Working Paper and Preprint 90/9

MACRO-SCALE LAND EVALUATION USING THE 1:1 M WORLD SOILS AND TERRAIN DIGITAL DATABASE

A possible approach

N.H. Batjes

August 1990
(First draft, for discussion)

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1. INTRODUCTION

The proposal for the development of a World Soils and Terrain Digital Database at a scale of 1:1 M, the SOTER Project, was officially endorsed during the 1986 Congress of the International Soil Science Society (ISSS) in Hamburg. The primary aim of the SOTER Project is to develop a worldwide computerized database of soil and terrain attributes with the view of providing decision- and policy-makers with a wide range of accurate, timely interpretative analyses. The ultimate SOTER database will also allow the update of the Soil Map of the World at a scale of 1:1 M (SOTER 1986b).

Research and development of methodologies relating to the Procedures Manual were the main technical activities during the first phase of SOTER (SOTER 1986a till 1990a, Shield and Coote 1988 and 1989). The procedures were tested for their applicability and usefulness in three pilot areas known as LASOTER (parts of Argentina, Brazil and Uruguay), BRASOTER (central part of Brazil) and NASOTER (parts of the USA and Canada). At the same time the basic requirements of the Relational Database Management System (RDBMS) and Geographical Information System (GIS) of the SOTER "computer" were identified (Pulles 1988, Van Engelen 1989). The final, hierarchical structure of the database was arrived at during an international workshop organized in Wageningen (SOTER 1990b), following circulation for comments of the latest revision of the Procedures Manual (SOTER 1990a).

The 1:1 M SOTER soils and terrain digital database linked with a Geographical Information System (GIS) forms an important tool for storing, updating and manipulating the spatial and attribute data of a wide range of climate, terrain and soil features. Applications of this database may include the assessment of crop suitability, crop productivity, irrigation suitability, soil degradation hazard and the monitoring of global change (Baumgardner and van de Weg 1989). Procedures for interpretation of soil degradation status and risk, as developed by Shields and Coote (1989), will soon be tested for their usefulness using the database of the NASOTER area (see SOTER 1990b). Suitable methodologies for other envisaged applications will be developed by SOTER staff in the near future.

The aim of this paper is to identify which kind of land evaluations are considered feasible with the 1:1 M SOTER database, and to assess how these could be carried out. This study remains largely of a theoretical nature pending the installation of the Geographical Information System (GIS) component of SOTER.

In Chapter 2 the structure and attribute files of the SOTER database are summarized. Possible alternatives for carrying out land evaluations at scale of 1:1 M are identified in Chapter 3 with a view to identifying a general approach. Some of the technical constraints which may be anticipated during the early stages of SOTER implementation are reviewed in Chapter 4, while conclusions as to the potential of the ultimate SOTER database for macro-scale land evaluation are presented in Chapter 5.

2. THE SOTER DATABASE ANNEX GIS

2.1 The system

The central SOTER "computer" consists of a relational data base management system (ORACLE; see Pulles 1988) linked to a Geographical Information System (PAMAP; see van Engelen 1989). Other systems may be used for applications at the regional or national level, provided they are compatible with the software and hardware configuration of the central SOTER "computer" (see SOTER 1990b).

The main purpose of a GIS is to answer spatially oriented questions (see Burrough 1986). The type of questions that can be asked is primarily determined by the type, format and manner attributes are stored in the database (see Section 2.2 and 2.3). Intensive analyses of both spatial and attribute data are generally required to provide the above answers. Often, particularly in case of complex calculations, these analyses cannot be performed efficiently within the structure of the GIS per se. Attribute data selected through queries from the RDBMS/GIS must initially be off-loaded to data files to be used as input in application software, such as theoretical or empirical models. The outcome of these models may then be reintroduced into the RDBMS/GIS, allowing for mapping. The ultimate aim when developing a GIS to support planning is to arrive at a fully integrated system consisting of a model base, which determines the type of information the system can provide to its users, with a matching database. Few fully integrated systems are available as yet (e.g. Meijerink et al. 1988), particularly at global level (see Mounsey 1988).

2.2 Terrain and soil attributes

There are three main levels of entry for terrain and soils attributes in the SOTER database (Figure 1). The basic SOTER "mapping unit", the terrain unit, is an area of terrain with a distinctive, often repetitive pattern of surface form, slope, parent material, soil and climate (Shields and Coote 1988). It is directly identifiable on remotely sensed imagery. Each terrain unit is considered homogeneous in terms of its constituting terrain and soil components (Figure 2), and may consist of one or more "polygons" with identical terrain and soil attribute data. Spatially referenced terrain units are uniquely coded for the world (see SOTER 1990a).

The terrain units are of a compound nature. The location of the respective terrain- and soil-components of a particular terrain unit, inherently, cannot be mapped at the scale of 1:1 M. The estimated area of occurrence of the respective soil components within a particular terrain-unit, however, is specified in the database. Thereby, results of quantitative analyses carried out at the level of the soil component can be aggregated to the level of the terrain unit, allowing for mapping.

A terrain component is defined as a segment of the overall regional landform of a terrain unit with comparable topographic and soil patterns (Shields and Coote 1988). Most terrain units will have less than 4 terrain-components while terrain-components usually contain less than two soil-components, but other combinations may occur as well (see SOTER 1990b).

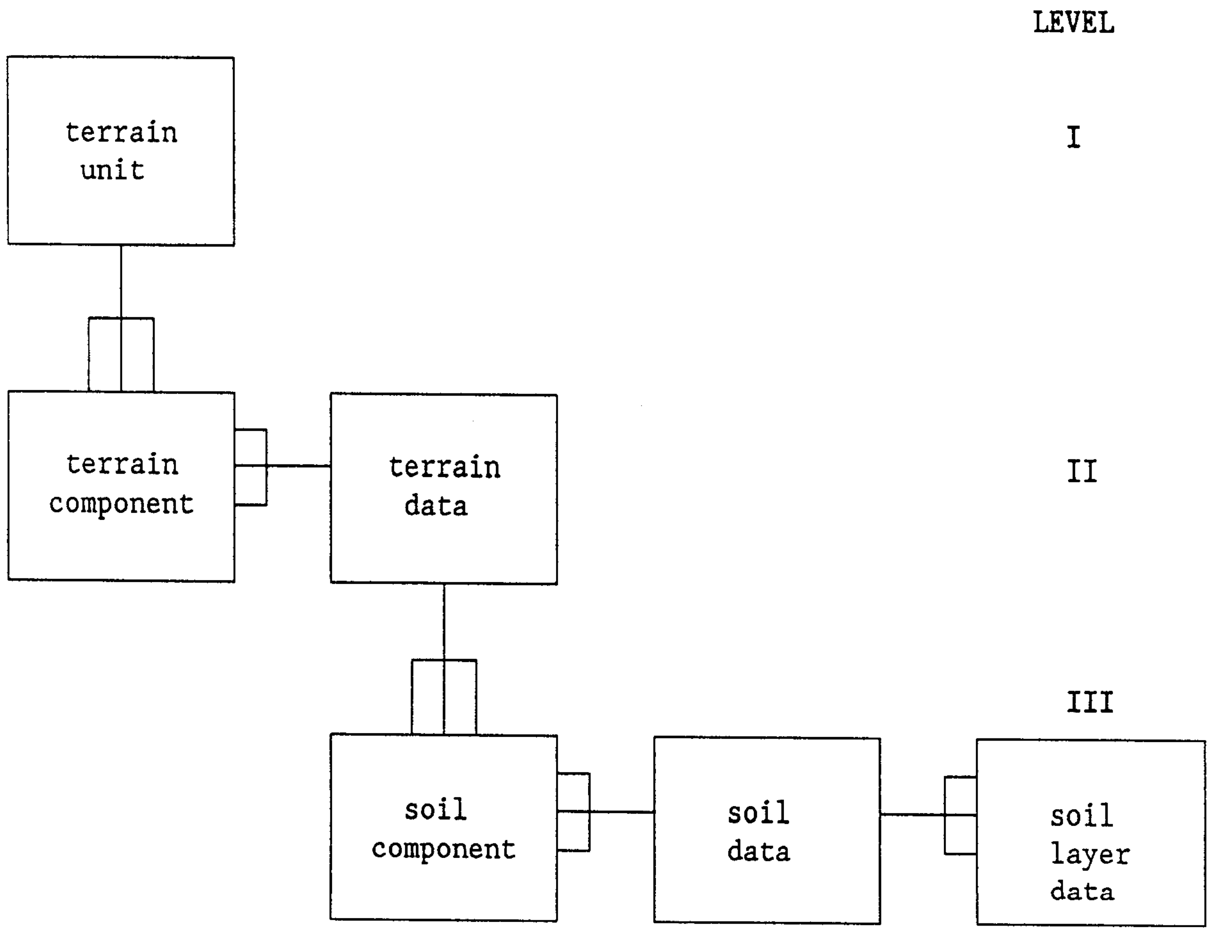

Figure 1. Hierarchical structure of the SOTER soil and terrain database (after SOTER 1990b).

Each soil-component is characterized using one representative soil profile which has been judiciously selected from amongst a set of (similar) reference profiles by an experienced surveyor. The references profiles are mainly derived from past surveys.

The list of SOTER terrain and soil attributes is included in Appendix I. Quantifiable attributes are presently being stored as numeric data (see SOTER 1990a) instead of the originally recommended "numeric class-values" (see Shields and Coote 1988). This introduction of numeric data will greatly enhance the flexibility and possible applications of the database because groupings in arbitrary classes need no longer be made a priori, i.e. at the data entry stage (Dyke 1987).

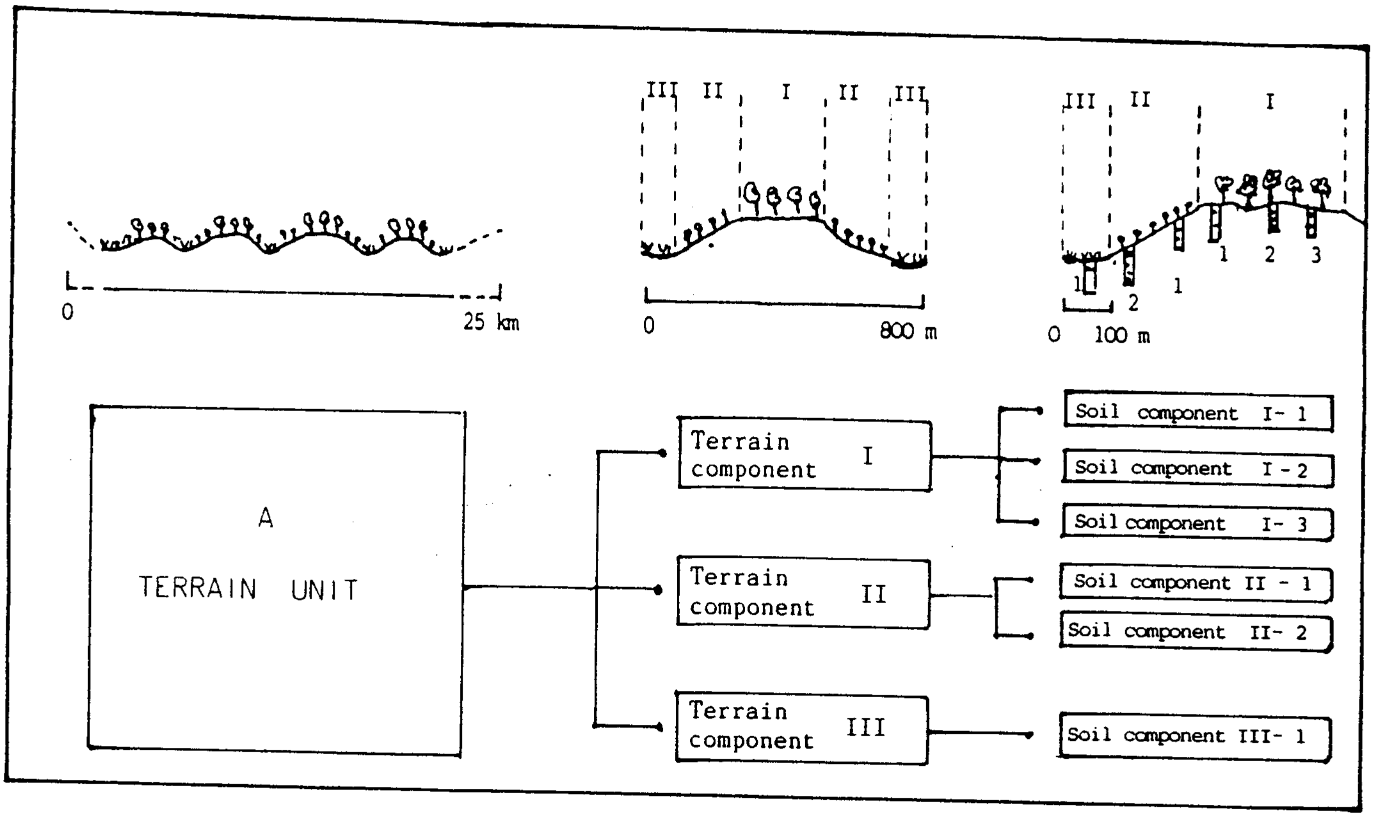

Figure 2. Schematic representation of the SOTER concepts of terrain units, terrain components and soil components (after Brabant 1990, distances are indicative only).

2.3 Climate attributes

A wide range of climate attributes for geo-referenced stations can be stored in SOTER, viz.: altitude of recording station, precipitation totals (decadal or monthly values), 75%-dependable rainfall, number of rain days, maximum 24-hour rainfall, mean daily air temperature (minimum, average and maximum), total radiation, bright sunshine hours, degree of cloudiness, relative humidity, mean 24-hour wind speed, potential evapo-transpiration (Penman, Hargreaves, and Thornthwaite) and evaporation (class A-pan, Colorado-pan and Piche).

In the near future, the SOTER climate database will also accommodate data about the risk and month of occurrence of severe climatic hazards, such as hailstorms and hurricanes, as well as the predominant wind direction (SOTER 1990b).

The importance and use of the above variables for agro-ecological zoning purposes is discussed by several authors, including Oldeman (1987).

3. MACRO-SCALE LAND EVALUATION

3.1 General considerations

Land evaluation is concerned with the assessment of land performance when used for specific purposes. It can provide a rational basis for taking land-use decisions based on analysis of relations between land use and land, taking into account both physical and socio-economic considerations and the need for conservation of the environmental resources for future use (FAO 1976, Beek 1978). The aspect of "sustainability" is particularly important in this era seen the ever progressing and intensifying rate of soil erosion, desertification, salinization and pollution (see e.g. GLASOD 1990, UNEP 1988), and resulting reduced productive capacity of land. This is even more so since the effects of these factors often transcend national boundaries, affecting the future livelihood of the whole sphere.

The degree of detail of conclusions which can be derived from land evaluation studies is strongly determined by the level of spatial aggregation of the climate, terrain and soil maps/data (see e.g. Bouma and Bregt 1989). At a scale of 1:1 M "micro-variations" in the environmental features are de-emphasized so as to highlight regional trends. Whereas the physical factors of the environment are of a relatively stable nature, assuming the use of sound management/ conservation practices, the socio-economic features are not. Macro-scale land evaluation, therefore, should in first instance deal with the relatively stable aspects of the physical environment, while macro socio-economic considerations may be introduced at a later stage. This kind of approach has been termed "two-stage" land evaluation by FAO (1976).

Qualitative and quantitative procedures have evolved as the two basic technical approaches to land evaluation (FAO 1976 and 1983). In many cases the choice of the approach is dictated by the amount and accuracy of input data available. The level of technical detail which can be used in land evaluation is further determined by the type of questions being asked (Bouma 1989). Consequently, different approaches have been used in macro-scale land evaluations including qualitative (e.g. Bouwman 1989, Brabant 1990, Hakkeling and Endale 1988), semi-quantitative (e.g. Buringh 1977, FAO 1979-1981, Thomasson and Jones 1989, Verheye 1986), mixed qualitative/quantitative (van Lanen et al. 1989a), and quantitative (e.g. SOW 1985, Dumanski and Onofrei 1989) techniques.

Qualitative evaluations are normally considered appropriate for low intensity surveys of large regions and for a wide variety of uses, and often "cheap" to run. They can form the basis for identifying areas where it will be meaningful to carry out semi-quantitative or quantitative follow-up studies at similar or larger scales. A limitation of qualitative land evaluation is that results are provided in general (qualitative) terms; as such they do not allow for comparative assessments of land suitability for a range of alternative uses (FAO 1976). Quantitative land evaluation, however, can provide this kind of information.

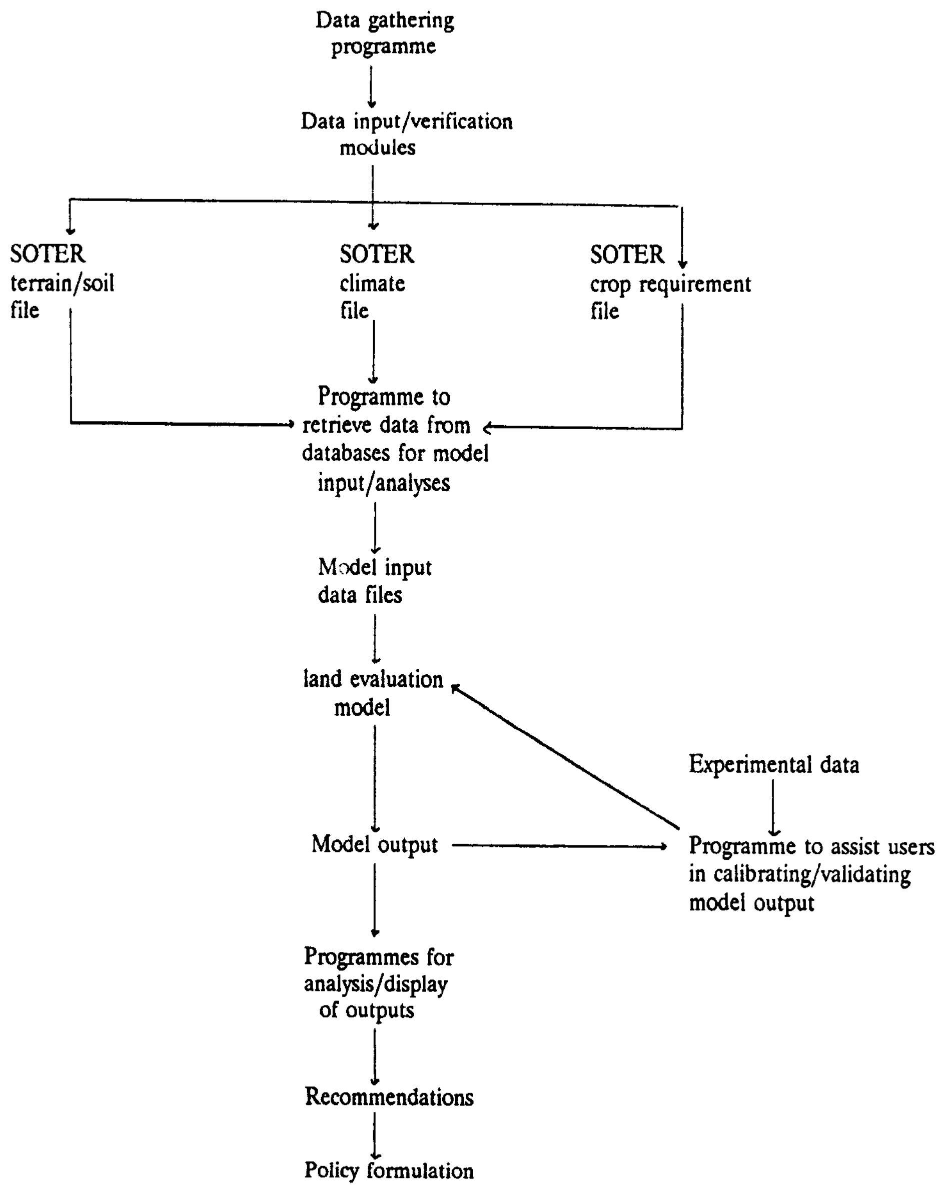

Figure 3. Flowchart illustrating general structure of envisaged integrated SOTER system for land evaluation.

Quantitative, physical land evaluation can be considered for studies covering a limited number of uses for which estimates of "actual" production, as obtainable under defined input situations, are required. They can provide essential input for rational planning of land use in macro-economic terms, allowing for the assessment of multiple scenarios.

Only a limited number of the land qualities which are considered of relevance for assessing land suitability can be rated in a quantitative manner (FAO 1983). The increasing need for quantitative data or techniques in land use planning is apparent from recent scientific research (see e.g. Beek et al. 1987, Bouma and Bregt 1989, Driessen 1986a, Groenendijk 1989, van Lanen and Bregt 1989). Several researchers, including Comerma and Guennie (1987) and Dumanski and Onofrei (1989), have discussed which steps have to be undertaken before quantitative models can be used to accurately predict land qualities or crop yields in a given location. They include regional validation, calibration and sensitivity analyses.

The level of information required for quantified land evaluation systems as used, for instance, in the United Kingdom (Thomasson and Jones 1989) and Canada (Dumanski et al. 1989) can be considerable. This "hunger" for data is a well-known practical problem associated with the use of quantitative models. Computerized databases are therefore often developed to suit a specific range of models, as is the case in the IBSNAT programme (Eswaran et al. 1987), ILWIS system (Meijerink et al. 1988) and the earlier cited systems.

The technical intricacies, and legal and institutional aspects, of building databases for global science are extensively reviewed by Mounsey (1988). Burrough (1989a) discusses some of the problems that need to be resolved when linking simulation models to a GIS. The above may, initially, form a practical limitation to the widespread application of existing models. The conceptually ideal situation of linking a number of validated quantitative models to a global database annex GIS will require prolonged research (see Figure 3). Therefore, it can be beneficial to use an approach which consecutively includes a qualitative and a quantitative land evaluation. The first, qualitative stage will permit identification, characterization and mapping of terrain units that are considered potentially favourable with respect to generally defined land uses, considering a limited number of (important) land qualities. Subsequently, semi-quantitative or quantitative procedures may be applied to the data sets of the selected terrain units. In view of the initial, qualitative filtering stage attribute data from a smaller number of terrain units will have to be processed during the quantitative stage, allowing for more cost efficient analyses.

The procedure described above has been termed "mixed qualitative/quantitative" land evaluation (see Bouma 1989). Its merits have been demonstrated for the Netherlands part of the 1:1 M Soil Map of the European Communities by van Lanen et al. (1989a). "Sifting" procedures are commonly applied in other studies as well (e.g. Driessen 1986a, Verheye 1986).

The general flowchart of the "mixed" land evaluation is shown in Figure 4, while additional details on the methodology are provided in the next subsections.

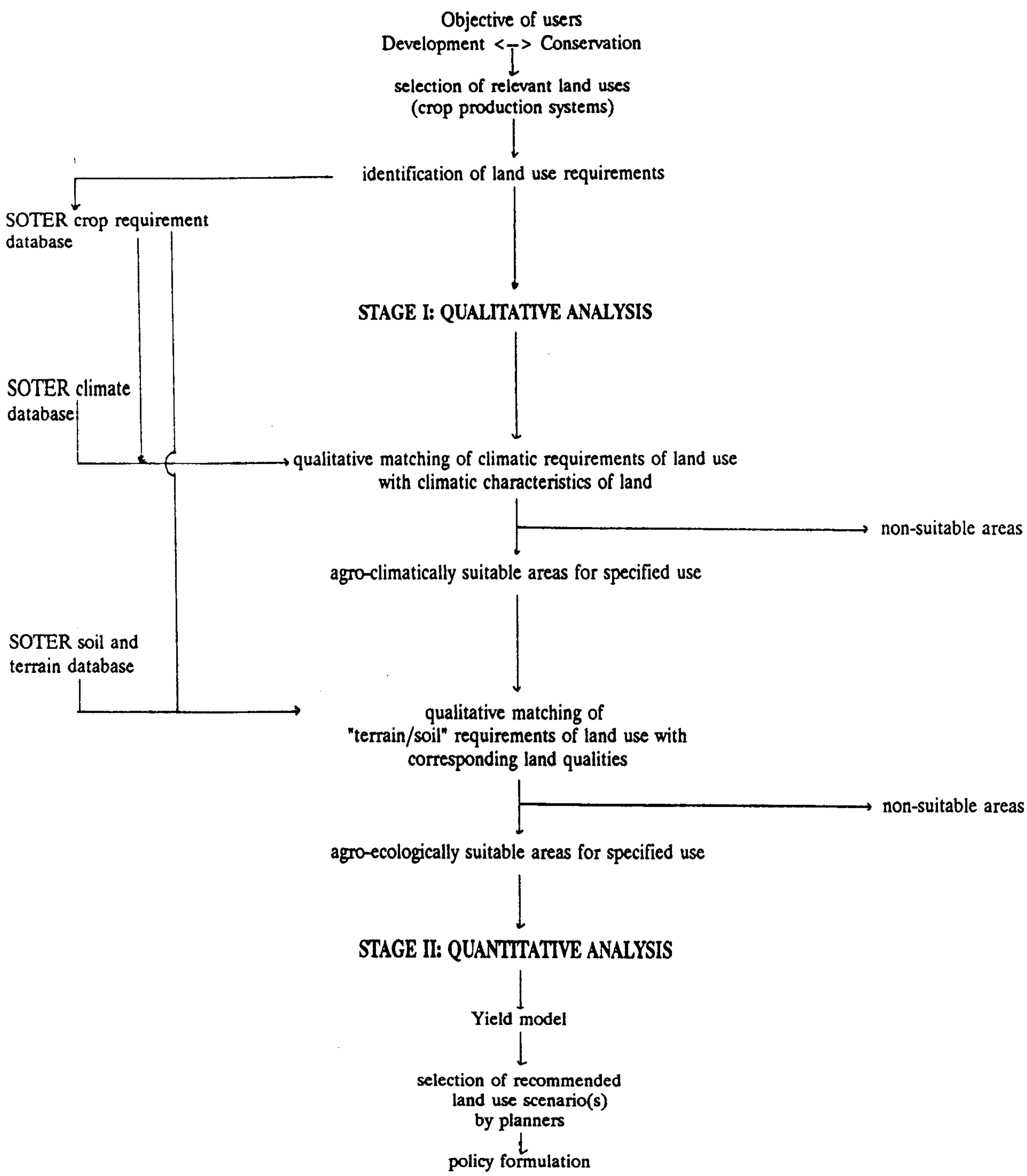

Figure 4. Schematic diagram of the "mixed" qualitative/quantitative land evaluation.

3.2 A sequential approach

3.2.1 Qualitative stage

Prior to outlining the general procedures and principles of the qualitative stage of the land evaluation it should be noted that, as a reconnaissance, simple queries of the SOTER database will permit identification of areas with similar agro-ecological potential/constraints. For instance, thematic maps can be generated which demarcate areas of similar rainfall conditions, topography, water-holding capacities and soil toxicities. More specific answers can be provided when the requirements of the land use systems are considered in the analysis, i.e. through land evaluation.

Land evaluation will initially be limited to rainfed uses. Assessments of land suitability for irrigated uses will require more data on e.g. hydrology than is stored in the SOTER database. The potentially irrigable acreage, however, can be estimated using SOTER.

A basic tenet of land evaluation is that the type of studies envisaged should be in accordance with the scale of the survey/database. At a scale of 1:1 M land evaluation permits identification of the suitability of land units for broadly defined land utilization types (LUT). Individual LUTs are defined as production systems in which a particular crop is grown under a generally described level of inputs. The objective of the user(s) primarily determines which land uses are to be considered in the analyses (see Figure 4).

The proposed, general procedure for carrying out the qualitative land evaluation is described below:

1) Each land utilization type has specific requirements relating to the type of crop grown, management and conservation practices. At a scale of 1:1 M these requirements may be specified in three classes, expressing conditions that are considered to be not suitable, moderately suitable and highly suitable at specified input levels (see 2 below). The overall production situation is taken into consideration because suitability of land for a particular crop varies with the "technical and socio-economic setting" within which it is produced (FAO 1976). In first instance, the use of three broadly defined production situations should be adequate at a scale of 1:1 M. The first approximating a low technological level which only includes manual cultivation, the second incorporating improved hand tools and/or draught implements and limited fertilizer/pesticide application and soil conservation, and the third involving complete mechanization with full use of optimum genetic plant material, necessary farm chemicals and soil conservation measures (see e.g. FAO 1982). Consideration of the first and last production situation will permit the assessment of the "current" and "potential" suitability of land units for a particular crop.

2) Computerized matching of land use requirements with land qualities requires specification of factor ratings. The latter express the degree in which a given land use requirement is fulfilled by particular conditions of the corresponding land quality (FAO 1983). At the moment there is no single authoritative handbook on crop requirements. The information needed can be derived from various sources (e.g. FAO 1979-1981, ILACO 1981, Keulen and Wolf 1986, Landon 1984, Sys 1985) which are to be complemented with regional expertise. The resultant information should be stored in a separate, digital "crop requirement" database; collaboration between FAO and SOTER may prove essential for international standardization.

It is common practice to define factor ratings using "crisp" values of discriminating criteria, forming the basis for defining mutually exclusive, discrete classes. "Fuzzy" class boundaries may give a better representation of the actual, complex situation (Chang and Burrough 1987). An example of the possible use of "fuzzy" boundaries is given in the Technical Paper of TROPENBOS (Touber et al. 1989). The advantages of using fuzzy mathematical models, as compared to the commonly used Boolean approach, for soil survey and land evaluation are discussed by Burrough (1989b).

The list of land use requirements/land qualities that can be studied using the SOTER database is shown in Appendix I; all of these may not be relevant at the considered scale of 1:1 M (see Chapter 4). The corresponding table also indicates at what hierarchical level the respective attribute data are stored in the database.

3) The primary environmental determinants of potential production for a particular crop in any location are solar radiation, temperature and length of the growing period (e.g. Keulen and Wolf 1986). The first stage of macro-scale land evaluation thus is the compilation of an agro-climatic zones map. A wide range of suitable procedures exist at the national and international level (see e.g. Young 1987). At the supra-national level, however, agro-climatic zones can best be demarcated according to the widely accepted Agro-ecological Zones approach (FAO 1979-1981, FAO 1986). Use of a common methodology will facilitate the international transfer of knowledge, thus forming a prerequisite for comparative assessments of agro-ecological crop yield potentials on a global scale.

4) A link has to be established between the respective agro-climatic units and SOTER terrain-units so as to permit an assessment of physical land suitability. Basically, this can be done according to two methods. The first one is a straight overlay of the agro-climatic map onto the "terrain unit" map. Since climatic features often transcend soil unit boundaries this approach may result in delineation of numerous small "polygons" or "slivers" (e.g. FAO 1979-1981). This feature may create logistical problems when the attributes of the newly created "agro-ecological" polygons are screened for their overall suitability for a particular land use (see 5). This kind of problem can be circumvented when each "terrain-unit" is assigned to a particular agro-climatic zone on the basis of its predominance therein (e.g. Dumanski et al. 1989, Thomasson and Jones 1989). The merits of both approaches should be tested upon installation of the GIS-component of the SOTER computer.

Terrain-units showing similar agro-climatic potential for specified uses can now be mapped, using the "agro-climatic" suitability decision tables.

5) Subsequent to the agro-climatic filtering stage, the edaphic, management and conservation requirements of the land use(s) are matched with the corresponding attribute data of the terrain-units. This series of matching exercises is restricted to the terrain-units which were identified as being "agro-climatically" suitable under stage 4. The objective of this second screening stage is to retain only those terrain units whose overall environmental conditions are considered non-limiting for the land uses under investigation.

The range of land use requirements/land qualities that need to be considered at this stage will vary with the scope of the study under consideration. Varying differentiating criteria are required when assessing land suitability for rainfed agriculture (FAO 1983), irrigated agriculture (FAO 1985), or silviculture (FAO 1984, Touber et al. 1989). Land with slopes of 8-16%, for instance, may be assessed as having no potential for mechanized agriculture (i.e. high input levels), while it may still be considered under manual cultivation (i.e. low input levels). It should have no physical constraints for forestry, provided the remaining agro-ecological conditions are favourable.

It is believed that screening for the important land qualities/land use requirements of topography, absence of flooding, adequacy of drainage condition, absence of rockiness/stoniness, rootable soil depth, adequacy of soil moisture supply, nutrient retention, nutrient availability, absence of salts and toxicities should be adequate at a scale of 1:1 M.

A wide rage of procedures for rating land characteristics into land qualities is available internationally. They include "matching tables" (e.g. FAO 1983, Nyandat and Muchena 1982, Sys 1985, Touber et al. 1989), parametric methods (e.g. Riquier 1974) and transfer functions (see Bouma and Bregt 1989), while a relatively new method consists in using decision trees (Rossiter, 1990). A suitable methodology for universal use in SOTER context needs to be identified.

6) The "matching" procedure is performed at the level of the soil-component. Results of this type of analyses are readily displayed in tabular form, providing a wealth of information to the user (see e.g. Appendix III). Direct mapping of results, however, is not feasible because soil-components are not spatially referenced within a terrain-unit. Hence the need for developing a procedure for aggregating results obtained for individual soil-components up to the level of the terrain-unit. The following general approach could be used:

Following the matching procedure the partial land suitability ratings are shown in tabular form (see Table 1). These ratings express the degree in which a particular land use requirement is met by the prevailing condition of the corresponding land quality (FAO 1983).

Table 1. General format of attribute file showing the partial suitability of individual soil-components for a particular land utilization type.

Terrain unit*	Terrain comp.	Soil comp.	% of TU	PR1	PR2	PR3	PR4	PR5	PR6	PRz
001	1	1	40	S1	S1	S1	S1	S1	S1	S1
	2	1	30	S2	S2	S1	S1	S1	N	S2
		2	20	N	S1	S1	S2	S2	S2	S2
		3	10	S1	S2	S1	N	S1	S1	S1
002	1	1	60	S2	S1	S1	N	S1	S1	S1
	2	2	40	S1	S2	S1	S2	S1	S2	S2
003	1	1	100	N	S1	N	S2	S1	S1	S1
...	.	.	.	.	.	.	.	.	.	.

Note: TU is the terrain unit (* including link to agro-climatic zone); PRz is the partial land suitability rating (S1: highly suitable; S2: moderately suitable; N: not-suitable).

Interpretative tables of the above type are very useful for land use specialists and planners, yet not considered user friendly. User acceptance of tabular output increases when they are supported by maps. This requires aggregation of results obtained for soil-components to the level of the terrain unit. For practical reasons this will require "regrouping" of partial land suitability ratings into two categories, viz. suitable (S) and non-suitable (N) for the specified use, at the level of the terrain unit (see Table 2). Subsequently, terrain units can be grouped on the basis the degree of prevalence of a "S" within the respective terrain units (see Table 3). The degree of prevalence of "S1" and "S2" ratings within the respective "S" classes can be visualized with a line plotter, using a line pattern or colour scheme.

The above procedure can be seen as an improvement over earlier mapping approaches in that it considers the properties of all the soil-components of a given terrain-unit, as compared to those of the dominant soil-component only (see e.g. Cochrane et al. 1984, van Engelen 1989), thus making full use of the available information.

Table 2. Proportion of terrain unit considered highly suitable (S1), moderately suitable (S2) and non-suitable (N) for a specific LUT for one single factor rating.

Terrain unit	Partial land suitability rating		
	S1	S2	N
001	50	30	20
002	40	60	0
003	0	0	100
...	.	.	.

* Example: partial land suitability rating for availability of oxygen for specified use (PR1).

Thematic maps, with supporting tabular output, can now be generated for each of the considered land qualities/land use requirements. Possible applications are manyfold, including the production of a map which demarcates the area and extent of land where aluminium toxicity is considered limiting for "sensitive" crops.

Table 3. Possible format for presenting results of qualitative assessments as thematic maps.

class	Percentage of terrain-unit with conditions considered suitable for specified use
1	over 75 percent
2	from 50 to 74 percent
3	from 25 to 49 percent
4	from 5 to 24 percent
5	less than 5 percent

* Indicative ranges only.

7) Studies of physical land suitability inherently consider at least several "major" land qualities resulting in a range of partial land suitability ratings. The respective values for the ratings will have to be combined in one way or another to determine the "final" land suitability class. The "overall" suitability is first determined at the level of the soil component. This can be done according to a range of methods (see e.g. Batjes and Bouwman 1989, FAO 1983, Wood and Dent 1983). Following interim validation, the "final" result of the qualitative stage of the land evaluation can be mapped using the general procedure proposed under 6.

3.2.2 Quantitative stage

Potentially suitable soil-components for the specified land uses - identified through qualitative screening for a selected number of land qualities/land use requirements - have been identified so far. In the conceptually ideal situation a validated quantitative crop-yield simulation model, whose data needs are covered by the database, can be applied to the corresponding attribute data. Possible applications of such models include estimation of chemical fertilizer rates needed to reach respectively the "water-limited" and "potential" yield levels (SOW 1985, Wolf et al. 1989), the calculation of present and future population supporting capacity of the world (FAO 1982), and simulation of effects of "global climate change" on potential crop production (Dumanski et al. 1989).

Penning de Vries (1980) gives a review of the phases of development of crop-growth models of which three main types exist, viz. preliminary, comprehensive and summary models. In preliminary models the insight in the processes of crop-growth and production is still vague. Comprehensive models describe a production system whose essential elements are thoroughly understood. They are often large, intricate and not user-friendly and, as a consequence, mainly used for scientific research. To arrive at workable models it is often necessary to give a simplified presentation of the occurring physiological and physical processes. This involves simplification of a comprehensive model into a summary model.

According to Dumanski and Onofrei (1989) crop growth models for macro-scale land evaluation should:

a) Estimate annual as well as long term yield data based on limited data.
b) Provide estimates of potential and actual yields within reasonable limits of accuracy.
c) Provide yield estimates for the major crops - in the considered region - and for several input levels.
d) Be constructed in such a way that they reflect the variability in the major state variables.
e) Be economical to run.

Dumanski and Onofrei conclude that mechanistic models of the summary type are the best realistic alternative for practical land evaluation at macro-level. Summary type models are often used where the effect of weather conditions and soil-moisture supply on yield performance needs to be assessed.

A "simple" summary type model is used in the AEZ programme (FAO 1979-1981). It calculates constraint-free (potential) yields per agro-ecological cell, as determined by crop phenology, solar radiation, temperature and length of growing period. Subsequent assessment of "constrained" yields under different management levels are made using semi-quantitative rules based on expert-judgement. The AEZ study was limited to the 12 major economic crops of the World.

Constraint free yields for major crops in Canada have been computed by Dumanski et al. (1989) using a yield model similar to the one applied by FAO (op. cit). Thereafter, quantitative estimates of soil moisture stress, fall workday probability and a soil index were used to calculate anticipated yields. The computed constraint-free yields were checked against yields gathered in agronomic trials with irrigation, corresponding with "high input" levels. Such a comparison proved more difficult for conditions of constrained yields so that relative yield classes were defined.

Many techniques for modelling crop production systems are available today (see e.g. Bouma and Bregt 1989, Keulen and Wolf 1986, Nix 1987). The most elaborate summary type model for use on micro-computers is probably WOFOST (see van Diepen et al. 1989). This model sequentially assesses to what degree crop production is restricted by incoming radiation, temperature and length of growing period (production situation (PS) 1: potential yields), soil moisture (PS2:

water-limited yields) and macro-nutrients (PS3: nutrient-limited yields). The underlying principles are universally applicable (Keulen and Wolf 1986). As such, the WOFOST model can in principle be applied to simulate multiple production scenario's throughout the world. The erratic and unpredictable (stochastic) nature of weather, however, is not incorporated explicitly in WOFOST, forming a possible limitation for the accuracy of yield prediction.

Quite a number of steps are required before quantitative models can be applied with reasonable confidence in a given location (Comerma and Guennie 1987, Comerma 1989, Burrough 1989a). FAO's (1986) experience has shown that "the reliability of and validity of each input and sub-model must be tested separately and before testing the interactions". Application of simulation models outside the range of conditions - crops and environment - for which they were originally developed may result in unjustified conclusions.

The WOFOST model, for instance, includes pedo-transfer functions for predicting soil moisture characteristics and soil hydraulic conductivity as a function of soil moisture tension. Said functional relationships were developed for a series of "standard" soil profiles originating from the Netherlands. Use of these functions in areas with markedly different soils, as is the case in large parts of the tropics and subtropics, will result in biased conclusions (van Diepen et al. 1989). Keulen and Wolf (1986) indicate which data have to be changed to apply WOFOST in the "user's" situation, viz. soil and crop (genetic) specific parameters.

An operational problem associated with the use of summary type models in the world embracing SOTER approach is the fact that the basic soil data for deriving transfer functions are not necessarily collected during routine surveys. A study of 146 soil survey reports from 46 countries showed, for instance, that soil physical data are seldomly described or measured in soil resources inventories (Msanya 1987). In such instances it may prove difficult to develop transfer functions with regional applicability.

A number of countries in the World does not yet have complete and accurate minimum data sets as required for in-depth simulation and model validation exercises. Under such conditions a qualitative physical land evaluation can already provide essential answers for agricultural planning at macro-level. It is believed that crop modelling techniques which estimate "actual" yields can best be developed/adapted by an inter-disciplinary team of soil scientists, agronomists and crop physiologists which operates at the national level or within the operational framework of multi-national pilot project. Within such a framework it may be possible to validate model predictions against crop-yield data collected for local production situations. Simulation can be a very unsatisfactory tool if output validation is not possible. Where this is the case results should always be specified in relative terms rather than absolute figures. The latter may suggest an aura of credibility that cannot possibly be supported by actual evidence.

4. DISCUSSION

The aim of this chapter is to stress the potential of the SOTER approach for macro-scale land evaluation, while at the same time identifying some of the constraints that need to be addressed during the initial stages of implementation.

1) The SOTER database can accommodate a wide range of soil and terrain attributes. Queries of the database will allow an inventory of the natural resources and form the basis for subsequent interpretative analyses. The latter may range from the assessment of the degree and extent of occurrence of certain "soil problems" to crop-suitability interpretations within spatially referenced terrain-units. Regions which require similar management measures to increase/diversify land productivity on a sustained basis can be identified using this knowledge. Research findings which are successful in one part of the world may be extrapolated to other parts of the globe where similar agro-ecological conditions prevail. Maps and tabular output generated with SOTER can be related to other environmental digital databases of similar scale. Sombroek (1990) gives a review of the required associated land databases (e.g. climate, hydrology, vegetation/land cover).

2) Physical land evaluation has a vital role in the development of rational policies for land use planning. It can provide sufficient information for establishing broad agricultural land use policies and guidelines. To be most meaningful, such policies should also be based on the expected needs for products, services or amenities, that is take into account the macro-scale social and economic dimension (Smit et al. 1984). The long term goal thus should be "integral" land evaluation which is the combined interpretation of information derived from physical land evaluation and socio-economic data. It is believed that SOTER can provide the physical basis for establishing this link at similar scale.

3) The SOTER digital database will be made accessible to a large spectrum of international users. Creation of a "clean" database is a most important and complex task, particularly in a world embracing programme such as SOTER. A good perception of, and strict adherence to the concepts and definitions of the Procedures Manual is therefore needed to ensure the success of the programme. The ultimate usefulness of the database will in first instance be determined by those who compile, enter and check the data. A decision should be taken as to whom is going to preserve the integrity of the central database (see SOTER 1990b).

4) When looking at the range of interpretative studies envisaged for SOTER one should not only consider the minimum data requirements - which determine the possible applications of the database - but also at the methodology according to which the respective attribute data have been measured or estimated. The need for re-thinking the quality requirements of soil data and data collection procedures with respect to mathematical modelling in particular is critically discussed by Driessen (1986b).

Where broad descriptive classes are defined, strict adherence to definitions generally should not result rapidly in misinterpretations. Criteria for defining specific classes, however, can vary markedly between organizations and countries (Vogel 1986) and thereby affect their usefulness for specific interpretations (see e.g. Burrough 1986). Soil sampling and analysis techniques vary with the envisaged applications. Soil attributes gathered for use in SOTER are mainly derived from soil survey reports, and hence primarily sampled and collected for pedological purposes (i.e. emphasis on subsoil properties). Such data are not necessarily suitable for deriving other interpretations such as an assessment of land use performance (see e.g. Msanya 1987, SOTER 1990b).

5) Analytical procedures for soil analysis vary widely in the World. Comparative studies of laboratory results have shown a great deal of variability between laboratories, even when identical analytical procedures are used (Pleijssier 1989, Brunt 1990). This is particularly the case for saline, calcareous and gypsiferous soils (van Reeuwijk 1983). Correlation problems may thus occur when interfacing analytical results collected in a wide range of laboratories. Implications for possible uses of the SOTER database can be significant.

To be widely applicable for land suitability assessment purposes, class differentiating criteria in "matching schemes" may have to be expressed according to a range of widely used analytical methods. This type of approach has been successfully applied in the Fertility Capability Classification (FCC) system (Sanchez et al. 1982). Alternatively, a number of international programmes use standardized procedures for soil analysis to reduce the above kind of problems, for instance IBSNAT (Eswaran et al. 1987), NASREC (National Soil Reference Collection Programme of ISRIC) and TROPENBOS (Touber et al. 1989). In the case of IBSNAT and NASREC all analyses are performed in one host laboratory. The dire need for standardization of analytical methods is also recognized in the SOTER programme but, out of necessity, as a long term objective (SOTER 1990b). In the interim the SOTER database contains a unique "label" which provides the key to the laboratory of origin, and hence to the corresponding set of analytical procedures (SOTER 1990a).

Cross-border correlation of analytical results, as obtained according to the procedures in use in Argentina, Brazil and Uruguay, for the LASOTER area was no simple task. Aguirre et al. (1988) and Palmieri et al. (1988) therefore pointed at the need for correlation of analytical results between countries. The former process could be facilitated if cores for a limited number of representative profiles are split and duplicate samples sent to laboratories in the co-operating countries as well as an internationally recognized "reference" laboratory for inter-laboratory checking/correlation (e.g. LABEX). This activity may further serve as a stimulus to aid countries in updating the quality of their soil data. Meanwhile, all analytical data should be screened thoroughly to ensure good compatibility before they are added to the database.

6) Shields and Coote (1989) pertinently observed that "when complete, the (SOTER) attribute files provide information required for many interpretations". In the initial stages of SOTER implementation, however, all the mandatory input variables may not be available for all sites (see Appendix I). In some cases, it may prove difficult to infer some of the mandatory attributes with reasonable accuracy where actually measured data are lacking, for instance for "very fine sand". Inference of groundwater fluctuations - minimum and maximum average depth - over the year from hydromorphic features recorded in soil profile descriptions may not be a practical solution where both fossil mottling and present mottling occur concurrently (see e.g. Driessen 1986b).

According to the Procedures Manual eventual missing values must be filled in using either expert-judgement or appropriate pedo-transfer functions. All "inferred" data must be clearly labelled (Shields and Coote 1988). Where certain features are not applicable, this should also be indicated in the attribute tables. Non-adherence to the above guidelines will make unambiguous queries of the database difficult.

7) With reference to the creation and application of transfer functions it is important to "flag" attributes in SOTER, depending on whether they are actually measured values or expert-

estimates. Consistent application of these labels forms a prerequisite for preserving the integrity of the database, and for meaningful subsequent interpretative analyses. Unfortunately, expert-estimates have not been systematically labelled in the LASOTER database contrary to the recommendations (see van Engelen 1988).

8) The "numeric classes" (Shields and Coote 1988), as originally applied in the database for the LASOTER area, should not be used for calculations but merely as a code for the class they represent (Pulles 1988). Indeed, use of these "numeric classes" in matching schemes, where critical limits for land use requirements are expressed as discrete values in accordance with common practice, proved to be difficult. This kind of problems will not occur any longer with the new approach which uses numeric data (see SOTER 1990a). The latter can also be used to derive a wide range of transfer functions and for statistical processing, provided they relate to attributes flagged as being actually measured values.

9) The range of simulation models, and related data requirements, tend to evolve rather quickly. New models will be needed where novel problems, such as global climate change, are recognized. In such instances model specific databases would quickly become obsolete. The structure of the relational database of SOTER, however, is flexible so that new attributes can easily be incorporated (Pulles 1988). As such, the minimum data sets of newly developed models can readily be accommodated. Conversely, the acquisition and storage of resource data for which there is no clear need, which are very difficult to obtain or infer, or which have no practical significance at a scale of 1:1 M can be seen as an inefficient use of resources.

With respect to the LASOTER area Palmieri et al. (1988) observed that "there is a disequilibrium between the required laboratory information and the level of abstraction on the map". Similar observations were recorded during an international workshop dealing with the latest Procedures Manual revisions (SOTER 1990b). In this context one might question, for instance, the relevance of mapping "Potassium availability in the topsoil" at a scale of 1:1 M (see e.g. Cochrane et al. 1984). This land characteristic is known to be extremely variable both in space and time, and generally not a criterion used in mapping. The emphasis should therefore be put on the more stable, mapped features of the land such as slope, texture and soil depth at the considered scale.

10) Judicious "siting" of the respective attributes in the hierarchical structure of the database is crucial for meaningful applications at a particular scale. For instance, should effective soil depth be stored at the level of the terrain-component (Shields and Coote 1989) or of the soil component (SOTER 1990b)? Should the mean depth of the groundwater table indeed be included at the level of the terrain component, or rather at that of the soil component (see e.g. terrain component II in Figure 2)? Or should it be included at all at a scale of 1:1 M (see 6)? A clear consensus still has to be reached on the above crucial issues.

11) Planners generally require information about ranges in land characteristics whereas modellers require point data. Inherent to most land evaluation approaches is the assumption that properties of terrain units are evaluated, while in fact soil scientists are often dealing with "one point in time, at one point in space" (Driessen 1986b). For SOTER this implies that individual soil-components of a particular terrain unit are considered to have the same spatial and temporal relations relevant to a range of land qualities. It may not always be possible to corroborate this assumption. The uncritical application of qualitative respectively quantitative schemes to data stored in computerized databases may produce results that conflict with

common sense; the necessity of checking provisional output against ground-truth or expert-judgement in pilot areas is apparent.

The foregoing point is illustrated using an example from Manitoba, Canada (Eilers 1990). Computerized mapping of the severity and extent of soil salinity at a scale of 1:1 M using solely electrical conductivity (EC_e) was not feasible as a result of the extreme variability of salt concentrations and distribution both in the soil and mapping units. Thus the study had to rely heavily on field-clues and electromagnetic induction techniques to evaluate the presence, extent and position of soil salinity in the respective soil mapping units. This means that the intrinsic variability of land qualities, both in space and time, within the respective terrain-units should be considered. Although this problem is widely recognized by natural scientists, no suitable solutions for global scale applications have been identified so far.

12) When either qualitative or semi-quantitative land evaluation systems are applied, internal variability of (complex) map units may result in uninformative classes for some mapping units and land uses. During the assessment of growth estimates for selected tree species in the Netherlands one of the final suitability classes read "good to poor growth estimates" (van Lanen et al. 1989a), which is not considered very informative for the planner. It should be recognized, however, that more specific information can be derived from accompanying tabular output when the relative proportions of the respective components of terrain units are specified, as is the case in SOTER.

13) Quantitative land evaluations will produce an average yield figure for each terrain unit by taking its composition into account. Alike numerous other researchers, van Lanen et al. (1989a) observed that "the end-user should bear in mind that this average figure is based on the results obtained for single representative profiles". Major soils, as characterized in SOTER by one representative profile, may show appreciable regional differences (see e.g. Olivieira et al. 1982). Ideally, several reference soil profiles should be described and sampled for each soil component so that a measure for the range in characteristics (random component) within a soil component can be shown in matrix tables. In view of the vast number of variables involved, the attribute data for these profiles cannot possibly be stored in the SOTER database proper. Hence the need for maintaining digital databases of "reference" profiles - i.e. the set of profiles from amongst which the representative soil profiles for SOTER have been selected -at the National level (see SOTER 1990b). These databases may be used for "detailed" simulation exercises.

14) Most of the input in SOTER consists of digital versions of cartographic products such as soil maps, with accompanying soil and terrain attribute data. The common lack of accuracy information in such products can lead to difficulties in spatial analysis; the data have to be taken at face value despite the obvious errors inherent in assuming homogeneity (Goodchild 1988). Map accuracy is still an important and unresolved issue so that assessment of accuracy of thematic maps is particularly difficult (Smith et al. 1987). The problem is compounded in GIS application when thematic or other maps with differing accuracy attributes are combined to produce new output (op. cit.).

Burrough (1989b) explains why the "fuzzy sets" approach is more suitable for exploring a "soils" database than the "exact Boolean" approach; the former provides more detail about the graduated evaluation of sites or objects in terms of the questions being asked. Accordingly, overlay techniques based on strict Boolean logic may have to be used sparingly. Possible sources of error propagation resulting from natural variation, original measurements, digitizing, processing and overlaying maps are extensively reviewed by Burrough (1986).

15) A reasonable future objective when developing a GIS for monitoring environmental change is that it should be capable of trailing and analyzing changes in the spatial information over time (e.g. land use, desertification, salinization). Map and attribute data in most current digital databases annex GIS's, however, are "atemporal"; they describe only one state of the data. Also, different datasets become current at different and, often, unknown points in time (see Langman 1989). In many cases, however, time forms an important part of the data (e.g. Price 1989). A review of current research in temporal information processing is given by Langman (1989).

Hunter (1988) observes that "since today's records are tomorrow's archives, future generations may well find themselves in an era of data poverty if few records have been kept". This is seen as a growing concern in today's information age. An obvious disadvantage of current GIS/databases is that it obscures the evolution of processes in time by overwriting "outdated" digital information, something analogue records do not do (Langman 1989).

5. CONCLUSION

SOTER provides information on a wide range of land characteristics with a level of detail that has not yet been achieved in any other world encompassing database. *It can be seen as the best possible alternative available to date; it is a logical step in the progression of agricultural data base development at global scale.* The potential of SOTER to become the most sought after "Global Agricultural Resources Database" for physical land evaluation at a scale 1:1 M is apparent.

The development of the SOTER database and related data analysis techniques is a world-embracing exercise concerned with the assessment of land suitability, crop productivity, soil erosion hazard etc. The success of the programme will depend to a large extent on how well SOTER can bring together the great variety of climate, terrain and soil data in the World, link a wide range of computerized interpretative techniques to the GIS annex database, and provide a scala of timely, accurate and relevant interpretations to planners and decision takers.

In the conceptually ideal situation from the planner's perspective land suitability for specified uses should be expressed in quantitative terms. Such data will permit comparison between alternative land use scenario's in terms of inputs/outputs, ultimately allowing for unambiguous, integral land evaluation. Policies aimed at increasing and diversifying food production for the rapidly expanding world population, while at the same time preserving the environmental resources, can be developed on the basis of this kind of information. Quantitative models can also serve as long term policy tools to investigate the possible effects of global climate change or soil degradation on crop production potential, population supporting capacity, and the macro-economic and social repercussions thereof.

The above described "ideal" situation of having regionally validated quantitative models, with matching climate, soil/terrain and crop databases, cannot possibly be obtained overnight. Particularly, within the framework of a world-embracing programme such as SOTER. It is mainly for that reason that a step-wise approach to land evaluation, which sequentially includes a qualitative and a quantitative stage, has been proposed for the early stages of implementation.

Initially, the minimum data requirements for quantitative modelling may not be met or appropriately scaled models may not be available for the main land qualities/land uses. The SOTER database should first be used to prepare intermediate maps for the respective land qualities/crop requirements as defined in the Framework for Land Evaluation (FAO 1976). These studies will permit identification of broad regional differences in the agro-ecological potential at a scale of 1:1 M; this is a clear gain in resolution as compared to the 1:5 M scale of the original Soil Map of the World (FAO/UNESCO 1974) which was used in the AEZ programme (FAO 1978-1981). The resulting SOTER products will be of great value to policy makers and decision takers who operate at the national or supra-national level. They can be used as the basis for formulating general policies to address main areas of concern (e.g. land degradation, desertification), and to select areas considered suitable for follow-up studies at similar or larger scales.

It is believed that quantitative modelling techniques should first be tested for their widespread usefulness and applicability within the framework of multi-national "pilot" areas, in close collaboration with national staff. Cross-border checking of preliminary model output against ground-truth of agronomic trials will provide a measure for the accuracy and reliability of these results. Once good relationships between observed and predicted data have been confirmed under a wide range of agro-ecological conditions, the confidence of user's in model output will increase. This degree of confidence will ultimately determine to which extent interpretative results can be used meaningfully as the basis for developing agricultural planning policies at macro-scale, and for formulating follow-up projects at the national or regional level.

The applicability of the proposed, mixed "qualitative/quantitative" approach under widely differing environmental conditions will be demonstrated upon the installation of the GIS component of the SOTER "computer". As such this study remains largely of a theoretical nature of necessity. Nevertheless, it has identified some of the technical difficulties which can be anticipated in the initial stages of implementation. The latter are particularly related to data availability, quality and consistency, the need for regional validation of results obtained according to a wide range of interpretative techniques against "ground truth", and the integrated linkage of a model base to the GIS.

Since global land resources have to be preserved for future generations, due attention and support must be given to the development of improved environmental resource information systems such as SOTER. Land use specialists and colleagues from other disciplines must work jointly to develop and implement effective global geographical information systems. Success of the SOTER programme will require long time commitment of funding agencies.

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REFERENCES

Aguirre, L., J. Molfino, C. Alvarez and C. Clerici, 1988. Progress Report Uruguay. In: SOTER, 1988b. Proceedings of the Second Regional Workshop on a Global Soils and Terrain Digital Database and Global Assessment of Soil Degradation (Porto Allegre, 12-15 December 1988). Edited by W.L. Peters, SOTER Report 4, International Society of Soil Science, Wageningen, the Netherlands. p. 31-35.

Batjes, N.H. and A.F. Bouwman, 1989. JAMPLES: A computerized Land Evaluation System for Jamaica. In: Bouma, J. and A.K. Bregt. Land Qualities in Space and Time. PUDOC, Wageningen, the Netherlands. p. 257-260.

Baumgardner, M.F. and R.F. van de Weg (Eds), 1989. Space and Time Dimensions of a World Soils and Terrain Digital Database. In: Bouma, J. and A.K. Bregt (Eds), p. 35-43.

Beek, K.J., 1978. Land Evaluation for Agricultural Development. ILRI Publication No. 23, Wageningen, the Netherlands.

Beek, K.J., P.A. Burrough and D.E. McCormack, 1987. Quantified Land Evaluation Procedures. ITC Publication No. 6, Enschede, the Netherlands. 165 pp.

Bouma, J., 1989. Land Qualities in Space and Time. In: Bouma, J. and A.K. Bregt (Eds), p. 3-13.

Bouma, J. and A.K. Bregt, 1989. Land Qualities in Space and Time. PUDOC, Wageningen, the Netherlands.

Bouwman, A.F., 1989. Land Evaluation for Rainfed Farming using Global Terrain Information on a 1° Longitude x 1° Latitude Grid. Working Paper and Preprint 89/1. International Soil Reference and Information Centre, Wageningen, the Netherlands. 25 pp.

Brabant, P. (In press). Le sol des forêts claires du Cameroun: Exemple d' une étude d' un site réprésentatif en vue de la cartographie des sols et de l' évaluation des terres. 2 Tomes. ORSTOM, Paris. (in French)

Brunt, J., 1990. The Laboratory Methods and Data Exchange Programme: Interim Report on the Exchange Round 1989. Working Paper and Preprint 90/1, ISRIC, Wageningen. 43 pp.

Buringh, P., 1977. Food Production Potential of the World. Volume 5, No.5-7. Pergammon Press, United Kingdom. p. 478-485.

Burrough, P.A., 1986. Principles of Geographical Information Systems for Land Resources Assessment. Monographs on Soil and Resources Survey No. 12, Clarendon Press, Oxford, United Kingdom.

Burrough, P.A., 1989a. Matching Spatial Databases and Quantitative Models in Land Resource Assessment. Soil Use and Management 5(1):3-8.

Burrough, P.A., 1989b. Fuzzy Mathematical Methods for Soil Survey and Land Evaluation. Journal of Soil Science 40(3):477-492.

Chang, L. and P.A. Burrough, 1987. Fuzzy Reasoning: A New Quantitative Aid for Land Evaluation. Soil Survey and Land Evaluation 7:69-80.

Cochrane, T.T., L.G. Sanchez, L.G. de Azevedo, J.A. Porras and C.L. Garver, 1984. Land in Tropical America. A guide to Climate, Landscapes and Soils for Agronomists in Amazonia, the Andean Piedmont, Central Brazil and Orinoco. Centro Internacional de Agricultura Tropical (CIAT), Empresa Brasiliera de Pesquisa Agropecuaria (EMBRAPA), Centro de Pesquisa Agropecuaria dos Cerrados (CPAC). Cali, Colombia.

Comerma, J.A., 1989. Considerations on the use of IBSNAT models to predict land qualities and its extrapolation. In: Bouma, J. and A.K. Bregt (eds). Land Qualities in Space and Time; proceedings of a symposium organized by the International Society of Soil Sciences, Wageningen, the Netherlands. p. 31-135.

Comerma, J. and L.B. de Guenni, 1987. The IBSNAT Simulation Models as a Means of QLE in Developing Countries. In: K.J. Beek et al. (Eds). Quantified Land Evaluation Procedures. ITC Publication No. 6, Enschede, the Netherlands. p. 44-47.

van Diepen, C.A., J. Wolf, H. van Keulen and C. Rappoldt, 1989. WOFOST: a Simulation Model of Crop Production. Soil Use and Management 5(1):16-24.

Driessen, P.M., 1986a. Quantified Land Evaluation (QLE) Procedures, a New Tool for Land Use Planning. Neth. J. Agric. Sci. 34(3):295-300.

Driessen, P.M., 1986b. Soil Data, a Matter of Concern. Annual Report, International Soil Reference and Information Centre, Wageningen, the Netherlands. p. 43-47.

Dumanski, J. and C. Onofrei, 1989. Techniques of Crop Yield Assessment for Agricultural Land Evaluation. Soil Use and Management 5(1):9-16.

Dumanski, J., R.B. Stewart and A. Bootsma, 1989. Macro-scale Land Evaluation using Crop Growth Models and Computerized Integrated Databases. In: Bouma, J. and A.K. Bregt (Eds), p. 219-229.

Dyke, P.T., 1987. Compiling and Managing Data Bases and Geographic Information Systems. In: A.H. Bunting (Ed.), Agricultural Environments: Characterization, Classification and Mapping. C.A.B. International, Oxon, United Kingdom. p. 127-135.

Eilers, R.G., 1990. Soil Salinity, Manitoba. Canada-Manitoba Soil Inventory, Land Resource Research Centre, Research Branch, Agriculture, Canada. 9 pp. + 1 map at scale 1:1 M.

van Engelen, V.W.P., 1988. SOTER Database Progress (Attribute and Point Data). In: SOTER 1988b, p. 11-20.

van Engelen, V.W.P., 1989. Selection Procedure of Geographic Information System Software for SOTER. Working Paper and Preprint 89/5, ISRIC, Wageningen, the Netherlands. 33 pp.

Eswaran H., J. Kimble, T. Cook and M. Mausbach, 1987: World Benchmark Soils Project of SMSS. Soil Survey and Land Evaluation 7:111-122.

FAO, 1976. A Framework for Land Evaluation. Soils Bulletin No. 32. Agricultural Organization of the United Nations, Rome, Italy.

FAO, 1982. Potential Population Supporting Capacities of Lands in the Developing World. Technical Report INT/75/113, Agricultural Organization of the United Nations, Rome, Italy. 139 pp.

FAO, 1983. Guidelines: Land Evaluation for Rainfed Agriculture. Soils Bulletin No. 52, Food and Agricultural Organization of the United Nations, Rome, Italy.

FAO, 1984. Land Evaluation for Forestry. Forestry Paper No. 48, Food and Agricultural Organization of the United Nations, Rome, Italy.

FAO, 1985. Guidelines: Land Evaluation for Irrigated Agriculture. Soils Bulletin No. 55, Food and Agricultural Organization of the United Nations, Rome, Italy.

FAO, 1986. The FAO Agro-Ecological Zones Approach to Quantification of Land Resources and Assessment of Crop and Population Potentials. Land and Water Development Division, Food and Agricultural Organization of the United Nations, Rome, Italy. 26 pp.

FAO, 1978-1981. Reports of the Agro-ecological Zones Project. World Soil Resources Report No. 48, Vol. 1 - Africa, Vol. 2 - Southwest Asia, Vol. 3 -South and Central America, Vol. 4 - Southeast Asia. Food and Agricultural Organization of the United Nations, Rome, Italy.

FAO/UNESCO, 1974. Soil Map of the World, 1:5000,000. Vols. 1-10, Unesco, Paris.

GLASOD, 1990. Global Soil Degradation Status Map (1:10 M). ISRIC/UNEP, Wageningen, the Netherlands.

Groenendijk, H., 1989. Estimation of the Waterholding-Capacity of Soils in Europe. The Compilation of a Soil Dataset. Simulation Report CABO-TT No. 19, Wageningen, the Netherlands. 18 pp.

Goodchild, M.F., 1988. The Issue of Accuracy of Global Databases. In: H. Mounsey, Building Databases for Global Science. Taylor and Francis, London. p. 31-48.

Hakkeling, R.T.A. and D.M. Endale, 1988. Soils of Eastern and Northeastern Africa at 1:1 Million Scale and their Irrigation Suitability. Consultancy/Mission Report 88/1, International Soil Reference and Information Centre, Wageningen, the Netherlands. 40 pp.

Hunter, G.J., 1988. Non-current data and GIS. Int. Journal Geographical Information Systems 2(3):281-286.

ILACO, 1981. Agricultural Compendium for Rural Development in the Tropics and Subtropics. Elsevier Publ. Company, Amsterdam, the Netherlands.

Keulen, H. and J. Wolf (Eds), 1986. Modelling of Agricultural Production: Weather, Soils and Crops. Simulation Monographs, PUDOC, Wageningen.

Landon, 1984. Tropical Soil Manual. Booker Agriculture International Ltd., Longman, Essex, United Kingdom.

van Lanen, H.A.J. and A.K. Bregt, 1989. Application of Computerized EC Soil Map and Climate Data. Proceedings of a Workshop in the Community Programme for Coordination of Agricultural Research (Wageningen, 15-16 November, 1988). Commission of the European Communities, Brussels, Belgium.

van Lanen, H.A.J., J. Bouma and Y. van Randen, 1989a. Mixed qualitative/quantitative land evaluation methodology applied to the EC Soil Map: Step I: Selection of potentially favourable areas. Report No. 5, The Winand Staring Centre for Integrated Land, Soil and Water Management, Wageningen, the Netherlands. 10 pp.

van Lanen, H.A.J., A.K. Bregt, Y. van Randen and M.R. Hoosbeek, 1989b. Use of GIS, EC soil map and land evaluation procedures to explore crop growth potential. Report No. 10, The Winand Staring Centre for Integrated Land, Soil and Water Management, Wageningen, the Netherlands 11 pp.

Langman, P., 1989. Temporal Database Research. Inter. Journal of Geographical Information Systems 3(3):215-232.

Meijerink, A.M.J., C.R. Valenzuela and A. Stewart (Eds), 1988. ILWIS the Integrated Land and Watershed Management Information System. ITC Publication No. 7, Enschede, the Netherlands. 115 pp.

Mounsey, H. (Ed.), 1988. Building Databases for Global Science. Proceedings of the First Meeting of the International Geographical Union Global Database Planning Project. Taylor & Francis, London, United Kingdom. 419 pp.

Msanya, B.M., 1987. Soil Resource Inventories: Characterization, Quality and Evaluation of their Adequacy for Specific Land Use. Phd. Thesis, Faculty of Sciences, State University of Ghent, Belgium. 230 pp.

Nix, H., 1987. The Role of Crop Modelling, Minimum Data Sets and Geographic Information Systems in the Transfer of Agricultural Technology. In: Bunting, H. (Ed.), Agricultural Environments: Characterization, Classification and Mapping. CAB International, Wallingford, United Kingdom. p. 113-117.

Nyandat M.N. and Muchena F.N., 1982. Land evaluation in Kenya with particular emphasis on the criteria used. Third Meeting of the Eastern Sub-Committee for Soil Correlation and Land Evaluation. World Soil Resources Report 51, FAO, Rome. p. 26-48.

Oldeman, L.R., 1987. Characterization of main Experimental Sites and Sub-sites and Questions of Instrumentation. In: Bunting, H. (Ed.), Agricultural Environments: Characterization, Classification and Mapping. CAB International, Wallingford, United Kingdom. p. 101-112.

Oliveira, J.B., J.R.F. Menk, J.L. Bambieri, C.L. Rotto and W. Fremocoldi, 1982. Levantamento pedológico semidetalhado do Estado de Saô Paolo: Quadricula de Araras. Instituto Agronomico, Campinas, Brazil. 180 pp. (in Portuguese)

Palmieri, F., J. Olmos, P. Fassolo and R. Potter, 1988. Progress Report Brazil. In: SOTER, 1988b, p. 36-38.

Penning de Vries, F.W.T., 1980. Simulation Models of Growth of Crops, particulary under Nutrient Stress. In: Physiological Aspects of Crop Productivity. Proceedings of the 15th Colloquium of the International Potash Institute held in Wageningen. International Potash Institute, Bern, Switzerland.

Pleijssier, L.K., 1989. Variability in Soil Data. In: Bouma, J. and A.K. Bregt. Land Qualities in Space and Time, PUDOC, Wageningen. p. 89-99.

Price, S., 1989. Modelling the Temporal Element in Land Information Systems. Int. Journal of Geographical Information Systems 3(3):233-243.

Pulles, J.H.M., 1988. A Model for a Soils and Terrain Digital Database. Working Paper and Preprint 88/8, ISRIC, Wageningen, the Netherlands. 32 pp.

van Reeuwijk, L.P., 1983. On the Way to Improve International Soil Classification and Correlation: The Variability of Analytical Data. Annual Report, International Soil Museum, Wageningen, the Netherlands. p. 7-13.

Riquier, J., 1974. A Summary of Parametric Methods of Soils and Land Evaluation. In: Approaches to Land Classification. Soils Bulletin No. 22, Food and Agricultural Organization of the United Nations, Rome, Italy. p. 47-53.

Rossiter, D.G., 1990. ALES: A Framework for Land Evaluation using a Micro-computer. Soil Use and Management 6(1):7-20.

Sanchez, P.A, W. Couto, S.W. Buol, 1982. The Fertility Capability Soil Classification System: Interpretation, Applicability and Modification. Geoderma 27:283-309.

Shields, J.A. and D.R. Coote, 1988. SOTER Procedures Manual for Small Scale Map and Database Compilation (First version). Working Paper and Preprint No. 88/2, ISRIC, Wageningen, the Netherlands.

Shields, J.A. and D.R. Coote, 1989. SOTER Manual for Small Scale Map and Database Compilation and Procedures for Interpretation of Soil Degradation Status and Risk (Revised version of Working Paper and Preprint No. 88/2). Working Paper and Preprint 89/3. ISRIC, Wageningen, the Netherlands.

Smit, B., Brklacich, M., Dumanski, J., MacDonald, K.B., Miller, M.H., 1984. Integral Land Evaluation and its Application to policy. Canadian Journal Soil Science: 64:467-474.

Smith, T.R., S. Menna, J.L. Star and J.E. Ester, 1987. Requirements and Principles for the Implementation and Construction of Large Scale Geographic Information Systems. Int. Journal of Geographical Information Systems 1(1):13-31.

Sombroek, W.G., 1990. Geographic Quantification of Soils and Changes in their Properties. In: A.F. Bouwman (Ed.), Soils and the Greenhouse Effect. John Wiley & Sons Ltd., Chichester, United Kingdom. p. 225-244.

SOTER, 1986a. Proceedings of an International Workshop on the Structure of a Digital International Soil Resources Map annex Database (ISRIC, Wageningen, 20-24 January 1986). Edited by M.F. Baumgardner and L.R. Oldeman, SOTER Report 1, International Society of Soil Science, Wageningen, the Netherlands. 138 p.

SOTER, 1986b. Project Proposal for a World Soils and Terrain Digital Database at a scale of 1:1 M (SOTER). Edited by M.F. Baumgardner, International Society of Soil Science, Wageningen, the Netherlands. 23 p.

SOTER, 1987. Proceedings of the Second International Workshop on a Global Soils and Terrain Digital Database (UNEP, Nairobi, 18-22 May 1987). Edited by R.F. van de Weg, SOTER Report 2, International Society of Soil Science, Wageningen, the Netherlands. 47 p.

SOTER, 1988a. Proceedings of the First Regional Workshop on a Global Soils and Terrain Digital Database and Global Assessment of Soil Degradation (Montevideo, 20-25 March 1988). Edited by W.L. Peters, SOTER Report 3, International Society of Soil Science, Wageningen, the Netherlands. 81 pp.

SOTER, 1988b. Proceedings of the Second Regional Workshop on a Global Soils and Terrain Digital Database and Global Assessment of Soil Degradation (Porto Allegre, 12-15 December 1988). Edited by W.L. Peters, SOTER Report 4, International Society of Soil Science, Wageningen, the Netherlands. 97 pp.

SOTER, 1990a. SOTER Procedures Manual for Small Scale Map and Database Compilation (Draft 3rd revised version). Working Paper and Preprint 90/2, ISRIC, Wageningen, the Netherlands. 69 pp.

SOTER, 1990b. Proceedings of the International Workshop on Procedures Manual Revisions for the Global Soils and Terrain Digital Database. Edited by N.H. Batjes, Working Paper and Preprint 90/5, ISRIC, Wageningen, the Netherlands. 25 pp.

SOW, 1985. Potential Food Production Increases from Fertilizer Aid. A Case Study of Burkina Faso, Ghana and Kenya (Volume I and II). Centre for World Food Studies, Wageningen, the Netherlands.

Sys, C. 1985. Land Evaluation (Volume I, II and III). State University of Ghent, Belgium.

Thomasson, A.J. and R.J.A. Jones, 1989. Land Evaluation at Regional Scale. In: J. Bouma and A.K. Bregt (Eds), p. 231-240.

Touber, L., E.M.A. Smaling, W. Andriesse and R.T.A. Hakkeling, 1989. Inventory and Land Evaluation of Tropical Forest Land. Guidelines for a Common Methodology. The TROPENBOS Foundation, Ede, the Netherlands. 170 pp.

UNEP, 1988. Environmental Report. United Nations Environmental Programme. Dotesios Printer Ltd., Bradford-on-Avon, United kingdom. 351 pp.

Verheye, W.H., 1986. Principles of Land Appraisal and Land Use Planning within the European Community. Soil Use and Management 2(4):120-124.

Vogel, A.W., 1986. Class Limits for Land and Soil Properties. A Comparative Literature Study for Use at the Establishment of a World Soil and Terrain Digital Database (SOTER). Working Paper and Preprint No. 86/3, International Soil Reference and Information Centre, Wageningen, the Netherlands.

Wolf, J., J.A.A. Berkhout, C.A. van Diepen and C.H. van Immerzeel, 1989. A Study of the Limitations to Maize Production in Zambia Using Simulation Models and a Geographic Information System. In: Bouma, J. and A.K. Bregt (Eds), p. 209-212.

Wood, S.R. and F.J. Dent, 1983. LECS Methodology. Manual 5. Ministry of Agriculture, Govt. of Indonesia/FAO-AGOF/INS/78-006.

Young, A., 1987. Methods Developed Outside the International Agricultural Research System. In: A.H. Bunting (Ed.), Agricultural Environments: Characterization, classification and Mapping. C.A.B. International, Oxon, United Kingdom. p. 43-63.

APPENDICES

Appendix I: Tentative list of attributes for terrain and soil data files.

TERRAIN UNIT

Terrain unit ID	M(andatory)
Year	M
regional landform	M
dominant elevation	M
relief intensity	M
general lithology	M
permanent water surface	M
density of drainage lines	O(ptional)
average distance between places of	O
permanent water surface (%)	M

TERRAIN COMPONENT

Terrain unit ID	M
terrain component ID	M
proportion of terrain unit	M
surface form	M
micro-relief	M
length of slope	M
predominant slope gradient	M
parent material	M
texture group of non-consolidated parent material	M
frequency of flooding	M
start of flooding (month)	M
duration of flooding (in days)	M
mean highest groundwater table	M
mean lowest groundwater table	M
electrical conductivity of ground water	M
surface drainage	M
surface rockiness (% coverage)	M
surface stoniness (% coverage)	M
size of stones	O
depth to consolidated parent rock	M
(predominant land use/vegetation ?)	M

Appendix I (cont.)

SOIL COMPONENT

- soil data

Terrain unit ID	M
Terrain component ID	M
Representative profile ID	M
% of terrain component occupied by soil component	M
internal drainage	M
infiltration rate	O
rootable depth	M
soil development (dominant process)	M
thickness of organic litter at surface	M
degree of decomposition of organic matter/litter on the surface	O
propensity to capping	M

- layer data (sensu master horizon)

Representative profile ID	M
master horizon number (subhorizon if needed)	M
lower depth of horizon	M
abruptness of lower horizon boundary	M
colour, moist	M
colour, dry	O
structure, form	M
structure, size	M
structure, grade	M
zoological activity	O
clay mineralogy	M
carbon content	M
total nitrogen content	M
P-Olsen	O
P-retention	O
CEC soil (NH_4OAc buffered at pH 7)	M
ECEC	O
AEC	O
exchangeable-Ca	M
exchangeable-Mg	M
exchangeable-Na	M
exchangeable-K	M
exchangeable-Al	M
exchangeable-Mn	O
Fe, dithionite extractable	O
Al, dithionite extractable	O
Fe, oxalate extractable	O
Al, oxalate extractable	O
pH-H_2O	M
pH-KCL	M
ECe	M
Calcium carbonate content	M
Gypsum content	M
coarse fragments, volume %	M
coarse fragments, size	O
texture class (USDA)	M
total sand	M
very fine sand	M
fine sand	M
silt	M
clay (pre-treated)	M
natural (water dispersible) clay	O
volume % water held at field capacity	O
volume % water held at permanent wilting point	O
bulk density	M
saturated hydraulic conductivity	O
diagnostic horizon	M
diagnostic property (dominant ?)	M

Source: SOTER 1990b

Appendix II. Land qualities/land use requirements related to rainfed agriculture that can be derived from the SOTER database.

Land qualities	land characteristics (expressed as SOTER attributes)	File
Radiation regime		
	total radiation	CL
	bright sunshine hours	CL
Temperature regime		
	mean minimum daily air temperature	CL
	mean maximum daily air temperature	CL
	mean daily air temperature	CL
Moisture availability		
	precipitation totals	CL
	number of raindays	CL
	potential evapo-transpiration	CL
	rootable depth	SC
	coarse fragments (volume)	SL
	soil moisture characteristics	SL
	depth to groundwater table	TC
	texture	SL
Drainage conditions		
	internal drainage	SC
	depth to groundwater table	TC
Nutrient availability		
	soil reaction (pH)	SL
	total exch. bases (Ca, Mg, Na, K)	SL
	Total Nitrogen	SL
	Available Phosphorus	SL
	Organic Carbon	SL
	Nature of parent material	TC
Nutrient retention		
	Effective cation exchange capacity	SL
	texture	SL
	clay mineralogy	SL
Rooting conditions		
	effective soil depth	SC
	soil structure	SL
	bulk density	SL
Flood hazard		
	flooding frequency, time of occurrence and duration	TC
Climatic hazards		
	occurrence of hailstorm	CL
	occurrence of hurricanes	CL
Excess of salts		
	soil reaction (pH)	SL
	electrical conductivity (ECe)	SL
	Exchangeable sodium percentage	SL
Soil toxicities		
	soil reaction (pH)	SL
	Exchangeable-Aluminium	SL
	$CaCO_3$ content	SL
	Gypsum content	SL

Appendix II (cont.)

Workability/ease of mechanization	
slope angle	TC
slope length	TC
surface soil structure	SL
rockiness/stoniness at surface	TC
coarse fragments in surface soil	SL
Erosion hazard	
slope angle	TC
slope length	TC
texture	SL
structure	SL
bulkdensity	SL
flocculation index	SL
rainfall regime	CL
Soil degradation hazard	
slope angle	TC
slope length	TC
texture	SL
structure	SL
propensity to surface crusting	SC
rainfall regime	CL
flocculation index	SL
clay mineralogy	SL

* SOTER Files:
  - CL: climate file
  - TU: terrain unit file
  - TC: terrain component file
  - SC: soil component file
  - SL: soil layer file

(See also comments in Chapter 4 re. scale aspect)

Appendix III. Fertility Capability Classification (FCC) for selected terrain units from the LASOTER area.

SOTER units				FCC classification																		
TU	TC	SC	SC%	Tt	Tg	St	Sg	g	d	e	a	h	i	x	v	k	b	s	n	c	FCC class	Mv
1	1	1	70	C		C					a		i			k					Caik(4-9%)	
	2	2	30	C		C					a		i			k					Caik(10-15%)	
2	1	1	70	C								h	i		v	k					Chivk(16-29%)	
	2	2	30	C		C					a		i			k					Caik(10-15%)	
3	1	1	60	L	''							h									L''h(0-3%)	
	1	2	30	L		C						h			v	k					LChvk(0-3%)	
	2	3	10	C		C					a				v	k					Cavk(0-3%)	
4	1	1	70	C								h	i		v	k					Chivk(16-29%)	
	2	2	30	C		C					a		i			k					Caik(10-15%)	
5	1	1	60	L	''							h									L''h(0-3%)	
	1	2	30	L		C						h			v	k					LChvk(0-3%)	
	2	3	10	C		C					a				v	k					Cavk(0-3%)	
6	1	1	70	C								h	i		v	k					Chivk(16-29%)	
	2	2	30	C		C					a		i			k					Caik(10-15%)	
7	1	1	70	C								h	i		v	k					Chivk(16-29%)	
	2	2	30	C		C					a		i			k					Caik(10-15%)	
8	1	1	70	C								h	i		v	k					Chivk(16-29%)	
	2	2	30	C		C					a		i			k					Caik(10-15%)	
9	1	1	70	C								h	i		v	k					Chivk(16-29%)	
	2	2	30	C		C					a		i			k					Caik(10-15%)	
10	1	1	60	L	''							h									L''h(0-3%)	
	1	2	30	L		C						h			v	k					LChvk(0-3%)	
	2	3	10	C		C					a				v	k					Cavk(0-3%)	
11	1	1	60	S		S				e	a					k					Seak(4-9%)	
	2	2	20	L		L					a					k					Lak(4-9%)	*
	3	3	20	C		C					a		i		v						Caiv(0-3%)	
12	1	1	50	C		C					a				v	k					Cavk(0-3%)	
	1	2	30	C		C		g			a				v	k					Cgavk(0-3%)	
	1	3	20	L		L				e	a					k					Leak(0-3%)	*
13	1	1	60	L	''							h									L''h(0-3%)	
	1	2	30	L		C						h			v	k					LChvk(0-3%)	
	2	3	10	C		C					a				v	k					Cavk(0-3%)	
14	1	1	60	S		S				e	a					k					Seak(4-9%)	
	2	2	20	L		L					a					k					Lak(4-9%)	*
	3	3	20	C		C					a		i		v						Caiv(0-3%)	
15	1	1	60	S		S				e	a					k					Seak(4-9%)	
	2	2	20	L		L					a					k					Lak(4-9%)	*
	3	3	20	C		C					a		i		v						Caiv(0-3%)	
16	1	1	70	C								h	i		v	k					Chivk(16-29%)	
	2	2	30	C		C					a		i			k					Caik(10-15%)	
17	1	1	60	S		S				e	a					k					Seak(4-9%)	
	2	2	20	L		L					a					k					Lak(4-9%)	*
	3	3	20	C		C					a		i		v						Caiv(0-3%)	
18	1	1	60	S		S				e	a					k					Seak(4-9%)	
	2	2	20	L		L					a					k					Lak(4-9%)	*
	3	3	20	C		C					a		i		v						Caiv(0-3%)	

Note:

- FCC classes call the user's attention to the major limitations that will be encountered within a given FCC class (see Sanchez et al. 1982). The FCC system can be used in land evaluation based on FAO's Framework (see FAO 1983).

- The FCC system consists of three categorical levels: type (topsoil texture, see Tt), subtype (subsoil texture, see St) and 15 modifiers, viz.: graveliness (Tg resp. Sg for topsoil and subsoil respectively; one prime ['] = 15-35% gravels, two primes ["] > 35% gravel), g (gley), d (dry), e (low ECEC), a (aluminium toxicity), h (acidity), i (fixation of phosphorus by iron), x (presence of X-ray amorphous materials), v (vertic properties), k (low in K-reserves), b (basic reaction), s (salinity), n (natric), c (cat clay).

- Substrata type is only indicated when there is a marked textural change form the surface (Texture: S: sandy; L: loamy; C: clayey).

- Mv stands for incomplete code due to occurrence of missing values (*) in database.