BIOPHYSICAL MODELS IN LAND EVALUATION

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Contents

Summary

Biophysical models are simplified representations of land use systems that allow prediction of the success of such systems prior to their actual implementation. They are classified according to their degree of computation (qualitative to quantitative), descriptive complexity, (empirical to mechanistic) and level in the organizational hierarchy (scale).

The simplest models are holistic local knowledge, which is difficult to formalize and can not be extrapolated. Expert models are formalizations of expert judgment about individual Land Qualities, following the FAO Framework for Land Evaluation. Empirical-statistical models are quantitative predictions of crop yield from a set of static Land Characteristics. Dynamic simulation models attempt to model biophysical

mechanisms, based on the laws of nature, to follow a system over time based on a time series of input data. Widely applied models in these various categories are discussed here, including ALES, MicroLEIS, WOFOST, PS123, DSSAT, APSIM, EPIC, GAPS, and LEACHM.

A stepwise approach is recommended, with simpler models being applied to limit the areas in which the more complicated models must be calibrated.

1. Introduction

A *model* is a simplified representation of reality with which we can compute outcomes without having to perform actual experiments. In land evaluation, models are computer programs that predict the performance of a land use on a land area, when given information on that area's land characteristics. *Biophysical* models predict the behavior of the land use system in physical terms such as crop yields, environmental effects, and effect on management. They thus provide a quantified procedure to match land with various actual and proposed land uses, as proposed by the FAO Framework for Land Evaluation.

Models can be used to predict *crop yields* under different management strategies, as well as individual *land qualities* that are important components of yield, such as moisture supply, nutrient supply, and radiation balance. They can also be used to evaluate individual land qualities important for the land use but not directly affecting yield, such as erosion hazard, trafficability, and workability.

2. Classification of Biophysical Models

In 1992, Hoosbeek and Bryant proposed a classification of models of pedogenesis (soil formation), which was adapted by Bouma (1997, 1999) for land evaluation models (Figure 1). In this scheme, models are classified in three dimensions.

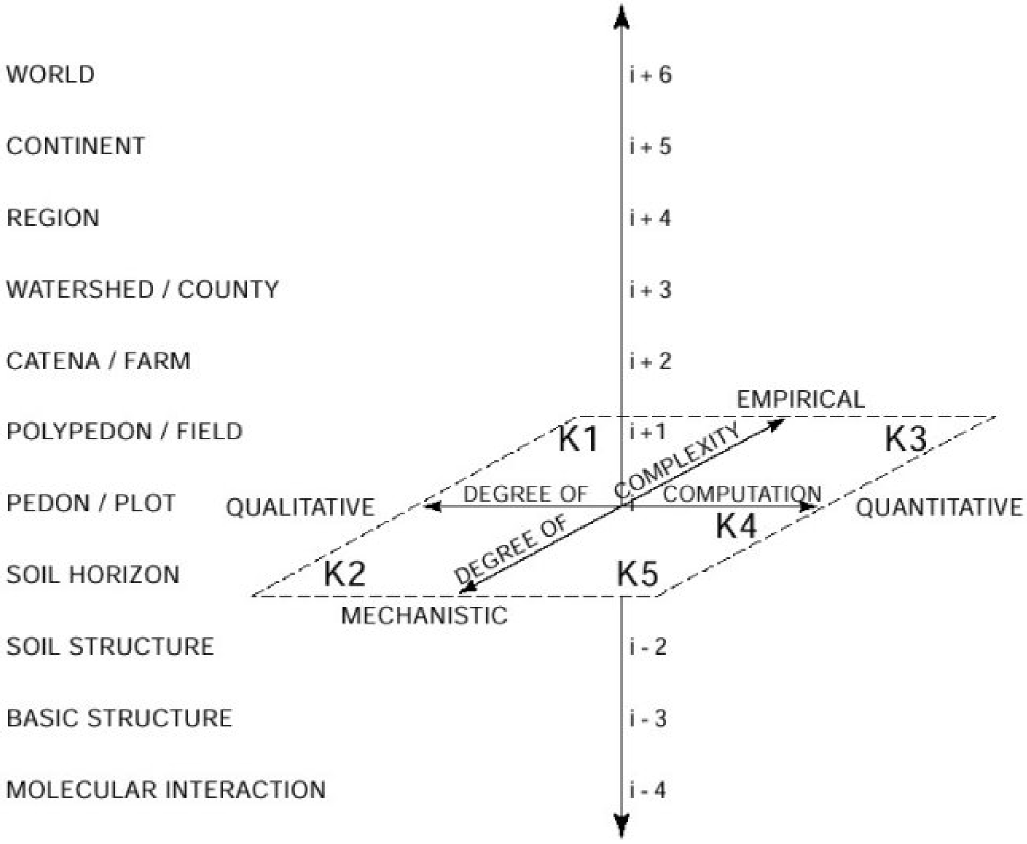


Figure 1. Conceptual framework to classify models, after Bouma (1999)

The first two dimensions are shown in Figure 1 on a horizontal plane: (1) the *degree of computation*, ranging from qualitative to quantitative; and (2) the *descriptive complexity*, ranging from empirical to mechanistic. The *degree of computation* refers to the precision of the model’s prediction. For example, the simplest qualitative model (at the left of the plane) could predict land suitability as “suitable” or “not suitable”, in other words, the use will succeed (to some degree) or fail; this could be adequate for some decisions. The most quantitative model (at the right of the plane) would give precise numerical predictions of crop yields and environmental effects. The *descriptive complexity* refers to the detail with which processes are made explicit in the model. An *empirical* model (at the back edge of the plane) is a model where processes are not known, but where relations are established based on experience. By contrast, a *mechanistic* model (at the front edge of the plane) is a model where processes, not just relations, are modeled.

The third dimension is shown on Figure 1 as the vertical axis passing through the plane formed by the first two dimensions: (3) the *level in the organizational hierarchy* (scale of processes being modeled), which for land evaluation range from region through field and “point” to soil horizons and finally molecular interactions. At any scale level, the first two dimensions are possible; in practice the more quantitative and functional models are generally found at smaller scales.

Along the plane formed by dimensions (1) and (2), Hoosbeek and Bryant distinguished several levels of knowledge, which they termed K1 (user expertise), K2 (expert knowledge), K3 (generalized holistic models), K4 (complex holistic models), and K5 (complex models of system components), which of course grade into each other in any actual model.

K1 models are empirical, qualitative expressions of the land user's experience. These have low descriptive complexity and require no computation. They are applied intuitively within the geographical and phenomenological area of the user's experience. K1 models are difficult to formalize, since they draw on the user's holistic experience, rather than a reductionist problem analysis.

K2 models are also qualitative, but consider mechanisms. In particular, the FAO approach with its analysis of land suitability as a set of Land Qualities has the reductionist structure required for these models, which are built by specialists who are trained to search for causes.

K3 models are empirical but quantitative. These are statistical relations between output (e.g. yield) and input (e.g. precipitation, heat units, soil fertility), usually established by regression analysis on large datasets. Predictive variables are selected based on a reductionist concept of causative factors. They can not be applied outside their area of calibration. All variables are static, and there is no attempt to simulate system behavior over time. They can only be applied to Land Utilization Types (LUTs) that are widely practiced; so they are not useful for new crops, new technologies, or new management strategies.

K4 and K5 models attempt to be mechanistic rather than empirical. This means that they are based more on scientific principles (laws such as conservation of mass and energy, diffusion, convection and dispersion, chemical kinetics and equilibrium) and less on site-specific empirical relations. It is thus expected that they will be 'universally' applicable. However, the line between empirical and mechanistic models is not clear, since all 'mechanistic' models have empirical components. These models, when applied to land evaluation, are usually driven by *daily weather data*. This allows the analysis of *dynamic* and *transient* phenomena that may affect land performance, so that these are commonly referred to as *dynamic simulation models*. Such models can be used to model individual *land qualities* such as moisture sufficiency (K5) as well as crop yield (K3). This is appropriate if the *timing* of the quality is important. Water stress is a good example: the yearly moisture deficit often isn't as important as the deficit in specific parts of the crop growth cycle.

In the following chapters these modeling approaches will be critically reviewed from least to most sophisticated.

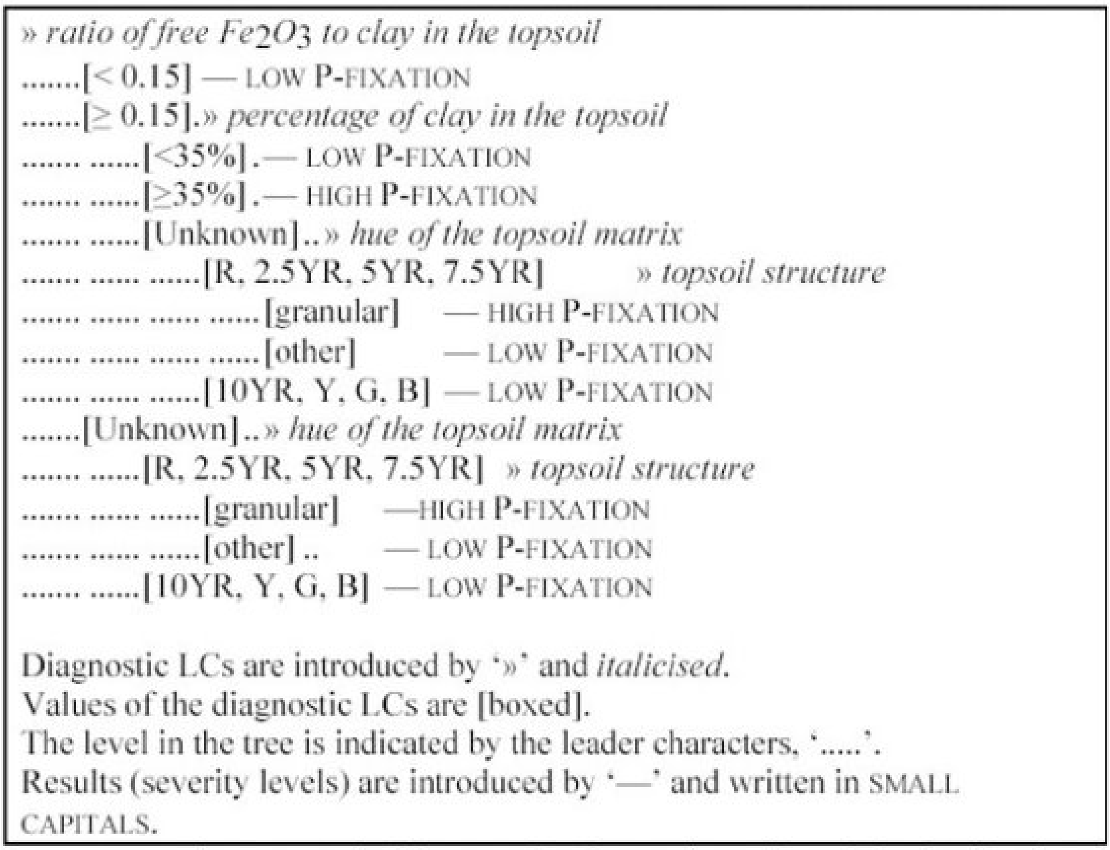
3. Models of Expert Knowledge

At the time that the FAO Framework was developed (mid 1970's), K2 expert knowledge was captured as a set of *matching tables*, one for each Land Quality (LQ), using the *maximum limitation method*, requiring a set of *diagnostic* Land Characteristics (LC) as input for each table. This was put in computable form and at the same time made more flexible by the ALES ('Automated Land Evaluation System') computer program, which was released in 1986 and improved until 1997. It is freely distributed by Cornell University, but requires a code from a commercial database vendor for legal operation.

ALES provides a *framework* with which land evaluators can build their own *expert systems* to evaluate land according to FAO Framework. Models are built to satisfy local needs, so that ALES does not provide a fixed list of LUT, LUR (Land Use Requirements) or LC. Rather, these lists are defined by the expert to suit local conditions and objectives. ALES does not include any knowledge about land and land use; these come from the expert. A good example of an ALES model is the LEV-CET model for central Ethiopia developed by Yizengaw and Verheye (1995).

A key innovation in ALES is the use of *decision trees* instead of maximum limitation tables to infer Land Qualities from a set of diagnostic Land Characteristics. These are hierarchical multi-way keys in which the *leaves* are results (severity levels of the LQ), and the interior nodes (*branch points*) of the tree are decision criteria (LC values). They are constructed by the model builder, and traversed during the computation of an evaluation result, using actual land data for each land evaluation unit.

Figure 2 shows a simple decision tree adapted from the Fertility Capability Classification of Sánchez and Buol (and now incorporated into the FAO's Topsoil Classification). The objective in this case is to predict the soil-related LQ "*risk of P fixation by iron*"; this LQ limits agricultural systems on some highly-weathered soils where the agronomist attempts to compensate for low soil P by moderate fertilization. Some soils fix ('eat') added P in an unavailable form, so that moderate doses are effectively wasted inputs. In the displayed tree, the diagnostic LC at the highest level is "*ratio of free Fe*2*O*3 *to clay in the topsoil*"; if this is below an expert-defined threshold (< 0.15), there is no risk and the decision is taken. If the ratio is higher, the second-level diagnostic LC "*percentage of clay in the topsoil*" must be considered; if this is below another expert-defined threshold (here, 35%), again there is no risk; above this threshold there is risk and in either case the decision is taken. A third possibility is that one of the two diagnostic tests was not done, perhaps because of expense or unavailability of a laboratory. In both cases, the expert allows the use of alternative LCs: "*hue (basic color) of the topsoil matrix*", followed in some cases by the "*topsoil structure*", both indicative of the form of iron-dominated clays. Since these two LCs can always be assessed in the field, a decision can always be taken. Note that the choice of LCs, the thresholds, and the decisions, represents *expert judgment*, in this case of an expert on fertilization of these soils.



» *ratio of free Fe_2O_3 to clay in the topsoil*
.......[< 0.15] — LOW P-FIXATION
.......[≥ 0.15].» *percentage of clay in the topsoil*
....[<35%].— LOW P-FIXATION
....[≥35%].— HIGH P-FIXATION
....[Unknown]..» *hue of the topsoil matrix*
....[R, 2.5YR, 5YR, 7.5YR] » *topsoil structure*
....[granular] — HIGH P-FIXATION
....[other] — LOW P-FIXATION
....[10YR, Y, G, B] — LOW P-FIXATION
.......[Unknown]..» *hue of the topsoil matrix*
....[R, 2.5YR, 5YR, 7.5YR] » *topsoil structure*
....[granular] —HIGH P-FIXATION
....[other] .. — LOW P-FIXATION
....[10YR, Y, G, B] — LOW P-FIXATION

Diagnostic LCs are introduced by '»' and *italicised*.
Values of the diagnostic LCs are [boxed].
The level in the tree is indicated by the leader characters, '.....'.
Results (severity levels) are introduced by '—' and written in SMALL CAPITALS.

Figure 2. A decision tree for the Land Quality 'Risk of P-fixation', after Sánchez, Couto and Buol (1982).

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Biographical Sketch

David G Rossiter is a Senior University Lecturer in Quantified Soil Modeling at the International Institute for Geo-Information Science and Earth Observation (ITC) in Enschede (NL). His main research interests are modern methods of soil resource inventory and multi-purpose interpretation of soil geographic databases for rural and urban applications. He teaches at the MSc level, supervises PhD students, and undertakes consulting missions in a wide range of topics related to these interests and to the ITC core mission of geo-information for development.

A native of Ithaca, NY (USA), he holds a BSc in agronomy and soil science, an MSc in computer science, and a PhD in agronomy and international agriculture from Cornell University (USA). He has worked as a soil surveyor, computer programmer, and systems analyst and has lived in the USA, Venezuela, and the Netherlands, with project work in Ecuador, the Dominican Republic, Indonesia, the Philippines, Mexico, Bolivia, Brazil, South Africa, Tanzania, Kenya, Cameroon, India, and Croatia. He designed and implemented the ALES computer program and was one of the principal authors of the GAPS environmental simulation model.