A theoretical framework for land evaluation[*]

by

David G. Rossiter[†]

with a discussion by

J. Bouma, P.A. Burrough, J.J. de Gruijter,

E. Van Ranst, A.K.L. Johnson, & A.B. McBratney

and a reply by the **Author**

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Abstract

Land evaluation is the process of predicting the use potential of land on the basis of its attributes. A variety of analytical models can be used in these predictions, ranging from qualitative to quantitative, functional to mechanistic, and specific to general. This paper classifies land evaluation models by how they take time and space into account, and whether they use land qualities as an intermediate between land characteristics and land suitability. Temporally, models can be of a static resource base and static land suitability, a dynamic resource base but static land suitability, or both a dynamic resource base and dynamic land suitability. Spatially, land evaluation models can be of a single area with no interaction between areas, with static inter-area effects, or dynamic inter-area effects. In the most complex case, land suitabilities for several land uses are interdependent.

[*] References to the paper should include the discussion and should be cited as:
Rossiter, D.G., (1996) A theoretical framework for land evaluation (with Discussion). Geoderma, xx: ???-???
References to parts of the Discussion should be cited as, e.g.,
Bouma, J., (1996) In Discussion of: D.G. Rossiter, A theoretical framework for land evaluation. Geoderma, xx: ???-???.

[†] Senior Research Associate, Department of Soil, Crop & Atmospheric Sciences (SCAS), Cornell University, Ithaca, NY 14853-1901 USA. Current address: International Institute for Aerospace Survey & Earth Sciences (ITC), Postbus 6, 7500AA Enschede, the Netherlands.

Introduction

Inappropriate land use leads to inefficient exploitation of natural resources, destruction of the land resource, poverty and other social problems. The land is the ultimate source of wealth and the foundation on which many civilizations are constructed. Society must ensure that land is not degraded and that it is used according to its capacity to satisfy human needs for present and future generations while also maintaining the earth's ecosystems. Part of the solution to the land-use problem is land evaluation in support of rational land-use planning and appropriate and sustainable use of natural and human resources.

Land evaluation may be defined as "the process of assessment of land performance when [the land is] used for specified purposes" (FAO, 1985), or as "all methods to explain or predict the use potential of land" (van Diepen *et al.*, 1991). Once this potential is determined, land-use planning can proceed on a rational basis, at least with respect to what the land resource can offer (FAO, 1993). Thus, land evaluation is a tool for strategic land-use planning. It predicts land performance, both in terms of the expected benefits from and constraints to productive land use, as well as the expected environmental degradation due to these uses.

The logic that makes land evaluation possible and useful can be summarized as follows:

1. Land varies in its physical, social, economic, and geographic properties ('land is not created equal');
2. This variation affects land uses: for each use, there are areas more or less suited to it, in physical and/or economic terms;
3. The variation is at least in part systematic, with definite and knowable causes, so that...
4. The variation (physical, political, economic and social) can be mapped by surveys, i.e. the total area can be divided into regions with less variability than the entire area;
5. The behavior of the land when subjected to a given use can be predicted with some degree of certainty, depending on the quality of data on the land resource and the depth of knowledge of the relation of land to land use, therefore...
6. Land suitability for the various actual and proposed land uses can be systematically described and mapped, so that...
7. Decision makers such as land users, land-use planners, and agricultural support services can use these predictions to inform their decisions.

Modern land evaluation practice grew out of agricultural land capability classification (e.g. (Klingebiel & Montgomery, 1961; U.S. Department of the Interior Bureau of Reclamation, 1951), as reviewed by McRae (1981) and Olson (1974), beginning with the work of Stewart (1968), through the doctoral dissertation of Beek (1978) and working groups of mostly European soil scientists in the 1970s. The Food and Agriculture Organization of the United Nations (FAO)'s Land and Water Development division (AGL), in the early 1970s, sponsored working groups, leading to publication of the "Framework for Land Evaluation" in 1976 (FAO, 1976). Subsequently, the FAO organized workshops leading to publication of guidelines for land evaluation in dryland agriculture (FAO, 1983), irrigated agriculture (FAO, 1985), forestry (FAO, 1984), extensive grazing (FAO, 1991); and steeplands (Siderius, 1986). A good textbook from this era of land evaluation is that of Dent & Young (1981); the concepts of FAO-style land evaluation are also considered standard practice in reference works for agricultural land assessment such as the Booker Tropical Soils Manual (Landon, 1984) and the Agricultural Compendium (EUROCONSULT, 1989).

Subsequently, practicing land evaluators saw the need for more quantified predictions of land performance; this resulted in several interesting symposia (Beek *et al.*, 1987; Bouma & Bregt, 1989; Wagenet & Bouma, 1993) and more research, especially in the quantitative prediction of individual land qualities (Hack-ten Broeke *et al.*, 1993). Quantified methods require more-or-less detailed models of land performance, and these models usually have high data requirements. In areas of the world with data deficits, or in application areas with knowledge gaps, qualitative and semi-quantitative models based partly on expert judgment still have an important role to play. Recently there has been some work comparing quantitative and qualitative assessments of land qualities, using the qualitative models to identify which land areas are worth further investigation with quantitative models, and which areas can be rejected as unsuitable without detailed study (van Lanen *et al.*, 1992a; 1992b). Van Diepen *et al.* (1991) provide a good review of the historical and current state of land evaluation practice.

To date, land evaluation has been largely ‘pedocentric’, i.e. emphasizing the soil resource and being carried out by soil scientists, mainly because the FAO land evaluation methodology was developed by soil scientists whose experience had been in agricultural land suitability classification. Of course, the soil resource is just one among many natural, economic and human resources that affect land suitability; in the theoretical framework presented in this paper they are all equally important. Some soil scientists working as land evaluators, realizing this, have incorporated non-soils information into their evaluations. However, as Bouma & Hoosbeek point out (1996?), soil scientists are not usually qualified to cover all specialties that are necessary for a useful land evaluation. The ideal situation is a specialist in land evaluation methods, not necessarily a soil scientist, working with a team of specialists in land resources and land use. A common theoretical framework should ease communication between team members.

Computers have been applied to land evaluation at different levels of detail. The first implementation of the FAO Framework was the LECS system in Indonesia (Wood & Dent, 1983); this has recently been incorporated into the FAO’s Agricultural Planning Toolkit (APT). A map-unit based, expert-systems approach is the ALES framework (Rossiter, 1990; Rossiter & Van Wambeke, 1995). ALES has been used to implement several provincial, country, and regional land evaluations (Delsert, 1993; Johnson & Cramb, 1991; León Pérez, 1992; Mantel, 1994; van Lanen *et al.*, 1992c; van Lanen & Wopereis, 1992; Venema & Daink, 1992). Another computer program is MicroLEIS (De la Rosa *et al.*, 1992) for land evaluations in Mediterranean climates. Land evaluation by map analysis techniques may be accomplished with any geographical information system (GIS) (Burrough, 1986; 1987). A GIS designed for land evaluation is the ILWIS system (Meijerink *et al.*, 1988) developed at the International Institute for Aerospace Survey & Earth Sciences (ITC). Many computer models of land processes have been used to evaluate single land qualities, for example the pesticide leaching model LEACHM (Hutson & Wagenet, 1991; 1992)

In all this work there has not been an explicit statement of the theoretical basis of land evaluation. Keyzer's (1992) title suggests that he is doing this, but the paper in fact develops a theoretical framework for optimal land allocation. Burrough (1989b) discusses the kind of models used in land evaluation, distinguishing between empirical, deterministic process and stochastic process models, but with only a few simple examples. Sklar & Constanza (1990) discuss spatial models in landscape ecology. Their relevant classes of models for land evaluation are *ecosystem* models with explicit material or information flows between spatially-distributed system components, and *landscape* models, either stochastic or process-oriented.

Hoosbeek & Bryant (1992), while primarily concerned with models of pedogenesis, provide a useful framework which can be applied to land evaluation models. They classify models in three dimensions: (1) *degree of computation*, ranging from qualitative to quantitative, (2) *descriptive complexity*, ranging from functional (empirical) to mechanistic, i.e. where processes are made explicit in the model, and (3) *level in the organizational hierarchy*, which for soils systems range from soil region through polypedon and pedon to horizons and finally molecular interactions. This organizational hierarchy ranges from specific or detailed to general.

In land evaluation, this concept of organizational level can be related to map scale and delineation size (Forbes *et al.*, 1982). Detailed land evaluation models predict at Hoosbeek & Bryant's level $i+1$ (soil polypedon), which corresponds to a minimum legible delineation (MLD = 0.4cm^2 on the map) of 0.1ha (1,000m^2) at a map scale of 1:5 000 up to a MLD of 1.6ha at 1:20 000. More general models predict at level $i+2$ (catena or landscape), which corresponds to a MLD of 10ha at 1:50 000 up to a MLD of 40ha at 1:100 000. Some very general models predict at level $i+3$ (soil region), which corresponds to a MLD of 250ha (2.5km^2) at 1:250 000 up to a MLD of 4,000ha (40km^2) at 1:1 000 000. Detailed land evaluation models may represent lower levels of the organizational hierarchy. such as pedon (= level i) or horizon (= level i-1), although they do not predict at these scales.

This paper proposes a unified theoretical framework with which to describe land evaluation models, independently of analytical method. After preliminary definitions, Part 1 presents the case where each land unit is evaluated separately, without regard to its actual position on the earth's surface. Then this constraint is relaxed, so that Part 2 presents the case where a land unit's location must be considered. Part 3 considers models of multi-area suitability, where a set of land areas must be evaluated together. Throughout, the theoretical framework is illustrated by actual land evaluation methods. In the conclusion, I summarize the classification, and also present a few thoughts on current and future land evaluation practice. The following table of contents shows the paper's structure:

Preliminary definitions

This paper makes use of certain terminology from FAO-style land evaluation. These definitions are synthesized and updated from those in (FAO, 1976; 1983; 1984; 1985).

Land: An area of the earth’s surface, the characteristics of which embrace all reasonably stable, or predictably cyclic, attributes of the biosphere vertically above and below this area, including those of the atmosphere, the soil and underlying geology, the hydrology, the plant and animal populations, and the results of past and present human activity, to the extent that these attributes exert a significant influence on present and future uses of the land by humans. In this paper, I extend this definition to allow time-series of land attributes, thereby weakening the requirement that these be stable or predictably cyclic.

Land Evaluation: The process of predicting the use potential of land on the basis of its attributes. It does not include optimal land allocation. However, land evaluation supplies the technical coefficients necessary for optimal land allocation.

Land Mapping Unit (abbreviation **LMU**): A specific area of land that can be delineated on a map and whose Land Characteristics (q.v.) can be determined. It is the **evaluation unit** about which statements will be made regarding its land suitability (q.v.). The LMU can be a grid cell, a single map delineation (polygon), or a set of map delineations with common Land Characteristics (q.v.), i.e. a legend category of a thematic map. Land that has not been, or can not be, mapped may be evaluated at specific locations.

Land Characteristic (abbreviation **LC**): a simple attribute of the land that can be directly measured or estimated in routine survey, including remote sensing and census as well as natural resource inventory. Cf. ‘Land Quality’. The same LC can be measured at different times, resulting in a time-series of values *LC(t)*. The LC can be measured at different points or areas within the LMU, but for land evaluation purposes, these individual observations are usually aggregated or summarized to a single value or a parameterized distribution. Bouma *et al.* (1996?) provide a useful classification of LCs along three axes: (1) sample size (‘point’ or minimum representative volume vs. area), (2) time-series or repeated measurements vs. a single point in time, and (3) method of obtaining the value: measurement, estimate, pedotransfer function or simulation model.

Land Utilization Type (abbreviation **LUT**): A specific land-use system with specified management methods in a defined technical and socio-economic setting, and with a specific duration or *planning horizon*. The description of a LUT may include a time-series of activities and outputs. The definition of a LUT is not a complete description of the farming or other land-use system: it includes only those attributes that serve to differentiate the suitability of land areas, for example, those that can be expressed as Land Use Requirements (q.v.) with critical values in the study area. The definition of a LUT also includes attributes that limit the land use options by discarding those that are *a priori* unfeasible over the entire evaluation area.

Land Use Requirement (abbreviation **LUR**): a condition of the land necessary for successful and sustained implementation of a specific Land Utilization Type. A LUT may be defined by a set of LURs. A LUR expresses the ‘demand’ side of the land use - land area matching procedure.

Land Quality (abbreviation **LQ**): a complex attribute of land which acts in a manner distinct from the actions of other land qualities in its influence on the suitability of land for a specified kind of use; the ability of the land to fulfill specific requirements for a LUT. It can not usually be measured or estimated in routine survey, and so must be inferred from a set of ‘diagnostic’ Land Characteristics. Cf. ‘Land Characteristic’. The LQ expresses the ‘supply’ side of the land use vs. land area matching procedure. If the LUT is defined as a set of LURs, land suitability (q.v.) is based on the set of severity levels (q.v.) of the LQs corresponding to the LURs. The value of a LQ may vary over time, resulting in a time-series of severity levels *LQ(t)*.

Severity level, also called **factor level** or **degree of expression** of a Land Quality: a ranking or classification of the LQ, according to the degree of limitation or hazard associated with the LQ of a particular land area. Severity levels are conventionally numbered from level 1 indicating ‘no limitation’ upwards to some maximum meaning ‘completely limiting’ in the context of a specific LUT.

Land Suitability: the fitness of a given Land Mapping Unit (LMU) for a Land Utilization Type (LUT), or the degree to which it satisfies the land user. In a more operational sense, suitability expresses how well the LMU matches the requirements of the LUT. It may be expressed on a continuous scale of 'goodness' (e.g. 0 to 100) or, more commonly, as a set of discrete classes, which are conventionally numbered from class 1 meaning 'completely suited' upwards to some maximum meaning 'completely unsuited'.

Yield: the amount of an output produced on a given area, either normalized to a unit of land area (e.g. per hectare) or not (i.e. the amount over the entire evaluation unit).

Notation

In this paper, a subscripted variable indicates that the variable is defined for each instance of the subscript. For example, S_{LUT} means that variable *S* (suitability) is defined separately for each Land Utilization Type. Functions are also subscripted to show the context in which they are defined. For example, $f_{(Out,LUT)}$ means that function *f* is defined for a specific output *Out* and within the context of a specific Land Utilization Type *LUT*. Vectors are summarized by a bold-face lower-case letter, e.g. $\boldsymbol{u}$. Matrices are summarized by a bold-face upper-case letter, e.g. **R** or with square brackets, e.g. [LC].

Part 1 : Non-spatial models of single-area land suitability

This first Part considers a single 'small' and 'homogeneous' area on the earth's surface whose suitability is to be determined, without any influence from surrounding areas, and without explicit reference to its actual geographic location. Since location is not taken into account, this analysis is valid for a mapping unit consisting of several 'small' areas, either contiguous or not, which share the same set of Land Characteristics, for example, the legend category of a natural resource inventory. The actual size and homogeneity don't matter, as long as the analysis is sufficiently precise. The evaluation units must be 'small enough' and 'homogeneous enough' for the objectives of the land evaluation, and must not exceed the precision of the natural resource inventory from which Land Characteristics are derived. For example, climate must be 'similar enough' for all of the delineations within a legend category

Case 1 : Static resource base, static land suitability

In the simplest case, Land Characteristics (the land resource base) do not change over time, except perhaps cyclically (e.g. seasonally). The LCs are *static*, so that the FAO definition of 'land' as having only stable or predictably cyclic characteristics is preserved. In this case, the various Land Characteristics which make up the resource base *R* can be considered as a one-dimensional vector $\boldsymbol{r} = (LC_1, LC_2, \ldots LC_n)^T$ or as a set of values $R = \{LC\}$. Since the land resource base is static, so is the land suitability.

Time can be taken into account in a limited way in this analysis. Even though each Land Characteristics is time-invariant, multiple LCs can be defined that in fact represent the same LC at different points in cyclic time, i.e. within a season or rotation. For example, we may define twelve LC of ground water level, one for each month. This restricted view of time is satisfactory if the resource base isn't changing, just cycling within a year or other short cycle, and if the static point of view produces satisfactory predictions. For LCs that are inherently time-dependent, such as weather, it is usual to aggregate the time-series to LCs defined by summary statistics of the time-series, for example, averages, durations, or extremes.

Evaluation based on Land Characteristics

The basic relation for predicting land suitability is a function, not necessarily continuous, smooth or crisp, from a set of *n* land characteristics $\{LC\}_{LMU}$ measured for map unit *LMU* to the land suitability $S_{LMU,LUT}$ of the map unit for each Land Utilization Type *LUT*:

$$S_{LMU,LUT} = f_{LUT}(\{LC\}_{LMU}) \quad \textbf{(1)}$$

The subscripts indicate that the function f_{LUT} by which suitability is determined depends on the Land Utilization Type, and that the set of Land Characteristics are measured for a specific Land Mapping Unit, so that the suitability is for a specific LUT, on a specific LMU.

S can be expressed on a continuous scale, for example, an economic metric (Rossiter, 1995?) such as expected gross margin of the LUT implemented on the LMU. *S* can also be expressed on a discrete or classified scale, for example as in the original FAO Framework for Land Evaluation (FAO, 1976), where each land area is assigned a suitability for a land use, from the 5-member set $S \in$ {S1, S2, S3, N1, N2} = {*highly* suited, *moderately* suited, *marginally* suited, *unsuited for economic* reasons, *unsuited for physical* reasons}. The form of *f* varies according to whether the result is continuous or classified. In general, these functions are functional and qualitative to partially quantitative, according to the terminology of Hoosbeek & Bryant (1992).

S can also be expressed as a set of *degrees of membership* in the set of suitability classes, rather than as a single suitability; in this case the techniques of continuous classification or 'fuzzy' logic (Burrough, 1989a) are used to define *f*. This approach was taken by Tang *et al*. (1991) and Triantafilis & McBratney (1993).

Before there was land evaluation as a quasi-scientific discipline, people observed the relative success of different land-use systems on different land areas, and indeed these observations continue today. Generally there is little or no analytical content to these assessments, and no or unsubstantiated hypotheses about causes, so that these 'land evaluations' based on local knowledge, while useful for existing land uses and within the original area of observation, can not be extrapolated to new areas or new land uses. The models are not made explicit; yet they can be thought of as realizations of equation (1). However, these mental models probably have discontinuous domains (knowledge gaps).

The land index

A historically-important realization of equation (1) is the *land index*. This is a simple rating of the 'goodness' of land on a continuous scale, usually from 0 (totally unsuited or without value) to 100 (highest suitability and value). The land index has obvious applications in land taxation or compensation for land taking by eminent domain. The classic example of a land index is the Storie index from California (Storie, 1933) which has been revised several times and adapted for other locations, e.g. Poland (Koreleski, 1988). These have been called 'parametric' indices in the literature (Riquier, 1974), a most confusing use of the term 'parameter', which is used in mathematics and modeling to mean a constant in a specific instance of an equation which can be varied in other instances of the equation.

Land indices are derived from a set of *standardized* continuous LC values, which are combined, possibly with weighting factors to arrive at land suitability *S*. The combination can be additive, multiplicative, or geometric:

$$S_{LMU} = \sum_{i=1}^{q} LC_{i,LMU} \cdot w_i , \quad \sum_{i=1}^{q} w_i = 1, \quad LC_i \in [0 \ldots 1] \tag{2}$$

$$S_{LMU} = \prod_{i=1}^{q} LC_{i,LMU} \quad , \quad LC_i \in [0 \ldots 1] \tag{3}$$

$$S_{LMU} = \sqrt[q]{\prod_{i=1}^{q} LC_{i,LMU}} \quad , \quad LC_i \in [0 \ldots 1] \tag{4}$$

In these formulations, suitability and the standardized LCs are measured on the interval [0…1]. Any scaling factor could be used; for example, all LC values could be multiplied by 100 so that the most suitable land would be rated '100%'. The higher rating represents the greater suitability. In equation (2), if all LCs are of equal weight, the weighting factors w_i are all q^{-1}, where q is the number of LCs. In equation (3), the LCs can be weighted by restricting the permissible range of the less-important factors; i.e. $LC_x \in [min_x \ldots 1]$ where $min_x \in (0 \ldots 1)$, so that this LC can not lower the land index too much. For example, in the original multiplicative Storie index, with the form of equation (3), LCs such as percent of sodium salts and poor drainage can cause ratings as low as 0.05, whereas low natural fertility can not lower ratings to below 0.80, presumably because low fertility is much cheaper to correct than an excess of sodium salts or poor drainage.

The above equations suppose that all LCs have already been standardized to the common scale [0…1]; this can be accomplished by any appropriate transformation of variable, linear or not depending on the presumed nature of the yield response to the variable, from the original scale of measurement of the LC to the standardized scale used in these equations. The transformation must ensure that the least favorable LC value be assigned to the minimum standardized value, either 0 or the restricted minimum, and that the most favorable LC value be assigned to 1. The simplest transformations are linear, and correspond to a change of scale and origin only. Weights should be derived by an analysis of variance of yields or land values based on the standardized LCs to be used in the index. In practice, field-measured yield is often so variable that statistical methods give unacceptably large reliability. In this case, weights are assigned *ad hoc*, with the proviso that the weights must seem 'reasonable' to a representative group of land owners and applied agricultural scientists. In fact, the original Storie index was developed in exactly this way (Storie, 1933 p. 4).

Land suitability based on crop yield

The normalized (per unit land area) *yield* of an output (product) *Out* of a productive LUT can be considered as a direct indication of land suitability (Dumanski & Onofrei, 1989). In this case, equation (1) can be rephrased as:

$$yield_{LMU,(Out,LUT)} = f'_{(Out,LUT)}(\{LC\}_{LMU}) \qquad \textbf{(1')}$$

The subscript notation (*Out,LUT*) means that the product *Out* is defined within the context of a specific production system *LUT*. This is because the production function $f'_{(Out,LUT)}$ may have different parameters or even a different form for the same output produced with different technologies. Yield is expressed on a continuous scale, so that f' must be continuous, although not necessarily smooth. An example of (1') is an empirical-statistical relation, typically a multiple regression (Draper & Smith, 1981), which predicts yield from a set of LCs usually including climate and soil data. In general, these functions are functional and quantitative, according to the terminology of Hoosbeek & Bryant (1992).

There have been numerous attempts to predict crop yield from land data, dating back at least to the 1930s (Murray *et al.*, 1939; Simonson, 1938) and continuing to the present (De la Rosa *et al.*, 1981, Olson, 1986 #279). An example from land evaluation practice is the crop yield prediction module of MicroLEIS (De la Rosa *et al.*, 1992), which uses a multiple regression, developed by De la Rosa *et al.* (1981), from soil characteristics to yield.

Economic land evaluation

Equation (1') is not a complete economic land evaluation, because it does not account for varying costs of production in different map units; it is only the 'benefit' side of the cost vs. benefit calculation. The 'cost' side of this calculation can be expressed with an analogous equation for the cost *C* of implementing a land utilization type on a map unit:

$$C_{LMU,LUT} = f''_{LUT}(\{LC\}_{LMU}) \qquad \textbf{(1'')}$$

If more than one output is produced by the LUT, equation (1') must be applied to each output, and the predicted normalized yields must be summed over time if necessary (e.g. for rotations), and weighted by some measure of the value of the output, for example, its selling price net of production costs $value_{Out}$, possibly discounted to present value (Newman, 1991; Rossiter, 1995?). Weighting over space (e.g. for intercrops) is not necessary if the yields of equation (1') are already normalized to their spatial proportion. Land suitability *S* is then computed as:

$$S_{LMU,LUT} = \left[\sum_{LUT} yield_{LMU,(Out,LUT)} \cdot value_{Out} \cdot c_{Out,LUT}\right] - C_{LMU,LUT} \qquad \textbf{(5)}$$

where $c_{Out,LUT}$ is the *cropping factor*, i.e. the ratio of the number of crops produced to the number of years in the planning horizon, and $C_{LMU,LUT}$ is the cost as computed by equation (1").

Evaluation based on Land Qualities

In many applications of the FAO Framework, including ALES models, the *n* LCs $\{LC\}_{LMU}$ are aggregated into *m* Land Qualities $\{LQ\}_{LMU,\,LUT}$ specific to the Land Utilization Type, where usually $m << n$, before computing a final suitability. In this case, function *f* of equation (1) is decomposed into two functions f_1 and f_2:

$$S_{LMU,LUT} = f_{1_{LUT}}(\{LQ\}_{LMU,LUT}) \qquad \textbf{(6)}$$

$$LQ_{LMU,LUT} = f_{2_{(LUT,LUR)}}(\{LC\}_{LMU,LUR}), \quad \forall LQ \in \{LUR\}_{LUT} \qquad \textbf{(7)}$$

where $\{LUR\}_{LUT}$ is the set of Land Use Requirements defined for the LUT. For each of these, the value of a corresponding Land Quality is calculated; this is the so-called 'matching' of the FAO Framework. The notation $\{LC\}_{(LMU,LUR)}$ shows that the set of diagnostic LCs to be used when evaluating a specific LQ is defined as part of the specification of the corresponding LUR. In other words, each LQ is evaluated from its own set of *diagnostic LCs*. Note that some LCs may be diagnostic for more than one LQ.

The subscript notation (*LUT,LUR*) means that the Land Use Requirement *LUR* is defined within the context of a specific production system *LUT*, hence any function for evaluating the corresponding Land Quality is also LUT-specific. This is because the same conceptual land quality, e.g. moisture sufficiency, may be determined by a function $f_{2\,(LUT,LUR)}$ with different parameters or even a different form for different land use systems or crop species. The values of the Land Qualities can be *continuous* (as in a empirical-statistical relation) or *discrete* (as in the FAO Framework); the function $f_{2\,(LUT,LUR)}$ is accordingly continuous or not. The sets $\{LC\}$ and $\{LQ\}$ can be fuzzy, in which case the functions f_2 and f_1 are continuous classifications.

In an evaluation based on Land Qualities, land suitability *S* can be considered the result of a composite function:

$$S_{LUT,LMU} = f_{1_{LUT}} \circ \{ f_{2_{(LUT,LUR)}} \} \qquad \textbf{(8)}$$

In the FAO Framework, function f_1 of equation (6) is suggested to be the *maximum limitation* function MIN($\{LQ\}_{LMU,LUT}$), and the functions f_2 of equation (7) are also suggested to be maximum limitation functions MIN($\{LC\}_{LUR}$). For these functions to be meaningful, all LQs and the final suitability must be expressed as *commensurate* classes, ranging from 1 (best) to the same maximum class number (worst). These functions can be written as maximum-limitation *matching tables* as introduced by Beek (1978) and used in the Brazilian land evaluation system (Ramalho Filho *et al.*, 1978). In a maximum-limitation matching table, a LMU's LQ value (severity level) is determined by the most restrictive LC, and the overall suitability is determined by the most restrictive LQ. Data may be collected as continuous LCs that are then classified by the table. Or, the land resource inventory may already present its LCs in classes that are presumed to contain most of the within-LMU variation in the class range, in which case these classes are used to construct the table. Ad-hoc methods of combining LCs or LQs are also permissible in the Framework; these may be presented as footnotes or restrictive clauses in the matching tables. The land evaluation course developed by Sys and colleagues at the State University of Ghent (Sys, 1985; Sys *et al.*, 1993) is a good example of a land evaluation based on maximum-limitation matching tables.

The maximum-limitation method does not allow interactions between LQs, supposes that LQs act completely independently in their effect on physical suitability and yield, and requires that all LQs be measured on a commensurate scale. A more realistic and flexible approach is taken in ALES models, where *decision trees* can substitute for the MIN functions in the determination of LQ severity levels (equation (7)), yields (equation (6')), and overall suitability (equation (6)).

Land suitability based on crop yield; economic land evaluation

As in equation (1'), the predicted *yield* of an output of the LUT can be considered as a measure of suitability, and this yield can be computed from the set of Land Qualities:

$$yield_{LMU,(Out,LUT)} = f'_{1_{(Out,LUT)}}(\{LQ\}_{LMU,LUT}) \qquad \textbf{(6')}$$

resulting in the composite function, analogous to equation (8) :

$$yield_{LMU,(Out,LUT)} = f'_{1_{(Out,LUT)}} \circ \{ f_{2_{(LUT,LUR)}} \} \qquad \textbf{(8')}$$

where equation (7) defines f_2, as before. Function f_1' of equation (6') may be taken as the minimum of a set of *yield factors* on the interval [0…1], i.e. $f_1' \equiv$ MIN($\{yield\_factor_{LUR,LUT}\}_{LUT}$), multiplied by an *optimum yield* which depends on the output and LUT. This is analogous to the maximum-limitation method for physical land suitability. Again, a decision tree to combine the yield factors allows a more realistic accounting for interactions between LQs.

Although most empirical-statistical models of crop yield are realizations of equation (1'), predicting yield directly from LCs, some of these models may include sub-models of what can be termed Land Qualities, each estimated by a subsidiary empirical model that then is a realization of equations (7), from LCs to LQs. The resulting LQs are then combined to predict yield with an empirical equation that is a realization of equation (6'). For example, (Olson & Olson, 1985) combined rainfall and water storage capacity of the soil into a composite measure of what could be called the 'moisture sufficiency' Land Quality; this LQ rating was then combined with other factors to predict yield (Olson & Olson, 1986).

If there is more than one product of the LUT, the yields of the several products can be combined to determine the overall suitability using equation (5) as before. Equation (1") can also be rephrased to calculate costs of production based on Land Qualities:

$$C_{LMU,LUT} = f''_{1LUT}(\{LQ\}_{LMU,LUT}) \qquad \textbf{(6")}$$

where equation (7) defines f_2, as before. This formula allows additional costs to be assigned to the Land Quality factor levels, and also allows for costs not dependent on the specific LMU; these are constants in f''_1.

Suitability for one LUT depends on suitability for a different LUT

When evaluating the suitability of a Land Mapping Unit for a Land Utilization Type, it may be necessary to consider the suitability of the same LMU for a different LUT. For example, for a LMU to be considered suitable for forestry, it might be required that it *not* be suitable for arable farming, as well as intrinsically suitable for forestry. In general terms,

$$T_{LMU,LUT_y} = f(S_{LMU,LUT_y}, S_{LMU,\{LUT\}_{\neq y}}) \quad \textbf{(9)}$$

where T is the final suitability taking into consideration the suitabilities S for each LUT considered separately, LUT_y is the LUT of interest, and $\{LUT\}_{\neq y}$ is the set of other LUTs whose suitabilities must be known in order to compute a final suitability for LUT_y. A set of these equations can be solved in two steps: first determine the 'intrinsic' suitabilities (i.e. without considering suitability for the other LUTs) and then apply the inter-LUT set of rules, equation (9).

Hierarchy of Land Characteristics

Equations (1) and (7) require a set of Land Characteristics $\{LC\}_{LMU}$, implying that these are all original data values. In fact, a hierarchy of LCs may be defined in which some of the members of $\{LC\}_{LMU}$ used to determine suitability are derived from a set of more 'primitive' LCs. This set of measured or estimated LCs may also be termed 'specific'; from these, the set of 'general' LCs may be inferred. These 'general' LCs could in principle be measured (which is why they are called Land Characteristics instead of Land Qualities), but it is more convenient or cost-effective to infer them from the more readily available data of 'specific' LCs. So an element LC_i of the set $\{LC\}_{LMU}$ of equation (1) may be inferred from another set of LCs:

$$LC_{i_{LMU}} = f_{LC_i}(\{LC\}_{LMU,LC_i}) \quad \textbf{(10)}$$

This relation may be applied recursively, thereby defining a hierarchy of LCs or even a directed acyclic graph (Tarjan, 1983 p. 14). These functions f_{LC} may be discrete (e.g. expressed as decision trees) or continuous (e.g. expressed as algebraic functions). They have been termed *pedotransfer functions* when applied to soils data (Bouma, 1989). The classic example is the derivation of 'general' LCs relating to soil-water, e.g. unsaturated hydraulic conductivity and water content at different moisture tensions, from 'specific' LCs measured in routine soil survey, such as particle-size distribution, bulk density and organic matter content (Kern, 1995; Ritchie & Crum, 1989; Vereecken *et al.*, 1989).

Case 2: Dynamic resource base, static land suitability

In this case, the resource base has an explicit temporal component, although there is still only one measure of suitability for each LUT, so that suitability is not allowed to vary over the time frame of the evaluation. There is only one time scale, namely, that of the resource base. Time is usually expressed in discrete steps, such as years or months, so we may define the time vector $\boldsymbol{t} = (t_0, t_1, \ldots t_q)$. This allows the resource base to change over time, either cyclically (e.g. seasonally) or not (e.g. according a trend). The

LCs are considered as a two-dimensional matrix of LC values (the column vectors) over time (the row vectors):

$$\begin{aligned}\mathbf{R} = \{LC(t)\} &= (\overline{LC_0}, \overline{LC_1}, \ldots, \overline{LC_n})^{\mathrm{T}} \\ &= (\overline{LC(0)}^{\mathrm{T}}, \overline{LC(1)}^{\mathrm{T}}, \ldots, \overline{LC(q)}^{\mathrm{T}}) \\ &= \begin{bmatrix} LC_0(0) & LC_0(1) & \cdots & LC_0(q) \\ LC_1(0) & LC_1(1) & \cdots & LC_1(q) \\ \vdots & \vdots & \ddots & \vdots \\ LC_n(0) & LC_n(1) & \cdots & LC_n(q) \end{bmatrix}\end{aligned} \quad \textbf{(11)}$$

Since {*LC*} has been replaced by {*LC(t)*}, equations (1) and (6) - (8) must be revised to an explicitly temporal form.

The set of LCs can include some static characteristics along with the time-series, in which case the appropriate parts of time-dependent equations reduce to their time-independent forms. This is the degenerate case where $LC(t) = LC(0)$ for all t, i.e., the LC value doesn't change during the time frame of the evaluation.

Evaluation based on Land Characteristics

If the analysis proceeds directly from a time-series of LC values to land suitability, we obtain the following time-dependent version of equation (1):

$$S_{LMU,LUT} = f_{LUT}(\{LC(t)\}_{LMU}) \quad \textbf{(12)}$$

or, using yield as a direct measure of land suitability as in equation (1'):

$$yield_{LMU,(Out,LUT)} = f'_{(Out,LUT)}(\{LC(t)\}_{LMU}) \quad \textbf{(12')}$$

This is the general procedure in dynamic simulation models of the atmosphere-plant-soil-land use system which predict crop yields, such as WOFOST (van Diepen *et al.*, 1989), CERES (Jones & Kiniry, 1986) and SOYGRO (Wilkerson *et al.*, 1983), and GAPS (Riha *et al.*, 1994). There is a time-series of input data but only one yield per cropping season.

Dynamic simulation models can be classified as mechanistic quantitative models of yield, according to the terminology of Hoosbeek & Bryant (1992). Compared to empirical-statistical models, they usually have a more mechanistic representation of processes at the *i* or lower levels. This often results in a mis-match between land data, provided at the *i* or *i*+1 level by routine survey, and the parameter requirements of the model. One solution is collect data in more detail than normal, but this is not practical for most land evaluations. In these cases, pedotransfer functions can be used to estimate the lower-level model parameters from more easily-available data.

These models also require data at a finer temporal resolution than may be available in routine survey. For example, hourly weather data may be required, but most stations may only provide daily data. One solution is to synthesize data at finer temporal or spatial scales than the available data, by extrapolating from more detailed studies on a subsample, for example by time-series modeling (Salas, 1992).

In some dynamic simulation models, accurate yield estimates were not the primary design objective. These models may instead be optimized for insight into the physical processes affecting crop production and land use, as well as tactical decisions regarding management options, such as the best varieties, row spacing, planting and pest-control dates etc. for a given production situation. They should be used with caution for yield prediction.

Dynamic simulation models use Land Characteristics as *driving* variables, if these LCs are measured over time and are provided as external data to the model; an example is daily precipitation. Note that *weather* variables (time-series) are used by dynamic models, instead of the *climate* variables (summary statistics derived from weather variables) used by empirical-statistical models. LCs measured once and provided as external data to the dynamic simulation model are called model *parameters*; an example is the particle-size distribution of a soil profile. These models also use a set of dynamic *state* variables, internal to the model and not measured (except perhaps to calibrate the model), at the same level of detail as LCs; an example is the daily volumetric moisture content of the soil profile. State variables do not appear explicitly in equations (12) and (12'), although they are part of the definition of the functions of these equations.

Evaluation based on Land Qualities

In land evaluations using dynamic simulation models of individual land qualities, functions (12) and (12') may be decomposed into two functions, resulting in the following modifications of equations (6), (7) and (6'):

$$S_{LMU,LUT} = f_{1_{LUT}}(\{LQ(t)\}_{LMU,LUT}) \quad \textbf{(13)}$$

$$LQ(t)_{LMU,LUT} = f_{2_{(LUT,LUR)}}(\{LC(t)\}_{LMU,LUR}), \quad \forall LQ \in \{LUR\}_{LUT} \quad \textbf{(14)}$$

$$yield_{LMU,(Out,LUT)} = f'_{1_{(Out,LUT)}}(\{LQ(t)\}_{LMU,LUT}) \quad \textbf{(13')}$$

The Land Qualities are time-dependent, exactly as the LCs from which they are inferred. They can be considered as row or column vectors or a two-dimensional matrix with the same form as (11), since they depend on time-series of Land Characteristics. However, the overall suitability or yield is still static, having one value for the entire analysis. For example, the LQ 'moisture sufficiency' could be computed each day from a time-series of rainfall, solar radiation, etc., and then this derived time-series could be used in a dynamic simulation model of crop yield. This is not a common approach in land evaluation.

The more common approach to a LQ-based land evaluation with dynamic simulation is to already derive static Land Qualities from the time-series of Land Characteristics. Equation (14) is replaced by:

$$LQ_{LMU,LUT} = f_{2_{(LUR,LUT)}}(\{LC(t)\}_{LMU,LUT}) \quad \textbf{(15)}$$

in which case equations (6) and (6’), instead of equations (13) and (13’), are used to determine land suitability and yield. For example, the LQ ‘moisture sufficiency’ could be computed as a single rating such as total water stress by a dynamic water-balance model from the entire time-series of rainfall, solar radiation etc., and then be used directly to predict yield in an empirical-statistical relation. An example of a realization of equation (15) is the pesticide leaching model LEACHM (Hutson & Wagenet, 1991; 1992). Dynamic simulation models have also been developed to predict LQs such as risk of nitrate leaching (Hack-ten Broeke *et al.*, 1993), risk of erosion by water (Nearing *et al.*, 1994), and fertilizer requirement (Smaling, 1993). The assessment of individual LQs can be a useful product of a land evaluation exercise, with or without their subsequent combination into overall suitability by equations(6) or (13).

Case 3: Dynamic resource base, dynamic land suitability

In this case, we accept that land suitability may change over time, and that a time-series of suitabilities or yields is more informative than a single value. The time-step on which yields and suitability are measured may be the same as that of the LCs, or it may be longer, e.g. a series of annual yields may be computed from daily weather data. To show this, another symbol for time must be introduced, namely $\boldsymbol{u} = (u_0, u_1, \ldots u_p)$, to represent the time vector for suitability (usually years or growing seasons). We continue to use the symbol $\boldsymbol{t} = (t_0, t_1, \ldots t_q)$ for the time vector on which LCs are measured (usually months, ten-day intervals, days, or hours).

There are two possible relations between the time scales. In the first, $u >> t$, or, considering the number of time periods, $p << q$. For example, if suitability is computed yearly but land data is measured daily, $u = 365 \cdot t$ and $p = q/365$. In the second, $u = t$ (equivalently, $p = q$) so that both land data and suitability are expressed on the same time scale. For example, each year’s average rainfall could be used to predict each year’s yield. In land evaluation, it is almost always the case that p divides q evenly (discounting minor discrepancies such as leap years); thus we can compute the number of shorter time series into which the longer time series is divided as $n = q/p$.

Evaluation based on Land Characteristics

Going directly from LCs to land suitability, the fully time-dependent version of equation (1) can be expressed as:

$$S(u)_{LMU,LUT} = f_{LUT}(\{LC(t)\}_{LMU}) \quad \textbf{(16)}$$

or, using yield as a direct measure of land suitability as in equation (1’):

$$yield(u)_{LMU,(Out,LUT)} = f'_{(Out,LUT)}(\{LC(t)\}_{LMU}) \quad \textbf{(16')}$$

Equation (16’) can be realized as an empirical-statistical model from a time-series of LC data, to arrive at a time-series of predicted yields. The temporal resolution of both time-series are the same, i.e. $u = t$. A dynamic simulation model can be another realization of equation (16’), but in this case, $u >> t$, so that the temporal resolution of the data (e.g. daily or monthly) is higher than that of the yield (e.g. yearly).

Evaluation based on Land Qualities

In land evaluation procedures based on individual land qualities, these functions must be decomposed into two parts. The extensions of equations (6), (7) and (6') are:

$$S(u)_{LMU,LUT} = f_{1_{LUT}}(\{LQ(t)\}_{LMU,LUT}) \quad \textbf{(17)}$$

$$LQ(t)_{LMU,LUT} = f_{2_{(LUT,LUR)}}(\{LC(t)\}_{LMU,LUR}) \quad \textbf{(18)}$$

$$yield(u)_{LMU,(Out,LUT)} = f'_{1_{(Out,LUT)}}(\{LQ(t)\}_{LMU,LUT}) \quad \textbf{(17')}$$

In this formulation, the LQs are expressed on the same time scale as the LCs.

Another approach for the case when $u >> t$ is to already derive Land Qualities that have the same time-resolution as land suitability from the time-series of Land Characteristics, and then combine these to arrive at land suitability for each time step $u \in [0 \ldots p\text{-}1]$:

$$LQ(u)_{LMU,LUT} = f_{2_{(LQ,LUT)}}(\{LC(t)\}_{LMU,LUR}), \quad t = t_{u_0} \ldots t_{u_{n-1}} \quad \textbf{(19)}$$

$$S(u)_{LMU,LUT} = f_{1_{LUT}}(\{LQ(u)\}_{LMU,LUT}) \quad \textbf{(20)}$$

$$yield(u)_{LMU,(Out,LUT)} = f'_{1_{(Out,LUT)}}(\{LQ(u)\}_{LMU,LUT}), \quad t = t_{u_0} \ldots t_{u_{n-1}} \quad \textbf{(19')}$$

where the finer time series $\boldsymbol{t} = (t_0, t_1, \ldots t_q)$ is divided into n shorter time series according to the coarser time series $\boldsymbol{u} = (u_0, u_1, \ldots u_p)$, so that to each u corresponds the shorter time series $t_{u_0} \ldots t_{u_{n-1}}$. For example, the LQ 'moisture sufficiency' could be computed as a single rating, from a time-series of weather data for each season, and then be used to predict yield in a statistical relation, for each season in turn.

Feedback

Dynamic simulation models usually contain feedback relations implicit in their function set, and this feedback may result in measurable changes in Land Characteristics. Feedback can be directly from the LCs, from LQs, from suitability, or from the yield of one or more products of the LUT:

$$LC(t+1)_{LMU} = h_{LUT}\ (\{LC(t)\}_{LMU}) \quad \textbf{(21)}$$

$$LC(t+1)_{LMU} = h_{LUT}\ (\{LQ(t)\}_{LMU,LUT}) \quad \textbf{(22)}$$

$$LC(t+1)_{LMU} = h_{LUT}\ (\{S(t)\}_{LMU,LUT}) \quad \textbf{(23)}$$

$$LC(t+1)_{LMU} = h'_{LUT}\ (\{yield_{Out}(t)\}_{LMU,LUT}) \quad \textbf{(23')}$$

The analysis of these relations is beyond the scope of this paper.

Time-series analysis of land suitability

Finally, the land evaluator may consider the entire time-series of land suitabilities *S(u)* or of predicted yields *yield(u)*, in order to compute a single measure of land suitability *S* for the entire time period of the evaluation:

$$S_{LMU,LUT} = g_{LUT}(\{S(u)\}_{LMU,LUT}) \qquad \textbf{(24)}$$

$$S_{LMU,LUT} = g'_{LUT}(\{yield(u)\}_{LMU,(Out,LUT)}) \qquad \textbf{(24')}$$

Some realizations of the functions *g* and *g'* do not depend on the time order of the individual values in the time-series; examples are the sum, mean, mode, percentile, minimum, maximum, as well as the *utility* expressed as a combination of the mean and variance (Hazell, 1986). For example, it could be required that yield be above a certain threshold for a specified proportion of years in the time-series, in order for land to be rated 'high suitable' for the land use.

Other realizations of the functions *g* and *g'* do depend on the time order; examples include any metric based on a predicted cash flow discounted over time, such as the internal rate of return (Newman, 1991; Rossiter, 1995?). Any meaningful statistic of the time-series can be used as a measure of land suitability, for example its duration above a certain threshold, and even characteristics of its power spectrum (Shumway, 1988) such as periodicities.

Part 2 : Spatial models of single-area land suitability

This second Part considers the situation when the suitability of a land area for a land use depends on its spatial location, i.e. its actual position on the earth's surface, which is related to any other position of interest by the earth's geometry. I refer to the framework of Tomlin (1990), which classifies spatial models in terms of the GIS operations required to implement them. Operations are either (1) *local*: "compute a new value for each location as a function of existing data explicitly associated with that location" (p. 64), i.e. no inter-cell effects; (2) *focal*: "compute a new value for each location as a function of its neighborhood" (p. 96), where a neighborhood is defined as "any set of locations that bear a specified distance and/or directional relationship to a particular location" (p. 96); or (3) *zonal*: "compute a new value for each location as a function of values associated with a zone containing the location" (p. 154), where these 'zones' correspond to legend categories of a thematic map. The 'values' of these definitions include severity levels and land suitabilities.

A single Land Characteristic may be described over two-dimensional space by an $(a \times b)$-dimension matrix of LC values:

$$[LC] = \begin{bmatrix} LC(0,0) & LC(1,0) & \cdots & LC(a-1,0) \\ LC(0,1) & LC(1,1) & \cdots & LC(a-1,1) \\ \vdots & \vdots & \ddots & \vdots \\ LC(0,b-1) & LC(1,b-1) & \cdots & LC(a-1,b-1) \end{bmatrix} \qquad \textbf{(25)}$$

This matrix represents space as a regular grid of *cells*, as in a grid-based GIS, so that the relation between areas (here, cells) is implicit in the grid structure, as is the distance between any two areas. In the case of a general division of space into irregular polygons, the *topology* of the polygon network must be made explicit using topological data structures from vector GIS (Burrough, 1986 p. 28-29), so that the matrix (25) is replaced by a polygon tesselation of the study area. In both representations the spatial structure of [*LC*] is referred to as a *thematic map*. Several thematic maps of single LCs cover the same area with the same cell resolution or polygon structure (or they can be so registered by GIS techniques), so that there is a third dimension to the data matrix, namely the data variable or LC, so that $\mathbf{R} = \{[LC]\}$. Land Qualities and land suitability can also be represented spatially as thematic maps, designated $[LQ]_{LUT}$ and $[S]_{LUT}$ respectively, with the same spatial structure as [LC].

Case 1: No inter-cell effects

If there are no inter-cell effects, a spatially-explicit land evaluation model is simply a matrix of suitabilities, each computed from an equivalent matrix of Land Characteristic data at that point, as in Part 1. The grid or polygon network is re-classified according to the suitability of each cell or polygon taken separately (e.g. using Tomlin's *local* operations), so there is no spatial analysis *per se*, only a spatial representation of each LC and the derived LQs, yields, and suitabilities. The analysis of Part 1 can be applied to each legend category of a natural resource inventory (the thematic source map) rather than to individual grid cells or polygon, since there are no LCs that depend on location. The GIS is only used to spatially represent the LCs for each cell or polygon as a thematic map, and present the results of the evaluation as a derived thematic map.

Case 2: Static inter-cell effects

If land suitability or a land quality of one land area is influenced by Land Characteristics of other land areas, but these effects are static, i.e. do not change over time, instead of considering a one-dimensional vector of static land characteristics at a point, a three-dimensional matrix of LC values {[LC]} over two-dimensional space, as in equation (25), must be considered. The first two dimensions are space and the third is the LC name These maps can be combined to calculate *static locational* LCs, i.e. those that depend on an area's actual location, and whose values do not change during the time frame of the evaluation. So, these LCs can be computed once at the beginning of the evaluation. Examples of static locational LCs are distance from a point (e.g. market), line or chain (e.g. nearest stream), or area (e.g. a protected zone), if these geographic features do not move or change size during the evaluation. These correspond to Tomlin's *focal* or *zonal* operations. If any locational LCs are considered, the analysis of Part 1 must be applied to each location (grid cell) or delineation (polygon) separately rather than as part of a legend category, since the set {[*LC*]} now has some LCs (the locational ones) with different values, even if they are from the same legend category of a natural resource inventory.

GIS-based land evaluation divides the land area to be evaluated into 'homogeneous' cells or polygons, and perform a separate land evaluation on each of these, independent of the others, after an initial step during which static location-dependent LCs such as distance are computed. A typical example is presented by Burrough (1986, pp. 93-100). This kind of *cartographic modeling* can be quite sophisticated, including, for example, topography, distance, and friction surfaces, but the analysis is still at each point considered separately.

Another example of a static inter-cell effect is when an evaluation unit must have a minimum or maximum area. In this case, the area of contiguous cells or polygons with the same suitability value is calculated by the GIS and the appropriate rule applied.

Case 3 : Dynamic inter-cell effects

In the dynamic case, the matrix of (25) is extended in the time dimension, so that there are a series of maps of the same theme over time:

$$[LC(t)] = ([LC(0)],[LC(1)],\ldots,[LC(q)])^{\mathrm{T}} \qquad \textbf{(26)}$$

The matrices $[LQ(t)]_{LUT}$ and $[S(t)]_{LUT}$ are defined analogously. In this case, there may be an inter-relation between suitability or LQ values over the map, and this relation may change over time. This is the spatially-explicit analog of Case 3 ('Dynamic resource base, dynamic suitability') of Part 1.

Sklar & Constanza (1990) define a *dynamic spatial model* as describing changes in a spatial pattern $\mathbf{X_t}$ (typically a regular grid of cells) over time as a function of an earlier time step's spatial pattern $\mathbf{X_{t-m}}$, and some set of variables $\mathbf{Y_{t-m}}$, also indexed by the time step, which determine the transition:

$$\mathbf{X}_t = f(\mathbf{X}_{t-m}, \mathbf{Y}_{t-m}) \qquad \textbf{(27)}$$

Y can be a matrix (typically a regular grid with the same dimension as **X**), a vector with only one spatial dimension (e.g. the location of a one-dimensional sink or source such as a river), a point, or a non-spatial scalar. The number of time steps *m* can be any positive integer, thereby introducing higher-order processes with a time lag between cause and effect. In land evaluation terms, $\mathbf{X}_t$ is a time-dependent matrix of Land Characteristics $\mathbf{LC}_t = [LC(t)]$ which can be combined according to the analysis in Parts 1 or 2 to determine a matrix of land suitabilities $\mathbf{S}_t = [S(t)]_{LUT}$ which in turn affect the Land Characteristics in the next time step, $\mathbf{LC}_{t+1}$. An example of this kind of model is of suburban expansion as affected by suitability for agriculture and suburban development; the suitabilities for these land uses are greatly affected by the current land-use pattern, which evolves through time in response to the suitabilities for the land uses as well as external factors such as development pressure.

A time-dependent matrix of Land Qualities $\mathbf{LQ}_t = [LQ(t)]_{LUT}$ can be an intermediate or final result of the analysis. For example, hydrologists have used dynamic spatial models to predict Land Qualities such as non-point source pollution over space and time (DeVries & Hromadka, 1992).

Case 4 : Suitability for a LUT depends on several contrasting LMUs

Some LUTs require a combination of activities, each of which has different Land Use Requirements. For example, a LUT of extensive grazing in a tropical area with a single rainy season may require some land that is dry all year (e.g. a levee) and which will produce pasture during the rainy season, and some that is seasonally flooded, that will produce pasture during the dry season, after floodwaters have receded. Both types of land are necessary for the success of the LUT, which is defined to include the movement of animals between the two areas according to the season.

To analyze this case, the LUT must be defined as a *compound* LUT, with several *homogeneous* (or, simple) constituent LUTs. Furthermore, the evaluation unit (the potentially-suitable land area) must be defined as a compound LMU, with several constituent LMUs. The general formulation is:

$$S_{cLUT,cLMU} = f_{cLUT}(\{S_{hLUT_i,hLMU_j}\}) \quad \textbf{(28)}$$

where *cLMU* is the compound LMU made up of a set of homogeneous constituents $\{hLMU_j\}$, $j = 1 \ldots n$, and *cLUT* is the compound LUT made up of a set of constituents $\{hLUT_i\}$, $i = 1 \ldots m$.

To evaluate suitability in this situation, each homogeneous LMU is evaluated separately for each homogeneous component of the compound LUT, resulting in one thematic map of suitability for each of the *m* homogeneous LUTs. Then, spatial analysis is used on the set of thematic maps to see if locational and size requirements are met for any of the compound LMUs. In the example, each homogeneous LMU is evaluated for its suitability for both dry and wet season grazing (i.e. the two homogeneous LUTs), and then these two maps are combined to find a compound LMU made up of homogeneous LMUs with the right proportion, area, proximity, and adjacency requirements for the compound LUT 'extensive grazing with migration'.

Case 5 : Interdependent suitability

In evaluating the suitability of a Land Mapping Units for a Land Utilization Type, it may be necessary to consider the suitability of 'nearby' LMUs for a different LUT. For example, one of the LURs for a 'biodiversity reserve' LUT might be that no adjacent management unit be highly suitable for agriculture, thereby lowering the risk of encroachment. In general terms,

$$T_{LMU_x,LUT_y} = f(S_{LMU_x,LUT_y}, S_{\{LMU\}_{\neq x},\{LUT\}_{\neq y}}) \quad \textbf{(29)}$$

where T is the final suitability taking into consideration the per-area suitabilities S; LMU_x is the map unit of interest, $\{LMU\}_{\neq x}$ is the set of other map units whose suitability must be considered, $\{LUT\}_y$ is the Land Utilization Type being evaluated, and $\{LUT\}_{\neq y}$ is the set of LUTs whose per-area suitability must be known. In general, this analysis requires simultaneous land evaluation of the interdependent LUTs, by iterative techniques, because the set of relations $\{T\}$ will form a directed graph which may have cycles. As with any set of simultaneous equations, there may be no solution or several solutions.

Part 3 : Models of multi-area suitability and the land allocation problem

In evaluating a set of LMUs that are to be planned together, for example, fields managed as part of the same farm or management parcels of a national park, there are often *global constraints* on the land use that apply to entire production or planning unit. Examples include a maximum or minimum land area to be allocated to each LUT, maximum or minimum production levels of each output, and a limited supply of labor, capital, or inputs. There may be one overall goal, e.g. to maximize economic return over the entire project, or, more typically, multiple goals corresponding to the different land users or to a variety of societal objectives.

Global constraints are modeled by a *constrained optimization* model, which may be linear or non-linear, whose technical coefficients are the predicted yields, input levels, capital requirements etc. as predicted by single-LUT land evaluation models. There are well-developed techniques for this class of models, e.g. (Dykstra, 1984; Hazell, 1986). They require *technical coefficients*, which are the predicted yields and input levels per unit area for each LMU; these coefficients are provided by land evaluation models. A complication in land allocation is that each LMU is generally to be assigned to exactly one LUT, leading to an *integer program*; these often do not have feasible solutions. In the case of multiple goals, the techniques of multiple criteria analysis (Janssen, 1992; Romero & Rehman, 1989) must be used.

These techniques are beyond land evaluation *per se*. Rather, they attempt to solve the general land-allocation problem for land-use planning, either for the individual land manager (e.g. farmer, park manager) or society (e.g. a planning authority). The relation to land evaluation is that the technical coefficients for land allocation models should be provided by land evaluation models which predict land performance and hence suitability for each use on each land area.

An example of a land allocation methodology is LUPIS (Ivie & Cocks, 1988), which uses a generalized least-upper-bound algorithm (Anderssen *et al.*, 1983) to solve an integer program. LUPIS attempts to allocate land units to land uses so as to satisfy a set of global objectives and constraints. The land evaluator specifies a set of adjacency requirements in the form of equation (29) as well as global goals for minimum and maximum land areas to be allocated to each use.

Conclusions

This paper presents a classification of land evaluation models according to eight more-or-less independent axes (the number of classes or continuous range is in parentheses):

1. Spatial vs. non-spatial analysis (2);
2. Static vs. dynamic concept of the resource base (2);
3. Static vs. dynamic concept of land suitability (2);
4. Evaluation based on Land Qualities or not (2);

5. Suitability expressed by physical constraints to land use, yields, or economic value (6);
6. Homogeneous vs. compound Land Utilization Type (2);
7. Spatial scale & minimum decision area (continuous: small to large scale);
8. Single-area vs. multi-area suitability (2).

Of course, some combinations are not meaningful. For example, it is impossible to have a dynamic concept of land suitability without also having a dynamic concept of the resource base. In the case where there is a dynamic concept of both the resource base and land suitability, we must also specify whether the time scales of the two concepts are the same.

With these axes we can intersect Hoosbeek & Bryant's (1992) classification of models according to their:

9. Degree of computation (continuous: qualitative to quantitative);
10. Descriptive complexity (continuous: empirical to mechanistic);
11. Level in the organizational hierarchy (continuous: molecular to continental).

For example, the Papua New Guinea Land Evaluation System (PNGLES) (Venema & Daink, 1992) could be classified as: (1) non-spatial; (2) static resource base; (3) static land suitability; (4) based on Land Qualities; (5) suitability expressed by physical constraints to land use; (6) homogeneous LUTs; (7) scale 1:500 000 but MDA = 0.2 to 20ha depending on LUT, (8) single-area suitability; (9) semi-quantitative; (10) empirical; (11) organizational level $i+1$ (soil polypedon or land facet) to $i+2$ (soil landscape or land system).

By this point in the paper, it should be clear that there is no single land evaluation modeling approach. The choice of technique affects the reliability and scope of application of the land evaluation, in particular, the types of predictions which can be made. The generality of objectives, the scale at which land data are available or can be acquired, the type of knowledge about land - land use relations, the minimum decision area, the desired precision of the evaluation results, and the temporal and spatial dynamics of the Land Utilization Types, all must be considered when selecting a land evaluation procedure.

A fundamental challenge facing land evaluation is to prove its relevance to the many pressing land-use problems of our day. Predictions of land performance, no matter how soundly based, are only useful if they will be used by decision makers, including individual land users, groups, or governments, to make better land-use decisions. We should take a step back, away from the question 'What predictions can we make with the data we have?', i.e. a data-driven approach, to the question 'Who are the decision makers who actually affect land use, how are they making their decisions, and how could their decisions be better informed?', i.e. a demand-driven approach. Land evaluators should also accept that not only professional land-use planners have relevant questions, and that not only soil scientists and agronomists have relevant knowledge.

Finally, we must make every effort to respect our clients and other stakeholders in the land-use planning decisions that will be made as the result of land evaluation. This respect includes being clear about what the predictions of land evaluation really mean, how we came to make these predictions, and the certainty with which we make them.

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Discussion

by**:** Professor **J. Bouma,** Professor **P.A. Burrough,** Dr **J.J. de Gruijter,** Professor **E. Van Ranst,** Dr **A.K.L. Johnson, &** Professor **A.B. McBratney**

with a **reply** by the **Author**

Professor J. Bouma

Department of Soil Science & Geology, Postbus 37, Agricultural University, 6700 AA Wageningen The Netherlands

David Rossiter has presented a systematic theoretical framework in which many studies on land evaluation, particularly the more classical ones, may fit. His distinction in three parts covering non-spatial and spatial models of single area land suitability and spatial models of multi-area suitability is theoretically quite interesting but leads to a complex text in which the consistent separate consideration of land characteristics and land qualities in Section 1 becomes rather tedious. Section 3, covering multi-area suitability and the land allocation problem is most appropriate considering modern land-use questions, at least the ones with which I am confronted. As the text progresses, fewer case studies are presented and I have a nagging feeling that perhaps too much attention is being paid to concepts that have had a useful function in the past but need updating, the more so since we have experienced a revolution in information sciences since the time that the original framework for land evaluation was presented some twenty years ago. In addition, our clients have changed, simulation models and expert systems have been developed, and we have learned that yield alone is certainly not a measure for "suitability", but that the soil **system** should function harmoniously in wider agro-ecosystems to have a fair chance of being sustainable. And what about the term "suitability" in this context? In my experience, there is an increasing number of users who are not primarily interested in our judgement about suitabilities of a piece of land for a given Land Use System (LUS). Rather, they want us to give them different realistic options for land use for a given piece of land, with proper technical coefficients. They are increasingly inclined to make selections themselves whether they are farmers or planners. Still, many applications call for judgements by land evaluators and the schemes provided in Sections 1 and 2 may then constitute a useful framework.

As Rossiter points out, land evaluation has traditionally been "pedocentric". In future, developments in land evaluation in my opinion are likely to follow the broader trends of Section 3 of Rossiter's paper. The issue then becomes how soil scientists can be most effective in interdisciplinary projects dealing with the use of land, including its allocation. I would agree that land allocation, as such, is not part of land evaluation and that our focus should be on providing technical coefficients to be obtained by comprehensive land evaluation models or expert systems. A recent land-use study in Costa Rica illustrates this approach and the specific input of soil scientists in an interdisciplinary team, including agronomists and economists (Bouma et al., l995). This input has two aspects:

(1) Running land evaluation models for pedons focussing on flow phenomena, solute transport and plant growth in field soils with highly "non-ideal" behaviour, while:

(2) interpolation techniques are used to obtain stochastic data for areas of land following geographic stratifications based on landscape analysis.

Here, pedotransfer functions are important to transform land characteristics into model parameters. Models can be used to estimate single land qualities, but increasingly many land qualities will have to be determined and some compromise has to be found in balancing contrasting demands between production, effects on soil and water quality and on surrounding nature areas. In fact, dynamic simulation of interrelated physical, chemical and biological processes in the entire system using different land-use scenarios is likely to take the place of considering separate land qualities in isolation. This is useful also because widespread use of the term "**soil** quality" (with a quite different meaning from land quality) is causing considerable confusion. I should like to work towards expressions which define the behaviour of a given soil type as a function of a wide range of LUS, thereby creating "windows of opportunity" which are characteristically different for each soil type (Bouma, l994). For me, Rossiter's still-skeletal Section 3 is most relevant for the future and much work is still needed to flesh out the details. But by scientifically defining steps 1 and 2 as a logical introduction to step 3, Rossiter has convincingly demonstrated that discussions about the future can best be based on a solid understanding of the past. He deserves credit for his effort.

Professor P.A. Burrough

Department of Physical Geography, University of Utrecht, Postbus 80115, 3508 TC Utrecht, The Netherlands

David Rossiter's paper is a brave attempt to bring a unified view to the widely varying practices of qualitative and quantitative physical land evaluation. He explores a wide range of approaches, varying from the simple-minded static, prescriptive approach to modern methods using quantitative yield models or quantitative models of site-environment interactions.

In most, if not all of his approaches, Rossiter follows the familiar top-down approach to land evaluation, and he explains this in detail in the introduction to the paper. The direction of reasoning is always from resource base to land utilization, which is fine in situations where there is much land, and the market is unconstrained so that farmers have a broad choice. This uni-directional approach is also followed even when the resource base, and hence the suitability, is supposed to change over time. As he points out (and he cites my own work and others), this kind of approach is easy to use with geographical information systems because these kinds of top-down modelling are what they do well.

As Rossiter points out in a recent paper in Soil Use and Management (Rossiter, 1995), the top-down physical approach is not the only way to conduct land evaluation, and in that paper he describes many alternatives, which in a modern world may be more important than a purely physical approach. Of course, physical resources of soil, water, nutrients and energy must be sufficient, otherwise plants will not grow, but the limiting factors in any given situation may not always be determined simply by natural site factors.

In parts of the world where farming is intense, land evaluation may have a different aim than in lands where the aim is to increase food production to match growing populations. For example, for economic, social or even political reasons, there may be a need to grow a given crop. The land evaluation reasoning is not then to ask "Where can this crop be grown?" for the answer to that question is known already. The answer may lie more in trade-offs between transport costs, environmental penalties for disposing of wastes (e.g. animal slurries) and the costs of suppressing disease. Such an analysis will use geographical data, but it will not be a top-down analysis but one that works more from the bottom up.

A corollary to the foregoing example is that if there are too few naturally endowed sites available then suitable growing conditions will be created by modification of the natural physical resources by draining, fertilizing, irrigating, use of greenhouses and hydroponics, and finally by the genetic engineering of suitable cultivars. This list of site modifications deliberately ranges from those that require modest extra inputs to those that are very expensive: as the expense increases, so the physical resource base becomes less important in relation to other factors such as distance to markets, infrastructure, skilled labour and organization. These factors also have a strong geographical component and the optimization of location is a non-trivial, and certainly non-linear problem that cannot be solved by simple top-down decision trees.

Other aspects of land evaluation concern social habits and prejudices. The pastoral industry in Australia persists because of historical factors - the production of cattle and sheep is only economic because huge areas of land can be devoted to their husbandry. In Mexico, almost all peasant farmers grow maize, not because the FAO Land Evaluation System says that their lands are good for that crop, but because their culture requires it – any maize is better than none (Corbett, 1995).

Rossiter's paper proposes a unified theoretical framework for land evaluation models; it is a valiant attempt, but in my opinion he has not achieved that holy grail, but rather a catalogue of what is currently possible. As he himself concludes, "t*here is no single approach*", which I read as "there is no unified theoretical framework", or at least, not yet. In order to achieve better unification we need to look more at the interactions between how the various tools for land evaluation can be used in different circumstances, and how physical, economic and social factors must be combined, as perhaps is done by marketing analysts on where best to locate a superstore or a fast-food outlet. The cost-effectiveness of different approaches needs to be considered. Of all the different approaches that Rossiter cites, each has different data needs and different qualities of prediction. We do not yet have rules that tell us when any given approach is adequate, or when we need to proceed to a more complex level of analysis, though surely these are questions that should concern all those involved in land evaluation and environmental prediction (cf. Burrough, 1992).

Dr J.J. de Gruijter

The Winand Staring Centre for Integrated Land, Soil and Water Research, Postbus 125, 6700 AC Wageningen, The Netherlands

I should like to congratulate David Rossiter on his paper. He has made an admirable attempt to develop a theoretical framework for land evaluation, which I regard as an essential step towards a general theory of land evaluation. I have two reasons for evaluating Rossiter's paper as 'suitable'.

First, as Rossiter points out, a useful theoretical framework for land evaluation has not previously existed, but is urgently needed. For pedology as a science and a profession it seems to me of great importance to be able not only to convey information to those who are involved in land-use issues, but also to do that in a scientific way. This requires at least :

(a) a set of concepts relevant to land evaluation, and

(b) a set of rules on how to apply these concepts in actual land evaluation studies.

Both the concepts and the rules should be clearly defined, able to be explained to users of land evaluation results, logically consistent and of proven utility. Also, there should be no more or less of them than needed. Clearly, this goes well beyond the collection of case-specific evaluation schemes and *ad hoc* procedures of data manipulation, which largely constitutes the practice of land evaluation to date. Any serious attempt to improve this situation deserves to be welcomed and supported by the soil science community.

Second, the results from Rossiter's attempt are in my view good enough. Not as the final answer, but as a useful starting point for further development. Fortunately this journal now offers the communication form of discussion papers (for which it deserves applause), and rightly chose that form for Rossiter's contribution. So my comments below are given in the spirit of constructive debate. Broadly speaking I see only minor problems in what is there in Rossiter's framework. My main reservations relate to what is missing. I have structured my comments accordingly.

While generally agreeing with the ideas represented in the Rossiter's framework, on closer reading I found some omissions and mistakes, which are especially unwanted in a theoretical framework. When summarizing "*the logic that makes land evaluation possible and useful*" Rossiter states:

"*3. The variation is at least in part systematic, with definite and knowable causes, so that...*

4. The variation (physical, political, economic and social) can be mapped by survey, i.e. the total area can be divided into regions with less variability than the entire area;"

This reiterates a misconception that lives in part of the pedological literature, namely that spatial variation such as in land or soil can be divided in a systematic and a random component on the basis of knowledge of its causes, and that only the systematic part enables mapping of the resource. This view seems to confuse 'random' with 'uncorrelated' with 'unpredictable', thereby entirely denying the theory and practice of geostatistics, for instance.

Furthermore, point 4 above implies that mapping by survey (dividing the total area into regions with less variability than the entire region) is essential for land evaluation. I disagree. The fact that mapping is a part of many current procedures does not mean that it is essential for land evaluation per se. Exceptions are: applications with a single evaluation unit, and procedures using continuous spatial models. It is anticipated that the latter will become more important in the future, especially in the context of continuous soil husbandry (McBratney and Whelan, 1995) or precision farming (Robert et al., 1995). Later, when defining the concept of Land Mapping Unit, Rossiter's text becomes inconsistent, admitting that "*Land that has not been, or can not be, mapped may be evaluated at specific locations.*"

The term 'Land Mapping Unit' seems unnecessary and extremely confusing. It is unnecessary because nowhere in the framework could I find an instance where this term could not be replaced by the more straightforward 'evaluation unit', a term also used by Rosshas iter as a synonym. It is confusing because in soil survey the term 'mapping unit' and 'map unit' long been used for the set of all delineations on a soil map with the same cartographic signature. A 'Land Mapping Unit' according to Rossiter may be a mapping unit in the sense above, but also a grid cell or a single map delineation.

Discussing the concept of 'Land Characteristic' (LC) Rossiter, following Bouma et al. (1996), distinguishes four methods of obtaining the value of a LC: measurement, estimate, pedotransfer function or simulation model. Two important methods are missing here: interpolation in space and/or time as in geostatistically based evaluations, and a priori choice as in 'what-if' studies, e.g. to predict future or potential suitabilities given certain changes in LC's, such as by an assumed climatic change or by a specific soil improvement measure.

In the sub-section, 'Evaluation based on Land Characteristics' of Section 1, Rossiter mentions that the suitability function *S* can also be expressed as a set of degrees of memberships in the set of suitability classes, rather than as a single suitability, referring to recent applications of fuzzy logic to land evaluation (Tang et al., 1991). Here I should like to mention an interesting alternative approach, namely the statistical technique of multiple discriminant analysis. Although its algorithms and interpretation differ entirely from that of fuzzy logic, this technique gives a similar type of result, viz. the conditional probabilities of the suitability classes, given the data of the evaluation unit in question. For any new evaluation unit these probabilities can be calculated directly from a training set of units with known suitability. An early application of this technique to land suitability for various tree species is presented in Bie et al. (1976).

In his sub-section 'The land index', nothing is said about the fact that none of the land index models as presented is able to account for the interactions that often exist between Land Characteristics. In general that should rule out these models as candidates for use in land evaluation.

The core of Rossiter's framework is a classification of models. As such it presents a systematic overview of possible strategies that is descriptive rather than functional. Little or nothing is said about how to choose from the plethora of possibilities. Rules on how to use the concepts and models in actual land evaluation studies are not presented. Yet, as indicated in my opening remarks, I believe that the framework in order to come alive needs rules for use, as flesh on bones. Descriptive classification to facilitate communication is often a necessary first step in science and is totally respectable. However, it does not solve any other problem than that. Land evaluators are likely to be more directly concerned with the question of how to design a cost-effective, yet soundly based evaluation strategy, tailored to the circumstances at hand. In a formalized form such application rules would naturally play a crucial role in expert systems for land evaluation. The demand-driven approach advocated by Rossiter seem a good starting point to develop these rules.

Another aspect not covered by Rossiter's framework is the definition, quantification and representation of uncertainty of land evaluation results. Only in the last line of his paper Rossiter states that “*This respect [... for our clients and other stakeholders ...] includes being clear about what the predictions of land evaluations really mean, how we came to make these predictions, and the uncertainty with which we make them.*”. However, in the absence of any substantiation in his framework this remained lip service. I believe that a theory of land evaluation, perhaps more than any other, must explicitly deal with uncertainty. Land evaluation and allocation is basically decision-making under uncertainty. The conceptual framework for this is offered by mathematical statistics and is ready to use. It is therefore remarkable that Rossiter decided, without explanation, not to make a distinction between stochastic and deterministic models (see e.g. Burrough, 1989). If we want to convince the decision makers that they should use land evaluation data along with other information and considerations, we should make sure that we can provide them with specific information on the reliability of our data.

A basic element in a theory of land evaluation, closely related to both the choice of strategy and the aspect of uncertainty, is the well-known economic principle of 'diminishing returns'. This does not only apply to agricultural production itself, but also to land suitability research. In this context the principle predicts that, when increasing the investments in land suitability research in a given application, the net returns from better land-use decisions through more precise and reliable land suitability data will finally diminish until a point is reached beyond which further investments are uneconomical. Of course this may be analysed for soil data separately, conditional on the existing knowledge of the other relevant characteristics and the way they collectively determine the suitability. Given the uncertainty of the nonsoil information and the suitability models, the break-even point in improving soil information might well be reached earlier than soil scientists tend to imagine. An interesting early study of this phenomenon can be found in Bie and Ulph (1972) and Bie et al. (1973). Clearly, the 'diminishing returns' principle is always to be considered in choosing a strategy on a rational basis, therefore it should form an essential element in any theory of land evaluation.

Professor E. Van Ranst

Laboratory for Soil Science, University of Gent, Krijgslaan 281 (S8), 9000 Gent, Belgium

The manuscript gives a comprehensive overview of all existing land evaluation methods and places each method in the same framework, defined in mathematical terms. Small aspects of the land evaluation process, such as the evaluation of a single land characteristic or land quality (e.g. water sufficiency) are described with the same mathematical definitions as a complex land allocation model that considers e.g. spatial interdependent suitability. The framework also places popular tools such as GIS in its proper position, namely as mere tools in the land evaluation process, without overestimating their importance.

The theoretical approach, however, does not provide new techniques, nor answers to often-asked questions, such as how to determine weighting factors or how to rate land-use requirements. This was clearly beyond the scope of the study. A further and much requested, step would be to write "*a practical framework for land evaluation*" to replace the outdated FAO framework. Unfortunately, this is probably too big a step to take, considering the complexity and interdisciplinary aspect of the land evaluation process.

Some specific remarks:

(1) Some of the terms, poorly defined in the FAO framework, have been taken over without comment; I refer especially to the term 'land quality'. Van Diepen et al.(1991) commented that "*no term in land evaluation has created so much confusion as land quality*". Sys (1993) commented on the term "land quality" and redefined it for a specific use. So I believe that in a new approach at least attention should have been given to confusing definitions.

(2) "*Land characteristics do not change over time*". This is correct if we evaluate for a well-defined land utilization type. However, the concepts "actual" and "potential" evaluation consider change of characteristics through improvement such as drainage, flood protection etc.

(3) For the calculation of land indices it is said that the combination can be additive, multiplicative, or geometric. Such a statement needs some comment. Indeed, the additive method should be rejected because high values of the land index can be obtained for completely unsuitable situations. Takes a land with unsuitable slope (rating 5) and all other characteristics optimal (rating 100), the additive method will give a high index for a land that can not be used.

(4) It is said that our work in Ghent (Sys et al., 1993) is a good example of a land evaluation based on maximum-limitation matching tables. Note that our suitability or requirement tables, for most tropical crops, are a basis for qualitative suitability appraisal to be used for different methods: maximum limitation method, limitation method regarding number and intensity of limitations, and parametric methods.

Dr A.K.L. Johnson

CSIRO Division of Tropical Crops and Pastures, Davies Laboratory, PMB PO Aitkenvale, Queensland, Australia

In general, I think that the paper makes a useful contribution in that it provides a formal classification of land evaluation "models" and methods currently in use. The author uses a unifying mathematical notation to link what he calls the "eight or more independent axes" in a most useful manner, however I am not entirely convinced that what has been presented is a theoretical framework. Rather it seems to be a mechanistic formalization of current practice. Whilst he uses a unifying notation, there appears to be no conceptual integration across the axes. He does introduce the concepts of Hoosbeek and Bryant (1992) and perhaps it is here that opportunity for conceptual integration exists.

I strongly support the author's contention that land evaluation must respond to clients needs by accepting a demand-driven approach to practice and provide clients with clear indications of the precision and accuracy of predictions made. As is correctly pointed out, this will by necessity require that the traditional pedocentric view of land evaluation be augmented by expertise from a range of other disciplines. Hence to arrive at a theoretical framework for land evaluation will require a more holistic view of the land evaluation process than appears in this paper.

I also think that his treatment of spatial and temporal variability and the impacts that these phenomena have on the utility of land evaluation output could be expanded somewhat. Temporal variability in particular receives limited attention. Land evaluation can gain much from developments in other areas such as decision theory and operations research. Similarly, recent developments in landscape ecology and spatial analysis (at scales larger than a field) have much to offer yet have received little attention in the land evaluation literature. These issues must be addressed comprehensively in any development of a theoretical framework for land evaluation.

I commend the author for his initiative in instigating thought and discourse in this area. A theoretical framework for land evaluation is highly desirable and I am sure that the paper will serve as an important basis for further debate in the land evaluation and associated communities.

Professor A.B. McBratney

Department of Agricultural Chemistry & Soil Science, Ross St Building A03, The University of Sydney, New South Wales 2006, Australia

A common and necessary process in disciplinary development is the systematisation of methods and bodies of knowledge derived from them. David Rossiter is to be commended for attempting this in a branch of soil science that has perhaps been neglected from this point of view.

My brief comments relate to how we should allocate land evaluation in the broader scheme of things. First, worldwide, organisations, such as the US Environmental Protection Agency, are developing environmental guidelines especially for contaminated land. It seems to me this is indeed a kind of land evaluation but with some soil and land and human -health attributes not used in conventional land evaluation. Second, there is a growing movement in the industrially developed countries to site-specific land management in the form of precision agriculture (Robert et al., 1995). This also seems a kind of land evaluation – albeit very fine-scale, quantitative and repetitive – that seems to merge into soil management. Do these developments require a modification to, or an extension of, the theoretical framework?

The Author's Reply

I thank the respondents for their fair and constructive discussion of my paper. If I do not mention a specific comment in what follows, it is because I generally agree with it.

I note first of all that none of the respondents disagreed with the main conclusion of the paper, namely the classification of land evaluation approaches. However, most of the respondents feel that too much of the paper is taken up with outmoded approaches. I agree that today we have new analytical techniques and tools for land evaluation, and that we should promote their use. I find, however, that practising land evaluators in many countries are usually not even using the FAO Framework or similar concepts correctly, and indeed they often persist in so-called land capability approaches. Land indices, despite their obvious problems such as not accounting for interactions and unjustifiable method of combining factors, are still in wide use by national soil survey organisations and taxation departments. When a resource-poor or knowledge-poor institution is called on to evaluate the relative fitness of land, especially for strategic planning, perhaps a simple method is not always so bad. For example, interactions are usually much harder to quantify than single-factor effects, for a given effort in experimentation or observation. Also, if a land evaluation is to be used for taxation or compensation for taking, all that is really necessary is that all landowners agree that the method is fair. Obviously the state-of-the-art should improve, but I do not see this happening very fast outside of Europe and Australia, except in projects where leading-edge practitioners are directly involved. I think that we are a long way from using interpolation techniques and process models in routine land evaluation in many areas of the world. This is why, for example, the ALES computer program has filled an important niche despite following firmly in the footsteps of the FAO Framework.

Professor Bouma mentions that land users and planners are inclined to ignore land evaluators. I agree, and think that this generally reflects the poor quality and low relevance of many actual land evaluations, as well as poor communication with clients. It is not sufficient to deliver a report and map; there must be continuous follow-up by the land evaluator as plans are implemented, not least to monitor if the recommendations were correct. Also, too many land evaluators do not choose an approach, they just follow whichever one they happen to have learned, often even without the necessary local modifications. As long as they are not called to task for poor recommendations, they have no incentive to improve. A demand-driven approach to selecting a land evaluation method would help reveal what predictions are really needed and at what level of certainty.

I disagree with Professor Bouma's distinction between 'suitability…for a LUS' and 'realistic options for land use…with proper technical coefficients'. To me, the LUS *is* a 'realistic option', which must always specify its technical coefficients (management, inputs etc.), and 'suitability' for the LUS simply is a statement of how successful that option is likely to be.

Both Professors Bouma and McBratney imply that productivity and economic benefit alone is not a sufficient measure of land suitability. I agree, and intended that, in the formulations of the paper, 'yield', 'costs', and 'benefits' could be replaced by any meaningful measure of utility, for example, taking into account human health as part of the benefits and counting soil degradation as part of the costs. It may not be easy to measure these utilities or to make them commensurate with better-understood utilities such as provided by mean-variance analysis of economic time series, but that is an area for research and ultimately for policy.

I agree with Professor Burrough and also Dr de Gruitjer that we need to develop an objective procedure for selecting a land evaluation approach and justifying its cost-effectiveness in each situation. I would add that we also need to consider the human resources and institutional framework available to carry out land evaluation in such a procedure, and include the necessary training and institutional strengthening in the costs of more sophisticated approaches (of course, training etc. will provide long-term benefits beyond the current project).

Professor Van Ranst thinks the time has come to discard the term 'Land Quality'. The confusion comes from the dual use in English of the word 'quality', meaning on the one hand 'value' or 'degree of goodness' (e.g., 'high quality land'), and 'quality' meaning 'attribute' (e.g., 'the land has the quality of high natural soil fertility'), so perhaps the FAO Framework should not have used the term in the first place. To add to the confusion, in the past several years there has been the most unfortunate choice of the term 'soil quality', as a linguistic analogue to 'water quality', to refer to a certain assemblage of land characteristic values which should better be referred to FAO-style Land Qualities such as 'workability' and ‘erodibility’, or even by the alternate term ‘soil health’, to indicate an intrinsic state of the soil. Even worse, this so-called ‘soil quality’ is defined without reference to a specific LUT, ignoring one of the basic principles of land evaluation approach. Still, I have not dared to replace the term Land Quality, since it has on its side precedence, and was the result of an international consultation among many of the leading workers of the 1970s. I think the definition in the paper is consistent and meaningful. If we use the term always capitalised or even abbreviated as ‘ LQ’, it can still serve.

I should add that I find the *concept* of Land Qualities (or whatever we choose to call them) as components of overall suitability (or equivalently from my point of view, Land Use Requirements when describing a Land Utilization Type) very useful as a way of organising my thinking about a specific land evaluation problem, and communicating with clients. This top-down approach of Suitability as a function of Land Qualitites that can be more-or-less independently assessed is also useful for multidisciplinary teams. I do not pretend that this is always realistic and indeed in some cases the interactions are so strong, or the multiple effects of a single land characteristic are so difficult to untangle, that it is easier to evaluate directly from land characteristics.

As for the use of the term ‘Land Mapping Unit’, perhaps it should be replaced with ‘evaluation unit’, which I also used in my recent Soil Use & Management paper (Rossiter 1995). However, the abbreviation ‘EU’ has already wide use with another meaning, so I suggest ‘Land Evaluation Unit’ = ‘LEU’.

Dr de Gruitjer takes me to task for my simplistic presentation of land resources survey. I have been accustomed to presenting to non-specialist audiences the concept, very strange to them, that the variation we see in the landscape has, in part, systematic causes. This indeed implies that the rest is random in the sense that it can’t be understood by landscape models, but should not imply that we don’t have tools to map this component. What I should have said is that the part that can be mapped by conventional land survey is that which we understand by landscape models, and the other part (or indeed the whole landscape if we wish) can be mapped by geostatistical techniques. I agree further that land evaluation can be performed at single points, and that mapping is a separate issue.

This discussion has indicated several important and challenging lines of work in land evaluation methods:

(1) “a practical framework for land evaluation” as suggested by Professor Van Ranst;

(2) a demand-driven cost-benefit approach to selecting land evaluation methods as suggested by Dr de Gruitjer, Professor Burrough, and Dr Johnson;

(3) a systematic approach to measuring and presenting uncertainty in land evaluation results as suggested by Dr de Gruitjer;

(4) the development of new measures of costs and benefits to include environmental and human health and their integration with existing measures of suitability as suggested by Professors McBratney and Bouma;

(5) a continued emphasis on multidisciplinary approaches to land resources assessment and evaluation, including the vexing question of how to best integrate disparate ways of thinking about land suitability.

To these research problems I would add that we should strive to improve land evaluation *practice*, which often lags well behind currently-available best practices.

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