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The land use systems approach to planning sustainable land management at several scales

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ABSTRACT

Land units, land utilization types and land use systems need to be defined differently for different scale levels, eg, for farm, regional and world levels, as illustrated in this paper. The Hoosbeek and Bryant diagram, showing methodology as a function of spatial scales, is used to illustrate research procedures based on user demands. Land use decisions are made on strategic, tactical and operational levels. On the farm level, point observations are made that are interpolated to areas of land to be used for precision agriculture. Taxonomic land units and static utilization types are irrelevant, the latter because management has to be proactive and dynamic. On the regional level, the traditional concepts of land evaluation fit best but modern application requires quantitative approaches in which different land use options and their trade-offs are compared using linear programming techniques. Finally, the world level involves gross simplifications, where agronomists use an abstract approach with grain equivalents to define production for large grids. Soil science has not as yet developed a satisfactory procedure to define representative soil parameters for each grid. Even though lack of data limits the work in developing countries at this time, we believe that access to information technology and modern techniques such as remote sensing will allow the future use of identical procedures all over the world for each of the different scale levels.

The terms: “land unit” (LU), “land utilization type” (LUT) and “land use system” (LUS) have been widely accepted since their introduction by FAO in the ‘70s [11]. When applied in the context of land evaluation, they have been effective in illustrating that the same type of soil can function in different ways, depending on land use. The functioning of soil has to be considered increasingly in a context broader than solely the production of crops. In many countries, environmental laws have been enacted calling for sustainable forms of land management, implying the realization of economically and socially acceptable production levels in production systems that are in harmony with nature and the environment [12]. In addition, new forms of direct interaction between scientists and a wide range of stakeholders are becoming increasingly important as we find that the traditional linear model of knowledge generation and dissemination is ineffective and obselete. Too many land evaluation reports wind up on the shelf, collecting dust. Rather than devise a top-down system of land evaluation that basically reflects the expert knowledge of scientists, we are moving towards demand-oriented systems of immense variety. As Bouma and Hoosbeek [5] pointed out, there are many different types of questions being asked at different scale levels, be it for farms, regions, countries or continents. Also, the spectacular advance of information technology provides us with many new tools, including geographic information systems, various sensors, global positioning systems and a wide variety of simulation models that allow the exploration of the effects of different types of land use.

Clearly, there is room for a new research paradigm for demand-oriented land evaluation, which allows interaction with stakeholders and the use of modern technology to provide these stakeholders with various options. This obviously contrasts with traditional approaches, where scientists pronounced certain types of land use system to be suitable or not for a given land unit. The objective of this paper is to present three case studies of direct practical significance: one at farm level, one at regional level and one at world level. In each, the meanings of “land unit”, “land utilization type” and “land use system” will be analyzed in the context of sustainability. Before discussing these case studies in broad terms—and as reference will be made to source publications—we will cover three items of general relevance to this paper:

- decision making at strategic, tactical and operational level
- working at different scales, in space and time, with different modern tools
- working in rich and poor environments.

DECISION MAKING AT DIFFERENT LEVELS

Establishing LUTs and LUSs implies that many management decisions have to be made. Procedures become more transparant when different levels of decision making are distinguished.

(1) *The strategic level*

Restricting the discussion to agricultural production systems, we may think of choosing between dairy farming, arable farming and mixed farming; between organic farming, which does not use agrochemicals, and high-tech farming, which does; etc. A decision to apply precision farming practices would also qualify as a strategic decision. Strategic decisions have a time frame of decennia.

(2) *The tactical level*

The choices to be made at this level include: which crop rotation to follow; which types of fertilizer (organic or non-organic) to use; which type of tillage to use. Tactical decisions have a time frame of a few years.

(3) *The operational level*

The choices here, with a time frame of days up to the next growing season, are: which crop variety to sow, and when to till, sow, plant, fertilize and harvest.

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WORKING AT DIFFERENT SPACE AND TIME SCALES

This issue has already been covered many times (*eg*, [1, 5, 3]). However, considering different spatial scales in terms of "i-levels" and types of modelling, as proposed by Hoosbeek and Bryant [13], is still quite relevant and can be helpful as a source for decision making. As shown in Figure 1, the central i level in soil science is the pedon; higher hierarchic levels are defined in terms of i+, while lower levels are defined in terms of i-. Using two perpendicular axes—one ranging from qualitative to quantitative, the other from mechanistic to empirical—five knowledge levels are distinguished:

K1 = user expertise
K2 = expert knowledge
K3 = knowledge derived from simple "black box" models
K4 = knowledge from comprehensive models covering entire systems
K5 = knowledge from very detailed specialistic models covering parts of the systems.

In research, we often jump into a problem, using a particular model or expert system without proper reflection on the nature of the problem to be studied or the questions being raised by stakeholders. The author proposed "research negotiations", where different K levels are compared in terms of a cost/benefit analysis before selecting a particular research methodology [3]. Although Figure 1 does not directly include a time dimension, this is implicitly present when modelling for multi-year periods in the context of knowledge levels K3, K4 and K5.

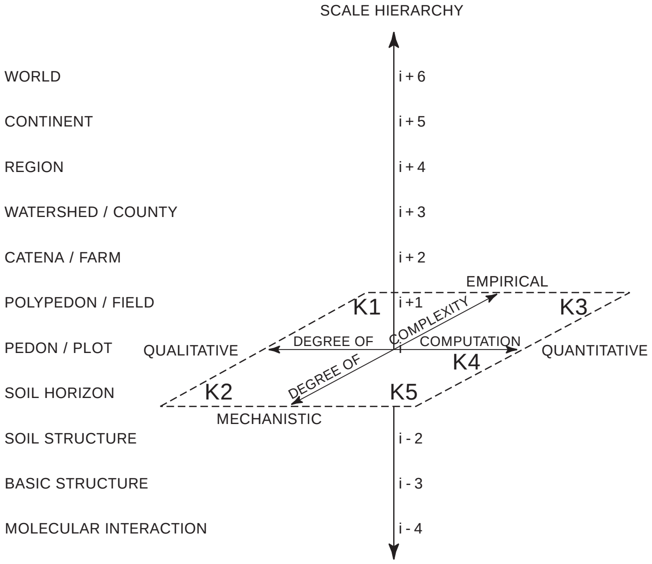


FIGURE 1 Classification of modelling approaches based on hierarchic scale levels, degrees of computation and degree of complexity. Five knowledge (K) levels are defined (after [13, 5])

WORKING IN RICH AND POOR ENVIRONMENTS

Soil surveys at different scales have been completed in many so-called developed countries. Databases are filled with soil data, and interpretations have been widely carried out for different types of land use. Even though there is growing concern about research funding, laboratories in universities and research institutes are usually well equipped and workers are well trained. Conditions are different in many developing countries, where resources are much more limited and few data are available. When discussing LUSs, should we therefore follow a two-rail track: one for the developed and one for the developing world? Bouma *et al* [6] essentially followed a two-track approach when discussing precision agriculture: a high-tech approach for developed countries and a low-tech one based on experiences in the Sahelian zone. This was realistic in the given context. Proposing the introduction of GPS-guided machinery with on-the-go yield monitoring and gadgets for precision application of agrochemicals would be unrealistic for many poor countries at this time. However, in the long run we should aim for unified approaches at different levels of detail (*eg*, [3]). The problems are essentially the same everywhere. How do we produce food in a sustainable manner? Conditions in developed countries may look better than they really are; databases contain much irrelevant data. Besides, information technology is now available everywhere. Researchers in developing countries should be placed in such a position that they do not repeat all our mistakes, but rather benefit from our experience—if only in terms of how not to perform research.

FARM LEVEL: PRECISION AGRICULTURE AS A TOOL TO ACHIEVE SUSTAINABILITY

PRECISION AGRICULTURE AND SUSTAINABILITY

Precision agriculture (PA) is a new development that is spreading very rapidly in the United States and, to a lesser extent, in some European countries. In principle, PA tries to fine-tune land management, with the objective of maximizing agricultural production and its quality while minimizing adverse environmental side effects. Technically, PA aims at immediately satisfying plant needs in farmers' fields during the growing season. Ideally, the effect is that natural resources such as nutrients, biocides and energy are used as efficiently as possible, that costs are cut and that environmental threshold values are not exceeded. "What is good for business, is good for the environment" (*eg*, [17, 9, 4]). In fact, the different elements of the definition of sustainable management, as proposed by FAO [12], are well covered. In conclusion, a proper PA procedure seems a practical way of implementing sustainable management at farm level. The concept is not restricted to a high-tech approach to be applied in developed countries. Heterogeneity in fields, and its consequences, are even more important in many developing countries—as Brouwer and Bouma [8] summarized for the Sahelian region. Precision agriculture requires management decisions mainly on the operational level.

THE LAND UNIT (LU)

The management units of a farmer are his fields. Here, we question the exclusive emphasis on land units in the definition of LUSs. Most often, different land units occur within single fields. A farmer knows this. He waits before sowing until the wetter spots have dried up, even though he knows that a longer growing season potentially offers higher yields and the dryer spots could have been sown earlier. The same goes for fertilization and crop protection. Of course, PA offers the opportunity of sowing different varieties at different spots and varying fertilization practices within the field. When defining a land use system in the context of precision agriculture, we can therefore again work with the land unit as defined in traditional land evaluation. In conventional agriculture, the farmer does not farm land units, he farms fields. In precision agriculture, he can farm the various land units within his fields differentially. This conclusion is valid for all regions in the world.

A SOIL DATABASE RATHER THAN A SOIL MAP

Land units refer to delineated areas on soil maps. For PA, we need detailed maps, *eg*, scale 1:5000. But even so, we don't know whether land units as defined by Soil Taxonomy are relevant in terms of management units within farmers' fields. After all, soil series that are different from a taxonomic point of view may act differently from a functional point of view (*eg*, [7]). Worse, soils that are taxonomically identical may act differently! We have therefore focused in our extensive PA work on point data obtained with a grid spacing allowing a minimal number of observations. Simulation techniques are used to obtain yields and solute fluxes for individual points. Patterns are obtained by geostatistical interpolation of these point data [23]. Patterns of weather conditions for many years can then be compared to distinguish subareas within the field that exhibit significantly different behaviour over the years. Maps with such subareas are suitable for use in operational PA procedures [21, 22, 23]. Differences between micro-highs and micro-lows at short distance and the occurrence (as in the Sahel) of crusting and termite activity also highlight the need for georeferenced point data in less endowed areas (*eg*, [8]).

INADEQUACY OF THE LUT CONCEPT

The LUT is defined in a static way, with detailed lists of the activities and capital input required (*eg*, [14]). This, however, is against the spirit of PA. While attention here is restricted to the operational aspects of PA, the farmer has to look ahead to an unknown future, where he faces a growing season with unknown weather. He may have to apply fertilizers several times when precipitation (and leaching) turns out to be high. He may have to apply multiple crop protection measures, sprinkling irrigation or reseeding if part of the crop does not establish itself. The questions he raises are of the "what if …" type, and they are not covered at all by a static description of a standard LUT. Decision support systems now being derived for PA focus on decision rules based on multi-year simulations of yields and solute fluxes. Weather generators and medium-term weather forecasts play an important role. The farmer faces comparable challenges under low-tech conditions, where weather variability in arid and semi-arid regions is notorious. Here too, LUTs are not static but dynamic.

A NEW SYSTEMS APPROACH FOR THE FARM LEVEL

The high-tech PA system briefly described above fits in the i+3/K4/K5 category. The low-tech system as described for the Sahelian region fits in the i+3/K2 category, because optimal placement of organic manure and crop residues within a field has to be based on the experience of farmers and experts. Sophisticated simulation modelling is not feasible because of the complexity of the system. We need properly spaced point observations in farmers' fields, and simulations and observations for each point, using measurements or pedo transfer functions to feed the models with proper data. Interpolation procedures can then yield patterns. In future, streamlining can be obtained by generating data for particular soil series and by classifying each observation point in terms of a given soil series. Data from the database can then be used to provide (simulated) data on the dynamic behaviour of the point. This approach (see [2, 10] for further details) may save much research effort in future and increase the use of existing soil surveys.

REGIONAL LEVEL: COMPARING OPTIONS FOR LAND USE IN COSTA RICA

TRADE-OFFS IN LAND USE: A KEY ISSUE

In areas where policies can have an impact on future types of land use, different interests associated with different land use alternatives have to be balanced very carefully to ensure a good decision making process. In fact, the more specific conflicting options can be compared, the better it is. The issue is particularly relevant for the Guacimo area (58,000 ha) in Costa Rica. Covered with tropical rain forest until the '50s, the area is now used for agricultural production. Still, questions remain as to which land uses are best and what effects particular policy measures may have on those land uses. The traditional land evaluation [11] does not and cannot provide adequate information. A separate estimation of the suitability of each land unit for a series of LUSs cannot lead to a well-balanced overall land use plan because not all relevant factors have been considered. In other studies, linear programming techniques have been succesful in comparing different land use options (*eg*, [25]). This approach was therefore followed for Costa Rica [19, 18]. Deciding among different land use options implies making strategic decisions.

LINEAR PROGRAMMING AS A TOOL TO COMPARE LAND USE OPTIONS

Studies in the Guacimo region of Costa Rica have been carried out using the USTED model (uso sostenible de tierras en al desarrollo: sustainable land use in development) [20]. The model evaluates effects of external factors on agricultural land use. The output of USTED (which is coupled with a GIS) is the selection and distribution of land use according to a goal and a set of constraints. The options in USTED are defined as combinations of a land unit and a land use type with a specified technology (LUST) [14]. Each LUST describes a quantitative combination of physical inputs and outputs in terms of technical coefficients, which are offered to a linear programming model [18]. Trade-offs between different policy goals are studied through scenarios in which the effects on land use are analyzed for different hypothetic changes in the socio-economic environment.

THE LAND UNIT

The results of linear programming are presented on georeferenced computer maps. Figure 2 shows an example with a predicted land use scenario following a 25 percent reduction in the price of palm heart. The scenario predicts that because of the price drop cassava, pasture and tree plantations will partly replace palm heart, resulting in a net decrease of 12 percent in farm income. Less biocides will be used, resulting in a 64 percent drop in the biocide index, which is distinguished as one of the sustainability indicators. This is only one example. Others relate to the effects of introducing an environmental tax, biocide regulation and capital availability [19].

Important in the context of this paper is the role of the land unit. In interdisciplinary projects, data from several disciplines have to be integrated, and even with modern computers this can create data handling problems. Each discipline is therefore urged to restrict its data to the utmost minimum. The discussion about the functionality of our taxonomic landscape units has been going on for years (*eg*, [24, 7]). The 1:150,000 soil survey for Guacima distinguished 50 major land units, which were generalized to three units for the USTED analysis. In all, 122 LUSTs were defined. Although attention must be paid to reducing the number of land units by "lumping", we can see that the land unit concept functions well in a modern regional study such as the one presented here. Economists do not necessarily like this, but soil differences within a region are usually so large that the implicit assumption that "anything can be done anywhere, economics permitting" does not hold—especially since emphasis on sustainability requires agronomic measures to be in balance with environmental requirements, expressed by threshold values for key indicators.

SPECIFICATION OF THE LUS IN SUSTAINABILITY STUDIES

The concepts of LU, LUT and LUS are still quite relevant in regional studies. Modern applications, involving sophisticated and knowledgeable stakeholders, require quantitative procedures, which specify trade-offs, to compare various land use options. The case of Guacimo illustrates this. The traditional land evaluation methodology follows an i+4/K2 approach; we need to upgrade this to an i+4/K3 approach, as shown above.

THE WORLD: CAN IT BE FED IN FUTURE?

EXPLORATORY STUDIES OF PRODUCTION CAPACITY

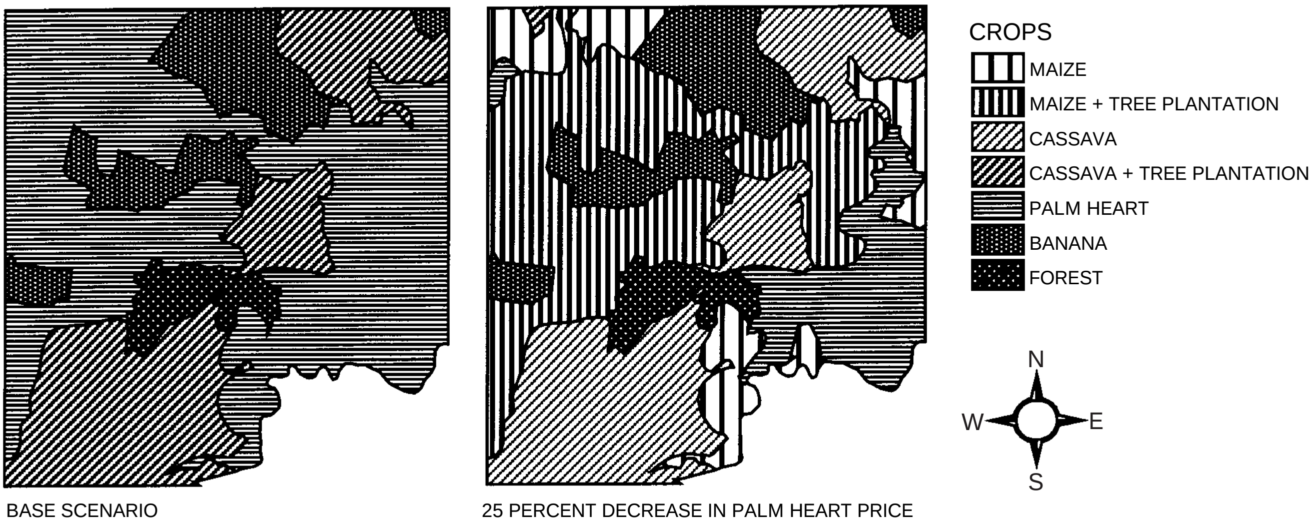
A recent study on global food security in 2040 illustrates the use of the LU, LUT and LUS concepts at world level [16, 15]. The interesting results of this study, which considered different scenarios including population growth and high versus low external-input agriculture, are intended to feed strategic decision making as to which policy issues are most relevant for which areas in the world. This paper, however, will focus on the treatment of the LUS concept.

THE LU AT WORLD LEVEL

The only available database for the cited studies was the NASA database [26], which was used earlier for climate impact studies. The world was divided into one degree grid cells (110 km by 110 km at the equator), for which three soil characteristics were selected: slope, soil phase and soil texture. These were derived from the FAO Soil Map of the World (1:5 million scale), and were assumed to represent the major soil type in the grid. Soils were supposed to be homogeneous, without layers or cracks; well drained; 0.6 m deep; and without runoff. Obviously, selecting representative soil parameters for the grid was very difficult and the assumptions made are clearly incorrect in many cases. However, simulations were aggregated for 15 regions in the world (as distinguished in UN population studies), and the authors used 15,500 land units occurring in 700 climatic zones. The problem of data reduction was much more severe here than it was for the Guacimo study. We conclude that the major land unit (as distinguished on small-scale maps) can be used in the context of world studies but that the composition of the soil association should be known in order to make a reasonable estimate of the composition of the arbitrary grid. No studies have been made on the error involved here.

THE LUT AT WORLD LEVEL

Some drastic simplifications were made by distinguishing only cereal crops (wheat for the temporal



BASE SCENARIO

25 PERCENT DECREASE IN PALM HEART PRICE

FIGURE 2 Two land use maps of the Guacimo area in Costa Rica, showing a base scenario and the predicted effects on land use of a 25 percent decrease in palm heart price (an arbitrary example from many different scenario runs). A linear programming procedure was used to quantify trade-offs between different land use scenarios, as a function of well-defined socio-economic boundary conditions (after [19]) region and rice for the tropics) and grassland, both expressed in grain equivalents (GE). Here a crop is used as an indicator of growing conditions, where the object is to provide indicator values. There is no direct relationship with actual land use. The results of the study are therefore of an exploratory character. What could be produced if ... . Of course, socio-economic or political conditions do not allow production to reach the indicated level or sometimes even to occur. At this scale level, the LUT becomes an indicator rather than a reflection of real land use patterns.

HOW TO DEAL WITH LAND USE SYSTEMS AT WORLD LEVEL?

Although the types of study of Penning de Vries *et al* [16, 15] are criticized as unrealistic and arbitrary, at least they give some agronomic indications as to what is possible in terms of food production under population growth scenarios and different production systems. There are, however, huge gaps in the procedure that can and must be filled. How to define “representative” soil data for the large grids being used is the question facing soil science. Systematic comparisons with larger-scale maps could be helpful to determine which factors are the most important. We need a soil variant of the intriguing approach by Penning de Vries *et al* in which they define agricultural production in terms of arable land and grass, using the GE concept as a common denominator.

CONCLUSIONS

(1) Land units, land utilization types and land use systems have to be defined differently at different spatial scales. The Hoosbeek and Bryant diagram, showing different methodologies at different spatial scales, is helpful in illustrating the choices to be made.

(2) Procedures should be based on user demands—which are different at different scales. Traditional land evaluation procedures are supply-oriented and focus on applying expert knowledge (K2) at the regional (i+4) level. This covers only a small part of the land use problems being raised.

(3) Land use decisions are made at strategic, tactical and operational levels and should be defined as such.

(4) Precision agriculture on farm level, both high- and low-tech, requires point data to be interpolated to areas of land, rather than land units defined by taxonomy. Land utilization types are not static but highly dynamic, as the farmer has to anticipate future weather conditions.

(5) Regional studies focus on alternative land use scenarios, with many interests at stake. Qualitative K2 procedures are unsatisfactory but the quantification of options can be obtained with linear programming techniques and simple modelling (K3 and i+4), as illustrated by a Costa Rican case study.

(6) Studies at world level imply gross simplifications, where representative soil data have to be defined for large grids and where production is generalized to grain equivalents. Soil scientists should define equivalent generalization approaches.

(7) Whereas many data in soil databases in developed countries are irrelevant and consequently not used, data availability in developing countries is at present a problem for land use studies. However, the availability of information technology and remote sensing data justifies the future application of identical techniques at different scale levels in developed and developing countries.

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RESUME

Les unités des terres, les types d'utilisation des terres et les systèmes d'utilisation des terres doivent être définis de façon différente pour différents niveaux d'échelle, par exemple pour la ferme, pour des niveaux régional et mondial tels qu'ils sont illustrés dans cet article. Le diagramme Hoosbeek et Briant, montrant la méthodologie comme une fonction d'échelles spatiales, est utilisé pour illustrer les procédures de recherche basées sur les demandes des utilisateurs. Des décisions d'utilisation des terres sont prises aux niveaux stratégique, tactique et opérationnel. Au niveau de la ferme, on fait des observations ponctuelles qui sont interpolées avec des zones de terre devant être utilisées pour une agriculture de précision. Des unités de terre taxonomiques et des types statiques d'utilisation ne sont pas pertinents, ces derniers parce que la gestion doit être pro-active et dynamique. Au niveau régional, les concepts traditionnels d'évaluation des terres conviennent mieux, mais l'application moderne exige des approches quantitatives, dans lesquelles différentes options d'utilisation des terres et leurs avantages sont comparés à l'aide de techniques linéaires de programmation. Finalement, le niveau mondial suppose de grosses simplifications, où les agronomes font une approche abstraite avec des équivalents de grain pour définir la production pour de larges grilles. La science du sol n'a pas encore développé une procédure satisfaisante pour définir des paramètres de sols représentatifs pour chaque grille. Bien que le manque de données limite le travail dans les pays en voie de développement jusqu'à present, nous pensons que l'accès à la technologie d'information et aux techniques modernes telles que la télédétection permettra la future utilisation de procédures identiques dans le monde entier pour chacun des différents niveaux d'échelle.

RESUMEN

Unidades, tipos de utilización y sistemas de uso de las tierras necesitan ser definidos diferentemente para distintos niveles de escala, por ejemplo para los niveles de finca, regional y mundial como ilustrado en este artículo. El diagrama de Hoosbeek y Bryant, que muestra la metodología en función de escalas espaciales, se usa para ilustrar procedimientos de investigación basados en las demandas de los usuarios. Las decisiones sobre el uso de las tierras se toman a niveles estratégicos, tácticos y operacionales. Al nivel de finca, se hacen observaciones puntuales, las cuales se interpolan a áreas de tierras que serán usadas para agricultura de precisión. Unidades taxonómicas de tierras y tipos estáticos de utilización no son relevantes porque el manejo tiene que ser pro-activo y dinámico. Al nivel regional, los conceptos tradicionales de evaluación de las tierras son los más adecuados, pero su aplicación moderna requiere enfoques cuantitativos para comparar diferentes opciones de uso de las tierras y sus implicaciones mediante técnicas de programación linear. Finalmente, el nivel mundial implica simplificaciones de conjunto, en las cuales los agrónomos usan un enfoque abstracto basado en equivalentes de granos para definir la producción en amplias celdas. La ciencia del suelo todavía no ha desarrollado un procedimiento satisfactorio para definir parámetros representativos de suelo para cada celda. Aun cuando hoy en día la falta de datos limita el trabajo en los países en vía de desarrollo, creemos que el acceso a la tecnología de la información y a técnicas modernas como la teledetección permitirá el uso futuro de procedimientos idénticos a través del mundo para cada uno de los diferentes niveles de escala.