated quality a laboratory should maintain (as a minimum) a quality control system according to the rules for Good Laboratory Practice. The principles of GLP have been developed in the framework of the Organisation for Economic Co-operation and Development (OECD) and were first published in 1981. Subsequently a series of further documents on related issues, notably compliance monitoring and inspections, have been established. Documents and activities of the OECD in this area can be consulted at http://www.oecd.org/ehs/glp.htm. Within this quality management system all relevant activities in a laboratory are documented in protocols, operating procedures and other instructions. These steps aim to prevent and track errors. With use of standard and reference samples the quality is monitored in time and can be statistically expressed in measures for the systematic and random error.

Guidelines for quality management in soil and plant laboratories have been compiled by van Reeuwijk (1998), and published as FAO Soils Bulletin 74 (http://www.fao.org). The ISO also provides a number of tools to establish a system to meet the customers' quality requirements in business-to-business dealings. Once implemented and certified the organization has proven to provide a customer with the stated or agreed quality. An important aspect is the participation in proficiency testing programmes or round robin tests, and the application of standardized methods agreed within technical committees (TCs). TC 190 deals with soil quality; its secretariat is at the Netherlands Normalisation Institute (Delft, the Netherlands, www.nni.nl).

Proficiency testing

With external quality control systems as provided by WEPAL and NATP the quality of laboratories can be compared. In these proficiency tests, uniform samples are distributed to participants –on a one-time or regular basis– and the results are rated according to their deviation from a central value.

The International Soil-Analytical Exchange (ISE) of the Wageningen Evaluation Programmes for Analytical Laboratories (WEPAL; http://www.wepal.nl) provides an international accredited proficiency-testing programme. Each quarter, this programme issues a statistical comparison of the results of the participating laboratories on a broad range of samples and with specification of the methods used. Deviations from (corrected) mean values are shown for each soil and leaf variable.

Data from the National Association for Proficiency Testing (NAPT, http://www.proficiency.org) program for soil and plant analysis laboratories indicate that for five different P test procedures the average variability is in the order of 10 to 15 percent, and that 65 percent of the participating U.S. laboratories produced results within this level of variability. Within any given laboratory, variability is lower. A user of any certified soil-testing laboratory may expect results on a specific sample to be reproducible to within 5 to 10 percent of the mean laboratory value (Kamprath *et al.* 2000).

METHOD SELECTION ON THE BASIS OF QUANTITATIVE PERFORMANCE CHARACTERISTICS

Estimation of the variability of a soil parameter in a specific tract of land and or over time requires selection of a laboratory method. Both the quality characteristics of the sampling and the particular analytical procedure(s) applied should fit the intended use. The selection can be based on the performance of a laboratory and method in a round robin test used in proficiency testing.

A first selection of method and or laboratory may be based on the descriptions in handbooks and laboratory manuals. Most of these laboratories are working in the field of soil fertility or soil characterization. They may also be involved in programmes related to the quantitative assessment of soil degradation and may be able to provide information on threshold values for their range of analyses.

Quantitative quality parameters of methods and laboratories can be derived from round robin tests such as ISE. ISE sends 16 samples per year to participants in four periods with four samples each. Participating laboratories analyse these according to their own methods. In the quarterly reports, the results are reported along with an indication of the applied digestion or extraction and detection method or other indications of the method applied. The results per round are available at the Web site www.wepal.nl.

Over the years a wide range of agricultural soils have been tested and have become reference materials. The generated quality characteristics are the spread of the results per sample (standard deviation) and (the indication of the) deviation from the targeted mean (consensus value) of the sample over the rounds.

These characteristics may be of help in estimating the performance of a participating laboratory in these types of programmes or quantifying the required quality of a non-member, as some of the reference samples are still available. They can be ordered and used as quality control samples in the selected laboratory.

For adequate selection the expertise of laboratory quality managers and field specialists should be combined. For instance, the Walkley and Black determination for total carbon includes a correction for incomplete oxidation of the organic material in the sample type. Total element analyzers (such as from Leco and others) claim to produce total contents without any correction. These kinds of differences between methods with similar titles should also be checked to judge a laboratory or a method with a view to the intended use of the analytical results.

Chapter 5
Use of crop growth models to generate indicators of land productivity change[1]

Introduction

Models are analytical tools for schematising a complex reality. They are attractive tools for studying processes or systems, especially where measurements on the actual processes are expensive or difficult. Increasingly, models are used as an alternative to monitoring environmental changes and their impact on the ecosystem. A model can be run for changed conditions, simulating processes for a defined scenario. To study the impact of changed climatic conditions such as higher temperatures and reduced precipitation on crop growth, a crop model can be run for a global warming scenario. The scenario conditions should be within the boundary conditions for which the model was developed and calibrated if meaningful results are to be obtained.

Driessen (1997) describes the potential role of models in monitoring land quality and delivering proxy indicators for environmental change. He states that a land use system –which in its simplest form is a land utilization type practised on one land unit– can be considered biophysically sustainable if the compounded sufficiency of relevant land attributes does not deteriorate under the applied land use, and that within a realistic time horizon. He claims sustainability to be an equilibrium problem. Crop growth modelling and monitoring of relevant land quality indicators are seen as the means to judge the sufficiency of the system's supply side –defined in terms of land management attributes– in the face of the compound land use requirements (the demand side), and the sustainability of the system over the years.

This chapter is based on a study in which several models were combined to explore potential productivity of land use systems at the national level and estimate the impact of erosion-induced land quality changes on crop production (Mantel 1999; Mantel et al. 2000; Mantel and Van Engelen 1997). Such information supplies indicators of sustainability. These state and pressure indicators of land quality can be used at higher system levels in land use analysis as one of the components in the identification of trade-offs (Kruseman et al. 1993). The following land utilization types were selected for case studies: traditionally cultivated (hoe-farming and low-input) maize in Kenya, mechanized, low-input wheat in Uruguay, and mechanized, high-input wheat in Argentina. The case study in Uruguay will be discussed below as an example.

About 20 years ago an integrated research effort was directed towards analysing the agricultural production system. The aim was to evaluate regional agricultural production possibilities by making quantified estimates of growth and production of the main agricultural crops in a region under a wide range of conditions and the means of production that are necessary to achieve these production levels (de Wit and van Keulen 1987). The crop ecological research carried out in Wageningen under the lead of C.T. de Wit produced an operational model of the deterministic type (Van Keulen and Wolf 1986; Spitters et al. 1989). Several models have been developed on the basis of that production model, such as WOFOST (Van Diepen et al. 1989, 1991), and PS123 (Driessen and Konijn 1992; Driessen 1997).

---

[1] S. Mantel

These mechanistic models calculate crop yields determined by three principal growth constraints. This results in theoretically defined situations that are hierarchically ordered according to increasing analytical complexity. The effects of the principal growth constraints are evaluated by making successive calculations of:

1. the constraint-free yield, or potential yield, reflecting the biophysical production ceiling determined by the crop's genetic potential under the ambient radiation and temperature regime;
2. the water-limited yield, additionally reflecting the influence of limited or excessive water supply; and
3. the nutrient-limited yield.

An example: the Uruguay case study

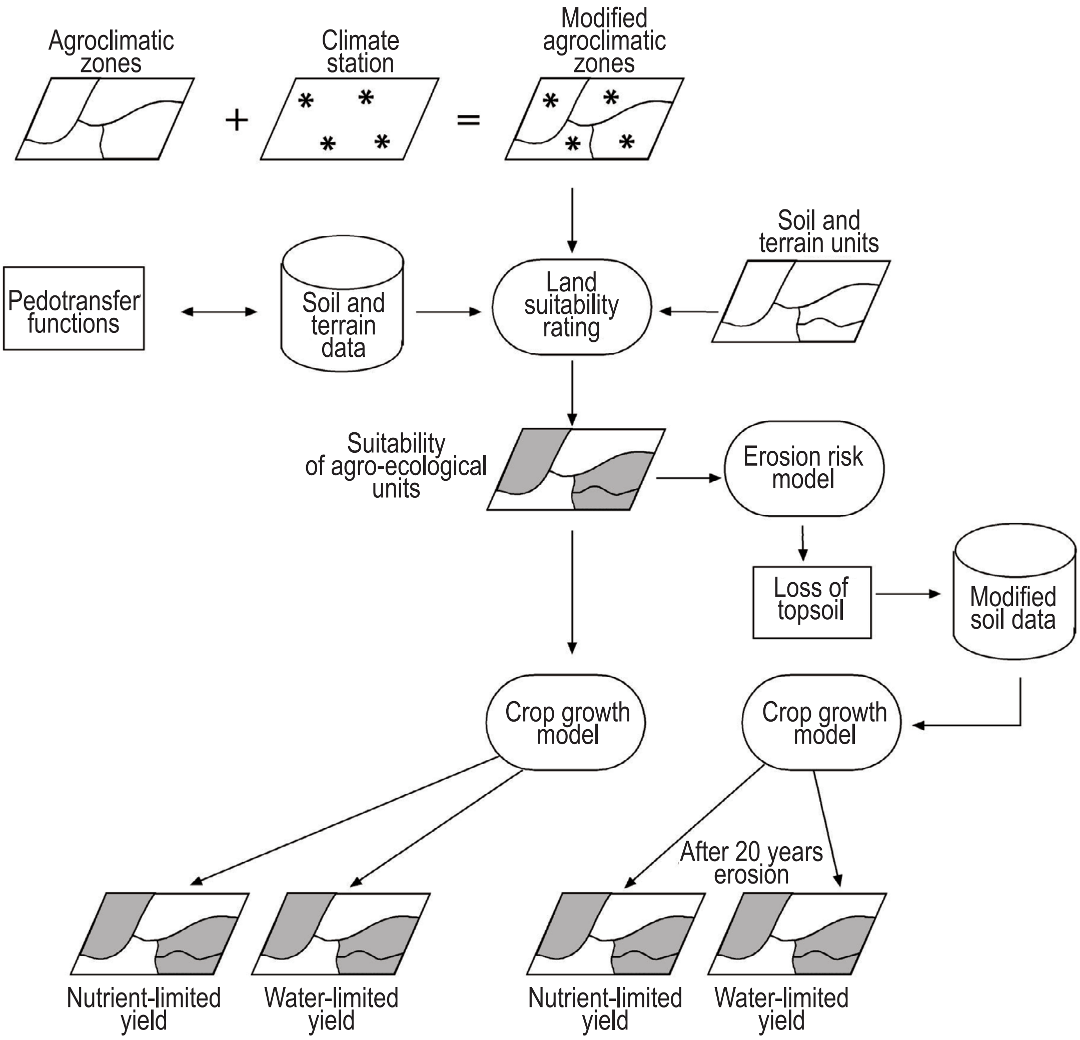
The Uruguay case study aimed to estimate the impact of change in soil properties induced by removal of topsoil through sheet erosion, influencing crop performance (FAO 2002). For that purpose, several models were combined (Figure 6). Data on land units were taken from national (1:1 M) Soil and Terrain (SOTER) databases, which were linked to a GIS for spatial analysis. Overlay of Agro-Ecological Zones (AEZ) maps with soils and terrain information created the basic units for evaluation, so-called Agro-Ecological Units (AEUs: aggregations of AEZ, rainfall zones and soil and terrain units). Land suitability was assessed for low-input, mechanized wheat cultivation, using a model defined in the Automated Land Evaluation System (ALES). Unsuitable areas could be ignored for further analysis. Erosion risk was assessed using a parametric model (SWEAP), and from that an erosion scenario was defined. The potential yield was calculated for each mapping unit that was evaluated as suitable for the land use, under actual conditions and under a scenario of 20 years of topsoil erosion. Yield declines because of topsoil loss through erosion over the 20 years were calculated by comparing yields estimated under the erosion scenario with the yields estimated for actual conditions (Figure 6).

Apart from erosion risk, which was assessed separately, about half of Uruguay (42%, based on dominant soils) was estimated to be suitable for mechanized wheat cultivation with a low level of inputs (Table 25 and Figure 7). Severe restrictions of the land qualities availability of moisture and available foothold for roots were the main cause for classifying land as unsuitable (11 and 18 percent of total land respectively).

Uruguayan soils are soils are vulnerable to water erosion (Figure 8) when a wheat crop is cultivated, although the relative differences in erosion risk are considerable. Severe erosion has taken place in the past, in particular just north of the capital Montevideo, when wheat was more widely cultivated. In the extreme west of Uruguay, continuous wheat cropping is combined with conventional tillage, and observations indicate erosion damage ranging from moderate to severe (Terzaghi 1996).

High average minimum temperatures in Uruguay entail a short growing season (rapid plant development) and limit wheat yields. Well-managed, commercial farms realize average yields around 4 t/ha and occasionally yields of 6 t/ha are recorded. In experimental plots, yields of 8 t/ha have been attained. Comparisons of the water-limited yield (WLY) and nutrient-limited yield (NLY) with the constraint-free yield (CFY), which is the maximum biophysically attainable yield, shows that the yield gaps are generally small for NLY and larger for WLY (Table 25). Figure 9 shows the distribution of the water-linked yield for wheat in Uruguay. Half of the land suited

Figure 6
Flow chart of modelling process to generate indicators of land change



Modified after Mantel & Van Engelen 1999.

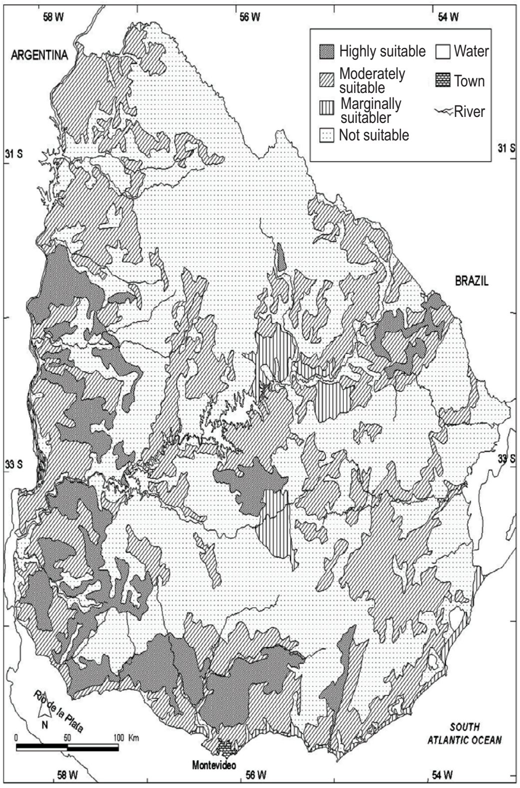
Table 25
Trends in wheat yield gaps for different production situations (relative to constraint-free yields) expressed as percentage of total area suitable for mechanized, low-input wheat

Production situation	Wheat yield gap (relative to CFY)			
	0-25%	25-50%	50-75%	75-100%
Water-limited yield	51	15	26	9
Water-limited yield, scenario	2	19	48	31
Nutrient-limited yield	88	6	5	1
Nutrient-limited yield, scenario	85	9	2	4

a) Yield gap = (1 - Prod. Situation/CFY) x 100

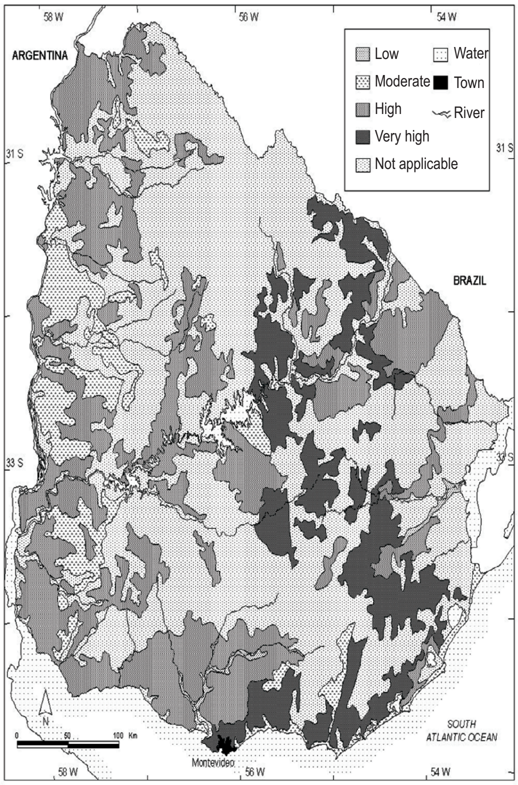
Note: The numbers in the table refer to the extent of the dominant soil and terrain components within the agro-ecological units suitable for the defined LUT with specific ranges of yield gaps, expressed as a percentage of the total extent of dominant soils suitable for the defined use (38 102 km^2).
Source: Mantel *et al.* 2000.

FIGURE 7
Suitability map for low-input wheat in Uruguay



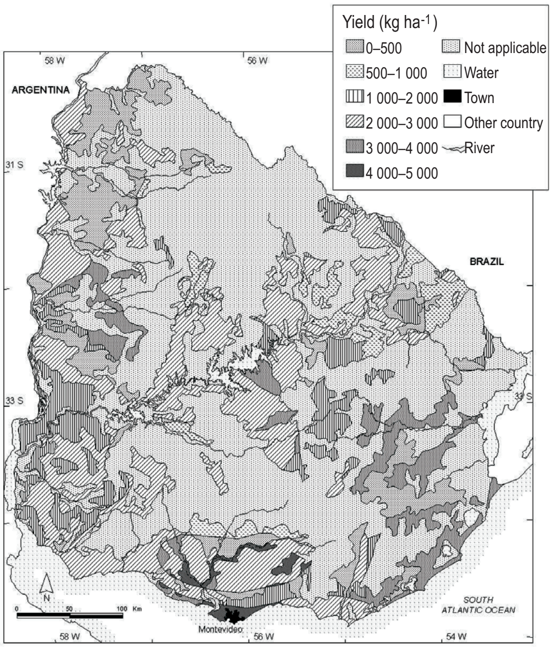
Source: Mantel *et al.* 2000

FIGURE 8
Erosion risk map for wheat in Uruguay



Source: Mantel *et al.* 2000.

FIGURE 9
Water-limited yield for wheat in Uruguay



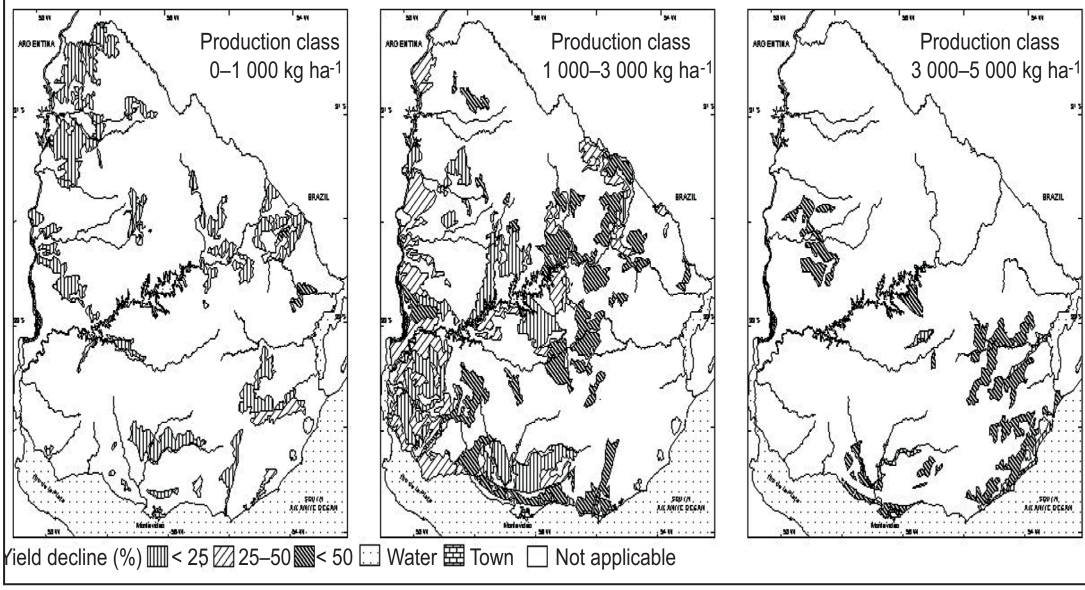
Source: Mantel *et al.* 2000

for wheat growing has a water-limited yield gap (relative to the constraint-free yield) of 25 percent or more (implicating that WLY is 75 percent or less relative to the CFY). WLY gaps are likely to be related to drought stress mainly during the grain-filling period (Van Lanen *et al.* 1992).

The high risk of erosion on land under wheat cultivation in Uruguay is reflected in a severe erosion scenario, with most land units estimated to lose 25 to 50 cm topsoil over 20 years. The main conclusion from the Uruguay case study was that the predicted erosion-induced soil changes had an impact mainly on physical land qualities. Moisture availability and drainage became more limiting after accounting for the erosion scenario, expressed in a decline in water-limited wheat yields (Figure 10).

Table 25 clearly expresses this; the extent of land with a water-limited yield

FIGURE 10
Water-limited yield decline after 20 years erosion scenario in Uruguay



Source: Mantel *et al.* 2000.

gap (relative to a constraint-free yield) of 25 percent or more increased from 49 to 98 percent of the total area suitable for wheat cultivation. Nutrient-limited yields are little affected by topsoil erosion on these generally deep and organic matter-rich soils. The few units that show a NLY decline of more than 50 percent (in the centre-east and southeast of the country) are all units with a worst-case scenario of 50 cm loss of topsoil. Considered at a national level in Uruguay –and for this particular crop-management combination–, the hazard of soil fertility decline because of water erosion is limited. The impact on physical soil properties is severe, however, as expressed in water-limited yield decline.

The model thus provides estimates of the degree to which erosion reduces the quality of the soil, but does not take into consideration its off-site effects, such as sedimentation of waterways and roads.

The changes in land quality status estimated by comparison of crop growth simulations for actual conditions and under an erosion scenario can serve as proxy indicators of agro-ecological sustainability of land use systems. Scenario analysis supports land management by exploration of issues such as: Where will erosion be most severe? How will production be affected if...? The approach may be used to support strategic decisions seeking to optimize land-use, prioritize research, and guide conservation planning at the national level. For the identification of trade-offs among objectives for different sustainable land use scenarios, the off-site effects and land management practices need to be quantified as well. Subsequently, all indicators that approximate the state of the natural resource or the rate of the process affecting its stock or quality can be balanced in quantifying sustainability of land use options (Mantel *et al.* 2000).

A model can be a helpful tool to support decisions about options for management of land resources. The power of a model is that it helps to understand the system studied, the interdependence of its components, and their reactions to changes. However, given the uncertainty in data and the assumptions about possible futures, the predictions of models should be interpreted with caution, and validated against factual, quantitative data.

Chapter 6
Case studies

MONITORING CHANGES OF FOREST SOILS IN INDONESIA[1]

This case study describes a practical method for measuring the impact of forest interventions such as logging on forest soils with a view to achieving sustainable forest management. In forest concessions in Indonesia, vegetation is often surveyed along strip line s. In this case study mini-transects are proposed as a way to monitor erosion status as indicator for changes induced by forest management (Mantel, 1999).

Logging-induced disturbance of the forest ecosystem

Human interference with the forest ecosystem causes a series of long- or short-term changes, most of which are detrimental to forest regrowth or to secondary land uses (Fölster in Lal et al. 1986). The disturbance of fauna is one of the most drastic effects of logging on the forest ecosystem. This is important not only from a conservation or biodiversity point of view, but also because animals have a role as seed dispersers; the survival of certain tree species within the forest may depend on their presence. With timber extraction, nutrients and carbon are lost from the forest ecosystem and changes in the nutrient and carbon pools are unavoidable. Other reported effects of logging on soil and vegetation include soil compaction on the skid trails, damage to vegetation as a consequence of the falling trees and of the skidding of logs, accelerated soil erosion, and silting of waterways. The severity and extent of the changes varies depending on the land conditions and on the logging and forest management techniques applied. The focus of this case is on effects of forest logging operations on soil conditions.

Indicators for change

The impact of forest management practices such as log extraction on the forest ecosystem and on its sustainability can only be evaluated properly when the temporal dimension is considered. Monitoring is essential for this objective, which implies repetitive observations of properties that adequately characterize forest qualities in relation to sustainability. With monitoring the possible environmental benefits of different sustainable forest management techniques can be assessed. Important criteria in the selection of properties for monitoring are the degree to which a property is a sensitive indicator of change; its relevance for forest management; and the adequacy with which it describes forest quality, or the degree of correlation with a similar or better indicator measured with more difficulty or expense. Variables that may serve as indicators for logging-induced changes are listed in Table 26.

The bulk density is a mandatory property when nutrients, toxins (e.g., exchangeable aluminium) or organic carbon are measured, since these are measured on a weight per unit-weight basis ($g.100g^{-1}$ soil), whereas weight per soil volume ($g.cm^{-3}$ soil) is the relevant parameter. In order to avoid serious misinterpretations bulk density should always be measured, and these data items should be converted to weight-per-volume units.

---
[1] S. Mantel

TABLE 26
Soil variables that may serve as indicators for logging-induced changes

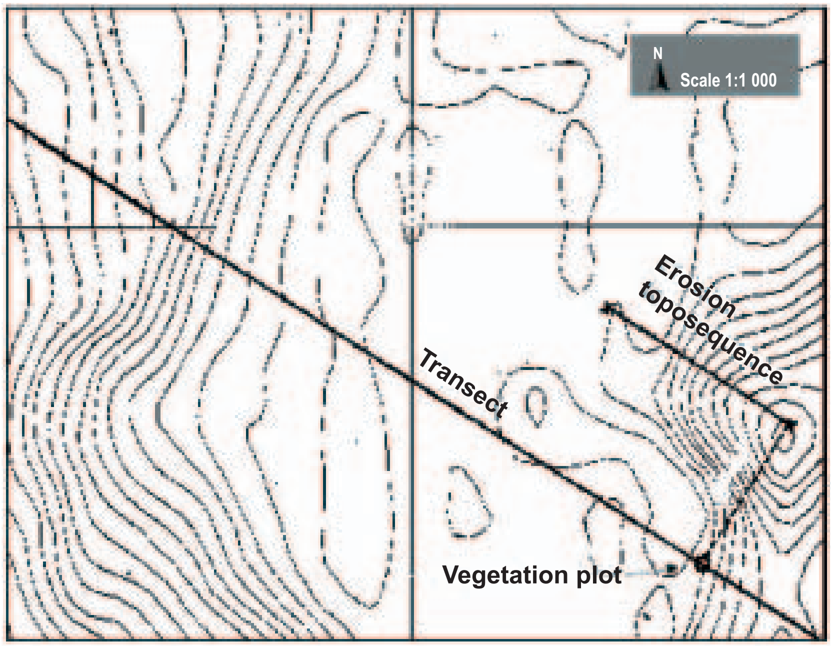
Variable	Indicator
1 Species composition of soil faunal population	Changes in soil fauna population
2 Topsoil pH	Change in soil acidity
3 Topsoil organic carbon	Change in soil organic carbon
4 (Soil) nutrients (N,P,K, bases)	Changes in nutrient status of forest ecosystem
5 Thickness of litter layer	Changes in carbon cycle and soil faunal population
6 Bulk density	Compaction
7 Infiltration capacity	Compaction
8 Depth to critical aluminium level	Degree of erosion (loss of topsoil) in acid soils
9 Depth to argillic B horizon	Degree of erosion (loss of topsoil)
10 Soil texture	Degree of erosion
11 Sediment load in river (draining a watershed)	Extent and degree of soil erosion
12 Extent and degree of soil erosion	Extent and degree of soil erosion

Many of the other expected environmental changes are associated with water erosion, e.g. changes in the chemical and hydrological cycle, and may be deduced from the water erosion indicators. An alternative to large-scale application of the plot-based method is proposed, in which the different aspects of water erosion are used as single indicators for environmental change. If strip lines are cut –e.g. by vegetation inventory teams–, they may be used as a basis for monitoring erosion status. Observations in these strip lines themselves or in the vegetation inventory plots may not be representative because of disturbance by frequent passage of people; observations therefore should be made along lines at some distance from the strip lines. These observations should cover the entire cross-section of a slope. Such an erosion toposequence (Herweg 1996) covers different land facets, or slope positions, from hilltop to valley floor. Qualitative and semiquantitative observations are made in different land and management units. Observations are repeated over the years to track changes. Table 27 specifies the properties to be measured at each location of an erosion toposequence. Soil and site conditions other than the erosion features proper should be recorded as well. In this way relations can be investigated between the observed erosion and the forest management and soil and terrain characteristics.

TABLE 27
Properties for description of current erosion damage

Soil and terrain characteristics	Erosion features
Slope (percent)	Capping, Sealing
Slope form	Rills (depth, width, length)
Length of slope (m)	Gullies (depth, width, length)
Soil texture	Evidence of sheet erosion (depth, extent)
Soil horizon boundaries (cm)	Soil accumulation (depth, extent)
Soil depth (cm)	Occurrence of landslides, slumps (length, width)
Soil colour	Soil accumulation (depth, extent)
Depth of litter layer (cm)	Evidence of soil accumulation, erosion
Gravel content (percent)	Evidence of erosion (depth, extent)
Stoniness, Rockiness (percent)	Indicator for erosion
Vegetative cover (percent)	Indicator for erosion

FIGURE 11
Experimental layout of monitoring erosion status using toposequences



Mantel, 1999.

The erosion toposequences should be measured along lines at some distance from the strip lines of the forest inventory. The advantage of this is that these strip lines are georeferenced; locations may therefore be linked to a map and can be revisited in the field. The map link is important since at a later stage the monitoring data can be linked to other information layers for analysis or stratification (by management unit, land system, etc.). Vegetation is described in plots on the strip lines, every 400 meters. The side path starts in the centre of the vegetation plot; from there perpendicular to the strip line to a point 40 m from the strip line (Figure 11). The distance may be further from the strip line, depending on the local terrain conditions. That point is the reference point for erosion assessment. From that point an erosion toposequence should be measured, in principle in the same direction as the strip line, or if in a different direction, specifying the orientation. When the reference point is located on the slope (middle, lower or upper) one should follow the toposequence up to the hilltop such that the reference point is on the line from the hilltop to the valley bottom (toposequence). The erosion toposequence should be assessed in a strip 20 m wide: 10 m to both sides of the line from hilltop to valley bottom. The side paths should be alternating to the right and to the left of the strip lines. In principle monitoring should be done at the same interval as the vegetation plots (every 400 m along the strip lines).

In terms of damage to soil of logging operations, a distinction should be made between *direct* and *indirect* effects. Direct effects include the soil disturbance on skid trails, such as compaction. Skid trails and logging roads may become important sources of runoff and sediment (Bruijnzeel 1990). Indirect effects are the increased susceptibility to erosion because of increased exposure due to thinning of the forest stand. The extent and degree of changes following logging within the skid trails are expected to be different from those in the area around them. Besides the transect observations, additional observations should be made on selected locations along a skid trail to assess the impact of skidding over a longer period.

Quantitative indicators formulated in terms of outcome (state and dynamics of a forest ecosystem) are only meaningful if reference values are available (Lammerts van Bueren and Blom 1997). Some transects should be located in forest without disturbance during the monitoring period, to compensate for the natural processes in interpreting the time series.

The main difference with the plot method, apart from the experimental set-up, is that with the plot method the field operator takes the samples and most of the actual observations are laboratory analyses, while in the transect method the field operator makes the observations directly in the field. One objection could be that the data are not fully quantitative and therefore less accurate. Much of the reliability of the observations depends on the experience and skill of the surveyor. On the other hand observations can be repeated many times, increasing reliability. Another advantage of visual field observations for long-term monitoring is that –in contrast to sample analysis– it is non-destructive, which means that the same site can be observed again at a different time. Visible erosion features include soil capping, rills and gullies, ‘staircasing’, and soil deposition. The indicators of erosion damage and expressions of its severity need to be classified and well documented to ensure the use of a common methodology, with support materials for estimation of observed features to make the procedure as objective as possible. Each monitoring observation should be done in undisturbed areas –preferably in each of the soil and terrain units– as well, in order to distinguish between the effects of human interventions and those of extreme climatic events and natural variation.

Conclusions

Expected changes in most variables listed in Table 25 are related to water erosion induced by logging. The objective of a monitoring programme for forest concessions could be to evaluate the environmental impact of logging operations and to assess the environmental benefits of alternative logging techniques. A monitoring method that meets these objectives should be practical, replicable in other projects and areas, and feasible within reasonable budget limits. To obtain information on changes in soil nutrient status as a consequence of logging operations, plot measurements are an option. However, the plot-based method has many practical pitfalls and theoretical problems that may not easily be overcome. Another constraint to the replicability of the plot method within acceptable budget limits is the fact that the sampling and interpretation of the results should be done by experienced soil surveyors. The transect method has theoretical weaknesses but practical advantages. A standardized methodology for field observations, with proper support materials –manuals and field handbooks– justifies more confidence in the data quality and reliability. However, the usefulness of the results will ultimately depend on the skills and experience of the surveyors.

Measurement of the sediment load of rivers draining the major catchments supplies valuable information on the degree of logging-induced erosion. This requires a long-term measurement scheme, as erosion is not a continuous process, but generally occurs in distinct events, often of short duration. These events are mainly related to climate and forest management. The results from such a scheme may well be related with the monitoring of erosion along transects as described above. By placements of poles at different slope positions in the catchments (with a mark at the soil surface), loss of topsoil may be assessed over the years. This may give clues on where soil loss is most severe in the toposequences within the catchment or where there may even be soil accumulation. This provides information based on which sediment load data can be interpreted better.

The monitoring effort will increase in value if the results can be combined with other observations for the same period, e.g. on vegetation characteristics (biodiversity) and hydrology (such as quantifying runoff and outflow from catchments during and after a storm). Additional vegetation recordings, e.g. counting of specific species as indicators of degree of disturbance (certain pioneer species), may supply useful information.

Information on the degree and extent of forest area affected by burning should be used as an additional information layer in stratification and analysis of monitoring data. Forest fires are disturbances of high intensity, which have a significant impact on the forest ecosystem. Changes in environment because of forest fires may easily obscure changes induced by forest management interventions.

Evaluation and monitoring of soil and water quality in Morocco[1]

A case study on the Evaluation and Monitoring System (EMS) of the soil and water quality in two irrigated areas of Morocco (Tadla and Doukkala) shows that the set-up of an evaluation and monitoring system (EMS) to assess the soil and water quality in irrigated zones is very useful. It should be well integrated in the strategy of environmental protection and considered as an important component in financial planning (Soudi 2001). This system makes it possible to follow the evolution of the quality of the resources with the aim of addressing, jointly with the land users, any inappropriate agricultural practices contributing to the soil and water degradation processes. That would guarantee sustainability of the productivity of the irrigated zones.

The report, illustrated by case studies, offers guidelines for setting up an optimal EMS. It is however important to underline that the natural resources in general and the quality of the soils and water in particular depend on the specific features of the area or site. It is therefore impossible to specify scenarios for all the various situations.

This report also highlights the final goal of a monitoring system, which consists of disseminating the results and formulating the actions to be undertaken to control the problems of deterioration revealed by the indicators of quality. These actions must obviously take into account their ecological, socio-economic and cultural impacts.

The following are among the main aspects considered in this report:

- the representativeness of the site;
- the integration of reference zones; and
- the choice of variables that may serve as indicators of soil and water quality.

The last aspect makes it possible to reduce the cost of monitoring and would guarantee the sustainability of EMS. The case study reported on the cost of the EMS. In summary, the following requirements should be met for setting up an EMS in an irrigated area:

- Infrastructure for a soil and water laboratory, in addition to the equipment with an estimated cost of US$ 150 000;
- US$ 0.20 per ha annual maintenance costs;
- Depreciation of non-expendable equipment for analysis and *in situ* measurements. The estimated depreciation for the equipment of the Doukkala irrigation scheme (65 000 ha) was US$ 9000 per year;
- Water and electricity consumption.

[1] G. van Lynden

Table 28
Summary of recommendations for an EMS

Parameter	Frequency	Density of observation points (n/1000 ha)	Remarks
SOIL QUALITY		0.5 to 1.5	As previously indicated, there is no standard density of the observations. This density depends on the number of different situations (soil types, cropping systems, irrigation systems). The absolute number of the observations depends more on the variation in situations than on the extent of the irrigation scheme.
S1. EC	1 to 2 times a year		
S2. pH (1:2.5)	1 to 2 times a year		
S3.Ionic composition	1 time a year to 1 time in 2 years		
S4. Exchangeable Na	1 time a year to 1 time in 2 years		
S5. Infiltration rate	1 time a year to 1 time in 3 years		
S6. Bulk density	1 time in 2 to 3 years		
S7. Organic matter	1 time in 2 to 3 years		
S8. Stable aggregates	1 time a year		
P, K	1 time in 2 to 3 years		Recommended (see text below)
GROUNDWATER QUALITY			In this specific case, the number of observations depends on: the depth of the water table, cropping system, soil type, lithology, any point sources of pollution.
E1. water table level	3 times a year to 1 time a year	0.5 to 2	
E2.EC	3 times a year to 1 time a year		
E3. pH	3 times a year to 1 time a year		
E4. NO_3^-	3 times a year to 1 time a year		
E5. Ionic composition	2 times a year to 1 time a year		

List of parameters :

Case 1. Limited resources : S1, S4, S6, S7 and E1, E2, E4

Case 2. Sufficient resources: All the parameters are monitored with additional special parameters (pesticides, organic pollutants, trace elements, …).

Because of the high cost of the pesticides analysis, it is recommended to monitor this parameter in a sub-network identified based on the intensity of the pesticides applications. High nitrate concentrations could indicate the probability of pesticides in the groundwater.

Source: Soudi 2001.

Table 28 summarizes the recommendations concerning the soil and groundwater quality parameters, the frequency of the monitoring and the density of the observations for different levels of (human and material) resource availability. Surface water is not considered here because of the low density of the required observations.

In the irrigated zones of the countries of the Maghreb, soil fertility (major elements P and K) is being monitored with a relatively high intensity because of the urgent need for fertilization recommendations. These data currently are not being considered as parameters of soil quality. In the monitoring of salinity in the zones with problems, it is recommended that the services in charge of monitoring consider these data on soil fertility as information of value in the accurate monitoring of the soil quality.

A key recommendation concerns the elaboration of the standards and norms for the interpretation of the soil and water quality parameters in the Maghreb countries. For example in the case of salinity, the standards used are not fully adapted to the context of the soils and water of the Maghreb. Moreover, these standards do not take into account the properties of the soils, the climate, the irrigation system and the interaction between these various factors related to salinization.

References

Acton, D.F. & Gregorich, L.J. (eds) 1995. *Toward sustainable agriculture in Canada*. Publication 1906/E. Centre for Land and Biological Resources Research. Research Branch, Agriculture and Agri-Food Canada, Ottawa.

Adriano, D. C. 1986. *Trace Elements in the Terrestrial Environment.* Springer, New York.

Ayers and Westcot 1976 cited from Landon 1984.

Baharuddin, K., Mokhtaruddin, A.M. & Majid, N.M. 1996. Effects of logging on soil physical properties in Peninsular Malaysia. *Land Husbandry* 1(1&2): 33-41.

Bakkes, J.A., Van den Born, G.J., Swart, R.J., Hope, C.W. & Parker, J.D.E. 1994. *An overview of environmental indicators: state of the art and perspectives*. UNEP/EATR.04-01; Environmental Assessment Sub-Programme, UNEP, Nairobi. 72 p.

Batjes, N.H. 1997. A world data set of derived soil properties by FAO-UNESCO soil unit for global modelling. *Soil Use and Management* 13: 9-16.

Benites, J.R. 1998. Land condition change indicators for sustainable land resource management. In: *Land quality indicators and their use in sustainable agriculture and rural development*. Land and Water Bulletin. 5. World Bank, UNEP, UNDP, FAO, Rome.

Blaikie, P.M. & Brookfield, H.C. 1987. *Land degradation and society*. Methuen, London and New York. xxiv and 296 pp.

Blum, W. E. H. 1988. *Problems of soil conservation*. Nature and Environment Series 39. Council of Europe, Strasbourg.

Breimer, R.F., Van Kekem, A.J. & Van Reuler, H. 1986. *Guidelines for soil survey in ecological research*. MAB Technical Notes 17. Unesco, Paris.

Bruijnzeel, L.A. 1990. Soil chemical changes after tropical forest disturbance and conversion: The hydrological perspective. pp. 45-61 in: A. Schulte and D. Ruhiyat (eds.) *Soils of tropical forest ecosystems*. Springer, Berlin.

Buol, S.W., Sanchez, P.A., Cate, R.B. & Granger, M.A. 1975. Soil fertility capability classification. In: E. Bornemisza and A. Alvarado (editors). *Soil management in tropical America*. North Carolina State University, Raleigh, N.C., pp. 126-141.

De Wit, C.T. & Van Keulen, H. 1987. Modelling production of field crops and its requirements. *Geoderma* 40: 253-265.

Domburg, P. 1994. A Knowledge-based System to Assist in the Design of Soil Survey Schemes. Thesis, Wageningen Agricultural University.

Doran, J.W., Coleman, D.C., Bezdicek, D.F. & Stewart, B.A. (Eds), Defining Soil Quality for A Sustainable Environment, SSSA Special Publication Number 35, 1994. Madison, Wisonsin, USA

Driessen, P.M. 1984. Erosion hazard and conservation needs as a function of land characteristics and qualities. In: W. Siderius (Editor), *Land evaluation for land-use planning and conservation in sloping areas*. ILRI, Wageningen, pp. 32-39.

Driessen, P.M. 1997. Biophysical sustainability of land use systems. *ITC Journal* 3(4): 243-247.

Driessen, P.M. & Konijn, N.T. 1992. *Land-use systems analysis*. Wageningen Agricultural University, Wageningen, 230 pp.

Dumanski, J. 1994. Workshop summary. *Proceedings of the International Workshop on Sustainable Land Management for the 21st Century.* Vol. 1: Workshop Summary. The Organizing Committee, International Workshop on Sustainable Land Management. Agricultural Institute of Canada, Ottawa.

Dumanski, J. 1998. Application of the pressure-state-response framework for the land quality indicators (LQI) programme. In: FAO (ed.). *land quality indicators and their use in sustainable agriculture and rural development.* FAO, UNDP, UNEP and World Bank, Rome.

FAO 1976**.** *A Framework for Land Evaluation.* Soils Bulletin no. 32. FAO, Rome.

FAO 1979. cited from Landon 1984.

FAO 1990. Guidelines for soil description. 3rd Edition (revised). FAO, Rome

FAO 1993. *World Soil Resources. An explanatory note to the FAO World Soil Resources Map at 1: 25000 000 scale.* World Soil Resources Report 66, FAO, Rome.

FAO 2001. Guidelines for the qualitative assessment of land resources and degradation. AGL/Misc/33/ 2001 (ftp://ftp.fao.org/agl/agll/docs/misc33.pdf). FAO, Rome.

FAO 2002. Global agro-ecological assessment for agriculture in the 21st century. Land and Water digital media series Nr 21. CD-ROM. FAO, Rome

Ferguson, C.C. 1999. Assessing risks from contaminated sites: policy and practice in 16 European countries. Land Contamination and Reclamation 7 (2): 33-54.

Finke, P.A. 1991. A sequential sampling procedure for estimation of the average of a spatially variable attribute (in Dutch). In: *Ruimtelijke statistiek voor bodem en water.* Rapporten en nota's. no. 24, CHO-TNO., Delft.

Geurts, P.M.H. & Van den Berg, M. 1998. A *simple agro-ecological zonation for fertilizer recommendations in Mozambique.* Soil Use and Management 14: 136-141.

Gobin, A., Govers, G., Jones, R., Kirkby, M. and Kosmas, C. 2003. Assessment and reporting on soil erosion. Background and workshop report. Technical report 94. European Environment Agency, Copenhagen.

Groenigen, J. W. van. 1999. Constrained Optimisation of Spatial Sampling. Thesis, Wageningen Agricultural University.

Harpstead, M. I. H., Bennett, W.F. 1997. *Soil Science Simplified.* (Third Edition), Iowa State University Press, Ames.

Herweg, K. 1996. Field manual for assessment of current erosion damage. Soil Conservation Research Programme, Addis Abeba.

Herweg, K., Steiner, K., Slaats, J. (eds) 1998. *Sustainable land management guidelines for impact monitoring. Workbook and Toolkit Module.* SDC, GTZ, the World Bank, and CDE, 81 & 133 pp.

Huber, S., Syed, B., Freudenschuss, A., Ernstsen, V. & Loveland, P. 2001. *Proposal for a European soil monitoring and assessment framework.* Technical report 61, European Environment Agency, Copenhagen.

Kamprath, E.J. (Chair of task force) 2000. *Relevance of soil testing to agriculture and the environment.* Issue Paper nr 15, June 2000. Council for Agriculture Science and Technology (CAST). Ames, Iowa, USA.

Kruseman, G., Hengsdijk, H. & Ruben, H., 1993. *Disentangling the concept of sustainability: Conceptual definitions, analytical framework and operational techniques in sustainable land use.* DLV report no. 2, CABO-DLO, Wageningen.

Lal, R., Sanchez, P.A. & Cummings, R.W. (Eds) 1986. *Land clearing and development in the tropics.* Balkema, Rotterdam.

Lammerts van Bueren, E.M. & Blom, E.M. 1997. *Hierarchical framework for the formulation of sustainable forest management standards*. Backhuys, Leiden.

Landon, J.R. (ed.). 1984. *Booker Tropical Soil Manual. A Handbook for Soil Survey and Agricultural Land Evaluation in the Tropics and Subtropics*. Booker Agriculture International Limited, London.

Liniger, H.P., G.W.J. van Lynden and G. Schwilch. 2002 Documenting field knowledge for better land management decisions - Experiences with WOCAT tools in local, national and global programs. Proceedings of ISCO Conference 2002, Vol. I. Beijing, pp. 259-267

López-Bermúdez, F., Barberá, G.G., Belmonte-Serrato, F. How to measure desertification and degradation processes. http://www.desertification.it/doc/AlgheroWEB/Lopez-Bermudez.htm.

Mantel, S., 1999. Soils and terrain of the Labanan area. Development of an environmental framework for the Berau Forest Management Project, BFMP report no. 10, Ministry of Forestry-European Union, Jakarta.

Mantel, S., & V.W.P. van Engelen, 1997. The impact of land degradation on food productivity, case studies of Uruguay, Argentina and Kenya. Working paper 97/01. ISRIC, Wageningen.

Mantel, S. & van Engelen, V.W.P., 1999. Assessment of the impact of water erosion on productivity of maize in Kenya: an integrated modelling approach. *Land Degradation and Development* 10 (6): 557-592.

Mantel, S., Van Engelen, V.W.P., Molfino, J.H. & Resink, J.W., 2000. Exploring biophysical potential and sustainability of wheat cultivation in Uruguay at the national level. *Soil Use and Management* 16 (4): 270-278.

Markert, B. (ed.) 1994. *Environmental sampling for trace analysis*. VCH, Weinheim.

McBride, M.B. 1994. *Environmental Chemistry of Soils*. Oxford University Press, Oxford, New York.

McQuaid, B.F., Buol, S.W. & Kelley, A. 1995. Application of the Soil Fertility Capability Classification in soil survey reports. *Soil Survey Horizons* 117-120.

Miller, W.R. & Donahue, R.L. 1990. *Soils – an introduction to soils and plant growth*. Sixth ed. Prentence-Hall International, London.

Min. Environment 2000. Technical annex (http://www.vrom.nl/docs/bij_seni.pdf) to *Target values and intervention values soil remediation* (in Dutch). Circular 24-2-2000 of the Netherlands Ministry of Spatial Planning, Housing and the Environment.http://www.vrom.nl/docs/milieu/circstreef-eninterv-maart2000.doc.

Moameni, A. 1994. *Assessment of the prevailing irrigation practices and their relation to soils, using remote sensing and GIS in the Hamadan area (Iran)*. Thesis, ITC, Enschede.

Ndegwa, E.N. 1997. Planning of sustainable land management: user needs and possibilities. Experiences from Kenya. In: K.J. Beek, P.M. Driessen and K. de Bie (eds.). *International conference on geo-information for sustainable land management* (on CD-ROM). ITC, ISSS, Enschede.

OECD 1993. *OECD core set of indicators for environmental performance reviews. a synthesis report by the group on the state of the environment*. Environment Monographs N° 83, Ocde/Gd(93)179, Organisation for Economic Co-operation and Development, Paris.

Oldeman, L.R. (ed.) 1988. *Guidelines for general assessment of the status of human-induced soil degradation*. ISRIC Working Paper 88/4. ISRIC, Wageningen.

Oldeman, L.R., Hakkeling, R. & Sombroek, W.G. S. 1991. *A global assessment of the status of human-induced soil degradation. An explanatory note*. ISRIC/UNEP, Wageningen, Nairobi.

Peverill, K.I., Sparrow, L.A. & Reuter, D.J. 1999. *Soil analysis – an interpretation manual*. CSIRO, Collingwood, Australia.

Pieri, C., Dumanski, J., Hamblin, A. & Young, A. 1995. *Land quality Indicators*. World Bank Discussion Papers 315. World Bank, Washington DC.

Quevauviller, Ph. (ed.) 1995. *Quality assurance in environmental monitoring – sampling and sample pretreatment*. VCH, Weinheim.

Richards, L.A. (ed.), 1954. *Diagnosis and improvement of saline and alkali soils*. Agriculture handbook No. 60. United States Dept of Agriculture. U.S. Govt Printing Office, Washington DC.

Sanchez, P.A., Couto, W. & Buol, S. W. 1982. The fertility capability classification system: interpretation, applicability and modification. *Geoderma* 27: 283-309.

Shulin, R., Desaules, A., Webster, R. & Steiger, B. von, 1993. *Soil monitoring, early detection and surveying of soil contamination and degradation*. Birkhauser Verlag, Basel.

Sillanpää, M. 1972. *Trace elements in soils and agriculture*. Soils Bulletin 17, Food and Agriculture Organization of the United Nations, Rome.

Sillanpää, M. 1982. *Micronutrients and the nutrient status of soils: a global study*. FAO Soils Bulletin 48, Food and Agriculture Organization of the United Nations, Rome.

Sillanpää, M. 1990. *Micronutrient assessment at the country level: an international study*. FAO Soils Bulletin no. 63, Food and Agriculture Organization of the United Nations, Rome.

Sillanpää, M. & Jansson, H. 1992. *Status of cadmium, lead, cobalt and selenium in soils and plants of thirty countries*. FAO Soils Bulletin 65, Food and Agriculture Organization of the United Nations, Rome.

Smaling, E.M.A. & Van de Weg, R.F. 1990. Using soil and climate maps and associated data sets to select sites for fertilizer trials in Kenya. *Agriculture, Ecosystems and Environment* 31: 263–274.

Smyth, A.J. & Dumanski, J. 1993. *FESLM: An international framework for evaluating sustainable land management*. A discussion paper. World Soil Resources Report 73. Rome, Food & Agriculture Organization, 74 pp.

Soudi, B. 2001. Case study on soil and water quality evaluation and monitoring system in irrigated areas. Land and Plant Nutrition Management Service (AGLL), FAO, Rome.

Spitters, C.J.T., van Keulen, H. & van Kraalingen, D.G.W. 1989. A simple and universal crop growth simulator: SUCROS87. In: R. Rabbinge, S.A. Ward and H.H. van Laar (eds). *Simulation and systems management in crop protection*. Simulation Monographs. Pudoc, Wageningen, pp. 147-181.

SRDIS & CIESIN 2001. Sustainable Rural Development System. http://srdis.ciesin.org/srdis.coesom.org/annobib/application.html.

SSSA 1994. *Defining Soil Quality for a Sustainable Environment*. Soil Science Society of America Special Publication 35. SSSA-ASA, Madison, Wisconsin.

Stein, A., Bouma, J., Kroonenberg, S.B. & Cobben, S. 1989. Sequential sampling to measure the infiltration rate within relatively homogeneous soil units. *Catena* 16: 91-100.

Stocking, M.A. & Murnaghan, N. 2001. *Handbook for the field assessment of land degradation*. Earthscan, London and Sterling (VA). xiii + 169 p. ISBN 1 85383 831 4

Stoorvogel, J.J. & Smaling, E.M.A. 1990. *Assessement of soil nutrient depletion in sub-Saharan Africa: 1983-2000*. Volume 1-IV. Report 28, The Winand Staring Centre, Wageningen.

Tan, K.H. 1982. *Principles of Soil Chemistry*. Books in Soils and the Environment., Marcel Dekker, Inc. New York, Basel.

Terzaghi, A. 1996. Soil Management for Improvement of Soil Physical Characteristics related to Erosion in Uruguay. PhD Thesis, Wageningen University, Wageningen.

Van Diepen, C.A., Van Keulen, H., Wolf, J. & Berkhout, J.A.A. 1991. Land evaluation: from intuition to quantification, pp. 139-204 in: *Advances in soil science*, vol. 15. Springer, New York.

Van Diepen, C.A., Wolf, J., Van Keulen, H. & Rappolt, C. 1989. WOFOST: a simulation model of crop production. *Soil Use and Management* 5: 16-24.

Van Engelen, V.W.P., Resink, J.W. & Gicheru, P.T. 1997. Kenya: A study using the SOTER methodology. pp. 114-116 in: N. Middleton and D. Thomas (eds). *World Atlas of Desertification*. Arnold, London.

Van Keulen, H. & Wolf, J. (Eds) 1986. *Modelling of agricultural production: weather, soils and crops*. Simulation monographs. Pudoc, Wageningen. 479 pp.

Van Lanen, H.A.J., Van Diepen, C.A., Reinds, G.J., De Koning, G.H.J., Bulens, J.D. & Bregt, A.K. 1992. Physical land evaluation methods to explore the crop growth potential and its effects within the European Communities. *Agricultural Systems* 39: 307-328.

Van Lynden, G. W. J. 1995. The European soil resource: current status of soil degradation in Europe: causes, impacts and need for action. Nature and Environment No. 71, Council of Europe, Strasbourg.

Van Lynden, G.W.J. 2000. Soil degradation in Central and Eastern Europe: the assessment of the status of human-induced soil degradation. Report No.05, ISRIC, Wageningen

Van Lynden, G.W.J. & Mantel, S. 2001. The role of GIS and RS in land degradation assessment and conservation mapping: Some user experiences and expectations. *ITC Journal* 3 (1): 61.

Van Lynden, G.W.J. & Oldeman, L.R. 1997. *Soil degradation in South and Southeast Asia*. ISRIC, Wageningen

Van Reeuwijk, L.P. 1984. *Laboratory methods and data exchange programme for soil characterization, a report on the pilot round. Part 2: exchangeable bases, base saturation and pH.* Technical Paper 8. ISRIC, Wageningen, 12 pp.

Van Reeuwijk, L.P. 1998. *Guidelines for quality management in soil and plant laboratories*. FAO Soils Bulletin 74. vi + 143 pp. FAO, Rome. ISBN 92-5-104065-6

Van Reeuwijk, L.P. (ed.) 2002. *Procedures for soil analysis*. Sixth ed. ISRIC, Wageningen.

White, R.E. 1997. *Principles and practice of soil science*. Blackwell Science. Oxford. 348 pp.

Wopereis, M., Kropff, M., Bouma, J., Van Wijk, A. & Woodhead, T. 1994. *Soil physical properties: measurement and use in rice-based cropping systems*. IRRI, Manila.

World Bank 1996. Environmental Performance Indicators: A First Edition Note. Environment Department, World Bank, Washington DC.

World Bank/ICRAF 1994. Land Quality Indicators for Rainfed Agricultural Systems in Arid, Semi-Arid and Sub-Humid Agroenvironments in Africa, 2nd International Workshop on Development Land Quality Indicators, 13-16 December 1994. (unpublished). ICRAF, Nairobi.

World Bank, FAO, UNDP, UNEP & CGIAR 2001. Land Quality Indicators. http://www-esd.worldbank.org/lqi/home.htm.

Young, A. 1998. *Land resources. Now and for the future*. Cambridge U. Press, Cambridge. 319 pp.

AGL MISCELLANEOUS PAPERS

1. Exploitation de Résultats d'Essais Agronomiques: Fixation Symbiotique de l'Azote. Analyse de la variance. G. Caraux, 1985 (F)*
2. A Review of Small-scale Irrigation Schemes in Kenya. J.H. Van Doorne. 1985 (E)*
3. Exploiting Agronomic Test Results. Symbiotic Nitrogen Fixation User's Manual: Analysis of variance on Apple II computer. G. Caraux. 1985 (E)*
4. Water for Animals. Ph. Pallas. 1985 (E)*
5. Landscape-guided Climatic Inventory Using Remote-sensing Imagery. F. van der Laan. 1985 (E)*
6. Biogas in Africa: Current Status and Strategies to Enhance its Diffusion. D.C. Stuckey. 1985 (E)*
7. Status Report on Plant Nutrition in Fertilizer Programme Countries in Asia and the Pacific Region. 1986 (E)*
8. Hydraulique pastorale. Ph. Pallas. 1986 (E)
9. Levels of Fertilizer Use in the Asia and Pacific Region. 1986 (E)*
10. Status Report on Plant Nutrition in Fertilizer Programme Countries in Africa. 1986 (E)*
11. Irrigation and Water Resources Potential for Africa. 1987 (E)
12. Effects of Agricultural Development on Vector-borne Diseases. 1987 (E)
13. Irrigated Areas in Africa. E/F. 1987 (E)
14. Manpower Planning for Irrigation. R. Carter, D. Mason and M. Kay. AGL/ESH. 1988 (E, F)*
15. NGO Casebook on Small-scale Irrigation in Africa. R. Carter. 1989 (E)
16. Water, Soil and Crop Management Relating to the Use of Saline Water. 1990 (E)
17. Water Harvesting. 1991.
18. Improved Irrigation System Performance for Sustainable Agriculture. 1991 (E)
19. Fertigation/Chemigation. 1991 (E)
20. Secondary Nutrients. 1992 (E)
21. Le travail du sol pour une agriculture durable. 1997 (F)
22. Planning Sustainable Management of Land Resources: The Sri Lankan example. 1999 (E)
23. Integrated Soil Management for Sustainable Agriculture and Food Security in Southern and East Africa. 1999 (E)
24. Soil Physical Constraints to Plant Growth and Crop Production. 1999 (E)
25. New Dimensions in Water Security. 2000 (E)
26. Guidelines for On-farm Plant Nutrition and Soil Management Trials and Demonstrations. 2000 (E, S)
27. Guidelines and Reference Material on Integrated Soil and Nutrient Management and Conservation for Farmer Field Schools. 2000 (E, F)
28. Simple Soil, Water and Plant Testing Techniques for Soil Resource Management. 2000 (E)
29. Water and Agriculture in the Nile Basin. 2000 (E)
30. Guidelines for Participatory Diagnosis of Constraints and Opportunities for Soil and Plant Nutrient Management. 2000 (E)
31. Soil and nutrient management in sub-Saharan Africa in support of the soil fertility initiative. 2001 (E)
32. Small dams and weirs in earth and gabion materials. 2001 (E)
33. Guidelines for the qualitative assessment of land resources and degradation. 2001 (E)
34. Preliminary review of the impact of irrigation on poverty with special emphasis on Asia. 2003 (E)
35. Overview of land value conditions. 2003 (E)
36. Guiding principles for the quantitative assessment of soil degradation – with a focus on salinization, nutrient decline and soil pollution, 2004 (E). Only available in PDF format at http://www.fao/ag/agl/public.stm.

Availability: January 2004

E - English ** Out of print*
F - French
S - Spanish