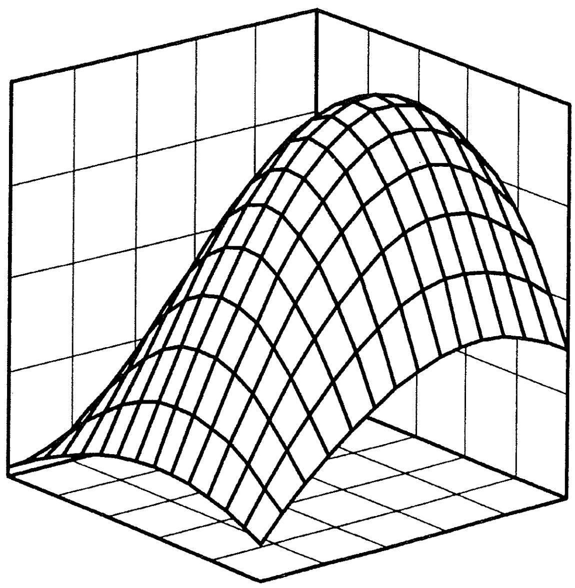
Information technology as a tool to assess land use options in space and time

Proceedings of an international workshop

Lima, September 28 – October 4, 1997



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Information Technology as a Tool to Assess Land Use Options in Space and Time

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Preface

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Researchers of different agricultural research institutes around the world have been working on tools for the analysis of land use options. Although the tools are being presented on conferences and workshops, one can question whether the usual 10-20 minutes available time span is enough to allow for a thorough discussion. On the other hand, we see specialized courses dealing with all the ins and outs of one specific tool. The C.T. de Wit graduate School for Production Ecology, the international Potato Center (CIP), the International Consortium for Agricultural Systems Applications (ICASA), and the DLO Research Institute for Agrobiology and Soil Fertility (AB-DLO) are dealing with the development of different tools for land use analysis. They started to realize the need for a thorough hands-on presentation of the different types of tools that have been developed and at the same time a setting where the tools are placed in a context. The workshop at CIP (Lima, Peru, September 28- October 4, 1997) of which the proceedings are presented here aimed specifically at filling this gap. The workshop forms a basis for other, more specific, courses. It includes introductions but at the same time enough detail is given to make appropriate selections. We would like to stress that the tools presented at the workshop are not intended to be a complete list. Many more tools have been and are being developed and may be included in similar courses in the future.

We thank the C.T. de Wit Research School for Production Ecology for their financial support. We would like to acknowledge the International Potato Center for hosting the event and their logistic support.

Table of Contents

1. Introduction

J. Bouma

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1.1. Backgrounds

An increasing number of tools for the analysis of land use is being developed. Although general methodological aspects and applications are being published in scientific publications and being presented at conferences, the ins and outs of the tools remain hidden while little attention is paid to the underlying assumptions and rationale and on operational aspects such as data availability and data reliability. Different international research organizations are now cooperating in the Latin America context. This workshop provides the possibility for different organizations to present their tools in detail in a hands-on setting while considerable time will be dedicated to the underlying assumptions and to the applicability of results obtained.

The workshop aimed at a discussion around the underlying assumptions and rationale of applying different methods to assess land use options at different scales ranging from fields and farms to regions. Six case studies have been demonstrated at field and regional level using operational procedures in a hands-on setting. Research centers as well as different donors urgently need information on the availability of tools, their limitations and their specific applications. The workshop aimed at an evaluation of results by discussing possible interactions between the various procedures and most promising future lines of research.

1.2. Land evaluation

Land use analyses was an important element of land evaluation as introduced by FAO (1976). Land evaluation was defined as follows:
"The process of assessment of the performance of land when used for specified purposes, involving the execution and interpretation of surveys and studies of land use, vegetation, land forms, soils, climate and other aspects of land in order to identify and make a comparison of promising land use systems in terms of applicability to the objectives of the evaluation".
Two elements stand out when considering this definition:

- Performance can only be assessed when specific purposes of the land use have been defined. In other words, we cannot judge performance in general, but only for specific types of land use. A piece of land may, for instance, function quite well as a campground but poorly when growing a wheat crop.
- Attention is not only paid to current land use but also to potential forms of land use, which may be more or less promising depending on the objectives of the evaluation.

Although currently land use analysis involves much more than the original land evaluation, the concepts are still worthwhile to study in more detail.

First of all land evaluation deals with land. What is "land"? It is more than soil: "Land is 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 extert a significant influence on present and future uses of the land by man".

"Land" is often represented as georeferenced "land mapping units" on soil maps. Such a land mapping unit is "an area demarcated on a map and possesses specified land characteristics and/or land qualities", to be defined later. The broad term "land use" is specified in terms of "Land Utilization Types" (LUT's) which define a particular type of land use in varying degrees of detail, but usually including listings of inputs and outputs. When combining the "Land Unit" with the "LUT" we obtain the so-called :"Land Use System" (LUS). Recent work in Costa Rica has defined such land use systems in terms of the type of technology (T) being used in each particular production system (Jansen and Schipper, 1995). They refer, therefore, to LUST's. An example is provided in Table 1.1.

Table 1.1 The static description of a LUST: a simplified example for a maize system in Costa Rica (after Jansen and Schipper,1995)

Operation	Date	Labour	Equipment	Materials
Land preparation	31/12/91	20 hours	machete	
Herbicide application	2/1/92	10 hours	knapsack sprayer	2 liters Gramoxome
Sowing	15/1/92	10 hours	planting stick	20 kilos local variety maize seed
Fertilizer application	30/1/92	10 hours		50 kilos ammonium nitrate
Harvest	15/05/92	50 hours		100 bags dry cobs

A key element in land evaluation is the "assessment of land performance". This is done, in principle, by comparing the requirements of a particular type of land use with what the land has to offer. When the two match, the land is suitable for a particular LUST. When they don't to varying degrees, suitability is less. Land suitability is correspondingly defined as: "the fitness of a given type of land for a specified kind of land use". This matching process, which is central in land evaluation, is handled by defining land qualities and land characteristics:

Land qualities are: "complex attributes of land which act 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 matching process is realized by expressing both land-use requirements and what the land has to offer in terms of land qualities, and by comparing the two expressions. Although this is not mentioned by FAO (1976), land qualities usually cannot directly be measured. Examples are the moisture supply capacity, the workability and the trafficability of land. They vary among the years and they are determined by land behaviour over extended periods of growing seasons. We will later discuss modern methods to determine land qualities. However, in the older land evaluation work attempts were made to find proxies for land qualities, the "Land characteristics". These are "Attributes of land that can be measured or estimated". We may think of texture, organic matter or carbonate content etc.

The basic elements of classical land evaluation have now been introduced. We have land which is being used for a particular purpose in a particular way. We not only look at current land use but also at other possible forms of land use which are of interest. We want to assess land performance for these different alternative forms of land use. We do so by comparing land requirements for each alternative form of land use with what the land has to offer. This matching process is made possible by defining important land qualities, often defined in terms of land characteristics in different classes. The overall analysis results in statements as to relative suitabilities of a given piece of land for a series of land use systems.

Much practical experience with this system is reflected in the work of Sys *et al.* (1991). We will now work out some examples to further illustrate the procedure and its limitations and to discuss some underlying concepts.

1.3. Beyond classical land evaluation

The classical land evaluation scheme has been applied widely and in many cases succesfully. Four problems have, however, become clear over the years:

- Even though the need to define objectives for any land evaluation has been stressed from the start, we see the development of a mechanistic approach (e.g. Sys *et al.*, 1991) in which land suitability is defined for a large number of LUST's, while it is not clear who is asking the questions or, worse, whether answers being provided address questions that are really being raised.
- Defining land qualities in terms of land characteristics has become a rigid qualitative procedure, even in automated computer-driven decision support systems (Rossiter, 1990), allowing little input from modern process-driven land research.
- The procedure is almost exclusively driven by the properties of the land, and even though the importance of socio-economic conditions is acknowledged, little is done to take these conditions into account. Land-use and its possible changes are usually more a reflection of socio-economic developments in society than of differences in soil suitabilities for different forms of land use. Moreover, land units as distinguished in earth science, hardly ever correspond with legal units in which decisions are made. A farmer farms a field with different land units; a district or county where land-use decisions may be made may cut through different land units etc.
- The procedure was implicitly defined as being scale independant. Most applications of classical land evaluation have been at regional level, but many land use questions are raised at farm or field level or at the continental or world level. Not only are the questions then quite different (see first point) but procedures to be followed should be different as well.

What we need now is a better evaluation of questions being asked at different spatial scales. Next, we need to define proper procedures to deal with these questions, realizing that we deal with a wide variety of stakeholders. And, finally, we need to define the proper role of the land in determining land use decisions. Certainly, decisions are not made for land units but for georeferenced surfaces on the earth that may contain many land units.

1.4. What is the question?

All over the world we see that land use patterns are more a reflection of the agricultural policies and the socio-economic environment than of relative suitabilities of different land units for different types of land use. Questions vary a great deal. Let us analyse some of them:

I. A farmer wants to know how he can obtain a high yield of profitable crops at minimal cost. Cutting costs, to be achieved by *e.g.* precision application of fertilizers and biocides or minimum tillage, is increasingly important. He certainly is not interested to hear that his land is "moderately suitable for wheat growing". He will know that. He wants quantitative information in terms of "what" to do "when".

II. An environmentalist will ask how use of agrochemicals can be reduced or even abolished, thus avoiding leaching into ground- or surfacewater. To answer such questions, detailed process-based simulation models may have to be applied to estimate the adsorption of agrochemicals as a function of management. Of course, the ideal is to combine the desires under (I) with those under (II): the basic concept of precision agriculture. This process clearly involves trade-offs between conflicting aims.

III. A regional planner may want to formulate alternative land use options within a region. Here, the existing land evaluation procedure may be useful but data are not specific enough for allowing quantitative trade-offs among the various options.

IV. A policy maker may see options for land use in a region or a country, formulated by procedures under (III). His question, however, is how attractive options can indeed be realized? How can stakeholders be influenced to do the "right" thing? Special taxes, bonusses, subsidies? Clearly, land evaluation does not primarily focus on such issues but they are crucial for future land use and should therefore be considered.

Considering the range of questions that are encountered, we may distinguish four broad approaches that have been used to answer them (Jansen *et al.*, 1996). The approaches can be applied, in principle, at any hierarchial scale:

- The prediction of future land use based on extrapolation of existing trends. The type of question to be answered is: What will be likely land-use changes if trends in land use are extrapolated to the near future? The past is used as a measure for the future: optimization of future land use considering trade-offs between contrasting objectives is not possible and land use changes may be predicted that are not feasible from a biophysical point of view. (Particularly applied at regional and higher levels: *e.g.* Veldkamp and Fresco, 1996)
- The exploratory approach which defines a number of feasible land use options for the area to be considered. The stakeholder makes a choice. The type of question to be answered is: What are the options for land use, how can we optimize land use for certain objectives and what are the trade-offs between these objectives? Whether or not such options are realized depends on the stakeholders. The exploratory approach does not predict but explores what has been called a “window of opportunity”. The approach is sometimes criticized because what is agro-ecologically possible may never be realized in agricultural production systems where socio-economic factors play a major role (particularly applied at regional and higher level. Examples are FAO (1976) and Van Latesteijn and Rabbinge (1994).
- Identification of policy instruments to realize particular land-use options. The type of question to be answered: What are effective policy instruments to induce changes in land use? Applied at all scales. An examples for the farm level was reported by Kruseman *et al.* (1995).
- Developing decision support systems to allow realization of sustainable land use. The type of question to be answered is: “what” should be done “when” and “where” in terms of land and crop management to realize a sustainable agricultural production system, in balance with nature (particularly applied at farm level *e.g.* Bouma, 1997[a]).

Different questions will require different procedures (and tools) to tackle the problem.

1.5. What is the proper procedure?

A diagram, introduced by Hoosbeek and Bryant (1992), has been helpful to illustrate various research procedures (Figure 1.1). They considered two perpendicular axes, one ranging from qualitative to quantitative and the other from empirical to mechanistic. The vertical axis represents the scale hierarchy, where the pedon level (the individual soil) occupies the central position (i level). Higher levels are indicated as i+, while lower levels are i-. The scale in Figure 1.1 ranges from molecular interaction (i-4) to the world level (i+6).

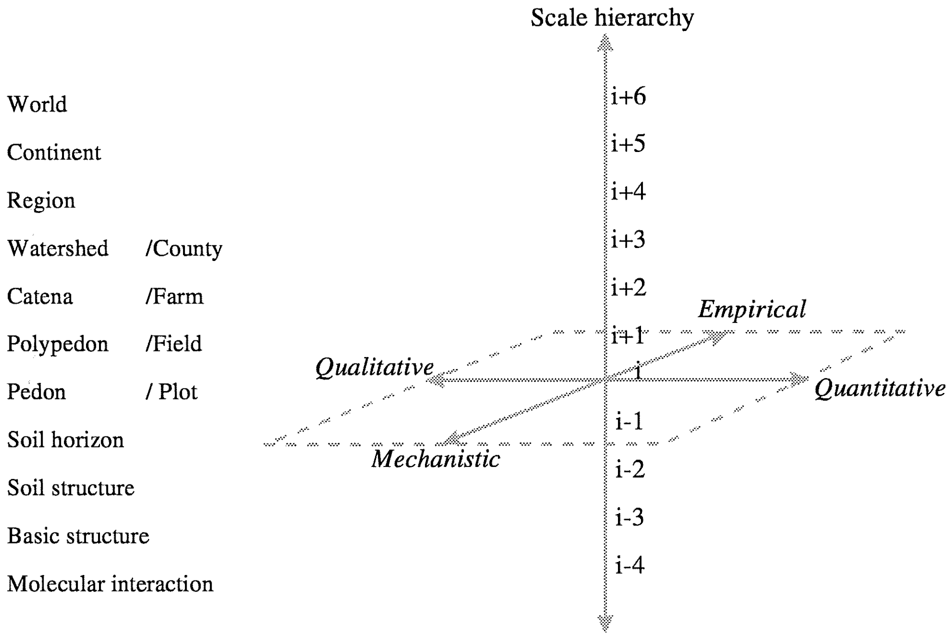

Figure 1.1 Classification scheme for research procedures

Different research approaches occur within the plane thus obtained (Figure 1.2):
K1 application of user expertise
K2: expert knowledge
K3: Use of simple comprehensive methods, including modeling
K4: Complex, mechanistic methods, including modeling
K5: Detailed methods, including modeling, which focus on one aspect only, often with a disciplinary character.
We can now place the classic land evaluation in the scheme at scale hierarchy "watershed or region" while the knowledge level is: K2. For other questions, raised above, we need different hierarchies and knowledge levels. For example, the farmer and environmentalist would require the i+1 field scale and a K4 knowledge level to get the necessary quantitative answers for their questions. The regional planner would operate at level i+4 and would need a K3 knowledge level, because the K2 level would be too descriptive not allowing a quantitative trade-off analysis. He would be smart, though, to combine K2 with K3 , by restricting the more detailed analyses of K3 to areas where a simpler K2 analysis could not provide answers. For example, Van Lanen *et al.* (1992) made a land evaluation for Europe in which potential for crop growth was established. They first screened out strongly sloping land and land with shallow bedrock using a K2 approach. Then, in the remaining 40% of the land area, they ran a K3 simulation model to predict crop growth. The K2 approach for these

soils ("land is moderately suitable for wheat") would not have been satisfactory. This introduces the possibility to combine approaches. A last example will be provided to further illustrate this attractive application of the scale diagram.

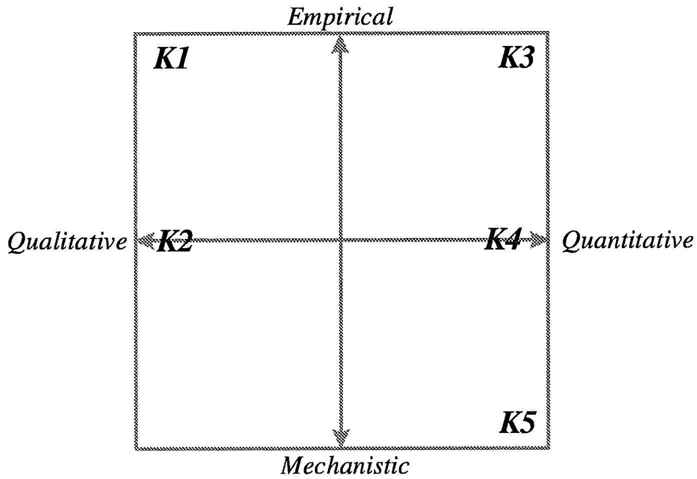

Figure 1.2 Different knowledge levels

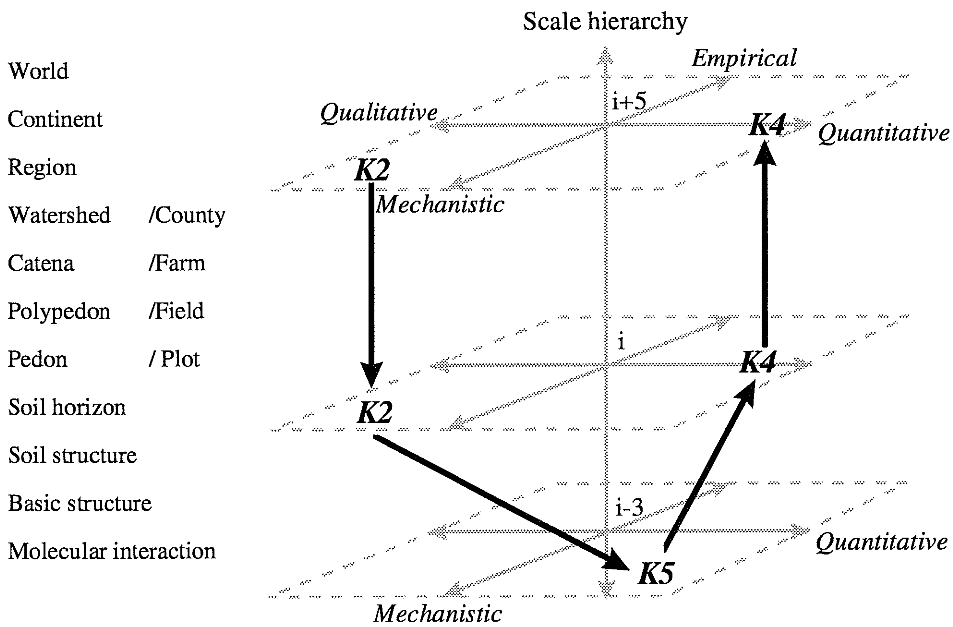

Figure 1.3 An illustration of a *research chain* representing the sequence of research activities at different scale hierarchies, applying different categories of research. This chain belongs to a study on critical loads on forests soils in Europe, as reviewed by Bouma and Hoosbeek (1995).

De Vries *et al.* (1992) did a study to determine the possible impact of acid rain on soil acidification. They dealt with non agricultural areas without fertilization. They divided Europe (scale i+5) (Figure 1.3) into grids and for each grid they determined the dominant soil type, using the soil map of Europe (K2 knowledge). Then, they selected a limited number of soil units (level i) that were considered to be representative for European soils (using K2 knowledge). In these soils they made some detailed measurements of weathering rates (scale i-4; knowledge level K5). Next this knowledge was scaled up again, resulting in effective K4 knowledge at European level. It would have been impossible to make the detailed K5 measurements of weathering rates in all European soils. By using expert knowledge at different scales, measurements could be made more efficient. Of course, ideally measurements should always include a measure for reliability and accuracy. An overall K5 approach for all soils would have the highest reliability but would be too expensive. We must know how much we loose in terms of reliability when we go from K5 to K4, K3 and K2. This is part of what has been called "Research Negotation" by Bouma (1997[b]). Decisions as to what to do can only based on this type of information.

The lines in Figure 1.3 represent a so-called "research chain" demonstrating how a given problem can be analysed by combining knowledge at different scales.

Before jumping into any land evaluation activity we advocate to first analyse the question being raised very carefully in close interaction with the stakeholder. Do we want to see what it means when trends from the past are extended? Do we want to explore alternative options? Do we want to define policy measures focused on the realization of one of these options? Or do we want to define a specific decision support system for the land user, guiding him to the right decisions? Or, perhaps, we want the entire logical sequence from exploratory, policy driven to decision support. Once the question has thus been analysed, we then proceed with defining the most efficient research chain.

Specifically, the following seven steps are therefore involved (from: Bouma *et al.*, 1997):

1. Problem definition in interaction with stakeholders.
2. Selection of research method (e.g. exploratory, predictive, policy oriented, decision support) and identification of participating disciplines.
3. Model development considering scale hierarchy.
4. Establish data requirements: to be satisfied by existing data and new data collection.
5. Model application.
6. Quality assessment: accuracy and reliability; risk.
7. Presentation: due attention to role of information technology.

1.6. What is the role of the land?

We have mentioned several times so far that decisions on land use are governed by many factors beyond those that are directly associated with the land. In fact, such socio-economic factors are most important. In this context, classic land evaluation and exploratory studies on land use which were based on agro-ecological principles have drawn considerable critism of non agriculturalists.

First of all, there clearly is a shift in focus during the last decades. Exclusive emphasis on food production and security after the Second World War has resulted in a technology explosion: problems in food production were there to be solved. Land that was too wet, was drained; Land that was too poor was fertilized, even at very high rates; Land that was too dry was irrigated and land where crops were suffering from pests and diseases was treated with biocides.

Initially these measures were taken with only food production in mind and this has locally lead to considerable pollution of land and water. Later, concern for the environment played an increasingly important role and as this process was unfolding, and as a balance had to be struck between agricultural production on the one hand and environmental quality of soil and water on the other, the importance of agro-ecological features of the land increased dramatically. There used to be the technology driven spirit:" Anything can be done anywhere". Now we realize again that a "sand" will never be a "clay" and that the natural dynamics of soils in different agro-ecological zones are the basis for developing sustainable production systems that are in harmony with nature and the environment.

However, we need to take a new look at the way in which we present our soils to international interdisciplinary research groups that work on sustainability and global change (Bouma, 1994; Bouma and Hoosbeek, 1995). The classical land evaluation approach was land centered and provided few contact points with other disciplines. Besides, it was based on a descriptive K2 approach (which was quite innovative at the time). Now, we are in a position to use modern K3, K4 and K5 methods to provide a quantitative analysis of agricultural production systems including important trade-offs between production and environmental quality. A strong emphasis should be on providing various options for any given land unit from which the stakeholder may choose. That is why the term “options” was used for this workshop.

There is one more point: soils do not occur in random patterns in a landscape. They are formed by geomorphological processes and soil forming factors that differ significantly in different agro-ecological zones. Much work in soil science has been done on soil classification: grouping of soils that are comparable in their basic soil properties. We advocate use of such groupings to describe soil behavior in terms of a "window of opportunity" for any given soil series (which is the lowest hierarchial unit of classification). We expect every soil series to present a characteristic "window" (a quantitative and scientific expression of the conviction that a "sand" will never act like a "clay" no matter what a farmer does!). Even though different forms of management will lead to different soil conditions even within the same soil series, the range of conditions (the "window") will be characteristically different for each series. We will not further explore this issue here and refer to van Lanen *et al* (1987, 1992) and Droogers and Bouma (1997) for further details. We do believe, however, that exploration of such “windows of opportunity” is a profitable route for future soil survey and pedology research.

1.7. Interaction with stakeholders in the information age

Interaction with stakeholders has been emphasized many times in the above sections, during problem definition and the research process including final reporting. In the past much research has been top-down. The researcher had an impression as to what the problem was that needed to be investigated and he or she was used to press forward using his favorite model, expert system or data-gathering techniques. In the end the results of the study were presented to the stakeholders. To be sure, there are many examples of fine and effective research being executed this way that has lead to succesful implementation. However, there are also too many examples of research efforts that were less succesful ending up in a desk, covered with dust. The challenge now is to involve stakeholders to the extent that research is being executed jointly with constant interaction having the effect that the end result of the work is also experienced as a "joint" product. “They” do not have a problem that “we” must solve. We have a joint problem and we need an interactive research approach.

A good example of poorly focused attention on stakeholders is the exclusive focus of land evaluation on land mapping units while areas of land for which decisions have to be made usually do not correspond with the boundaries of land units. A farmer is faced with his fields which often are composed of different types of land. What is being done in terms of management is largely determined by the proportion of these different land units: wet parts of the field cause a delay of tillage and sowing while the dryer parts would have allowed this much earlier. Precision agriculture attempts to base management on such differences, occurring within fields. Again, at higher scale hierarchies land units do not necessarily correspond with units of management. Recently, therefore, resource management domains have been defined which are relatively homogeneous in terms of agro-ecological properties and socio-economic conditions (Dumanski and Craswel, 1996).

Modern information technology has an important role to play in stimulating interaction with stakeholders. Visualization of alternative land use patterns, associated with different options, is a very powerful tool to involve stakeholders. "A picture says more than a thousand words". Interactive computer technology allows, for instance, generation of alternative land use scenarios with all associated input data provided jointly by researchers and stakeholders. Also, the above-mentioned expected improvement of results when moving from K2 to K3, K4 and K5 approaches can be visualized as well by showing the accuracy of the obtained land-use maps. The stakeholder can decide whether or not the costly improvement of the product is worth the cost. As Bouma (1993) has pointed out, several problems can be well solved with a relatively cheap K2 approach. This may be scientifically less challenging, but it is quite important from a practical point of view.

1.8. The workshop

In the workshop several tools were presented. Most tools deal with a specific scale level and with specific time horizons (Figure 1.4). At the same time we see that some have a more qualitative character and empirical character whereas others follow quantitative and mechanistic lines of research. Data requirements will change with approach and determine in many cases whether the tool is suitable for practical applications. We therefore need to discuss the different procedures that we can use to answer our stakeholders. Important characteristics of the tools determine whether the tools are predictive, explorative or are focused on decision support. Our focus is on providing land use options. Models are a tool, not a purpose in themselves.

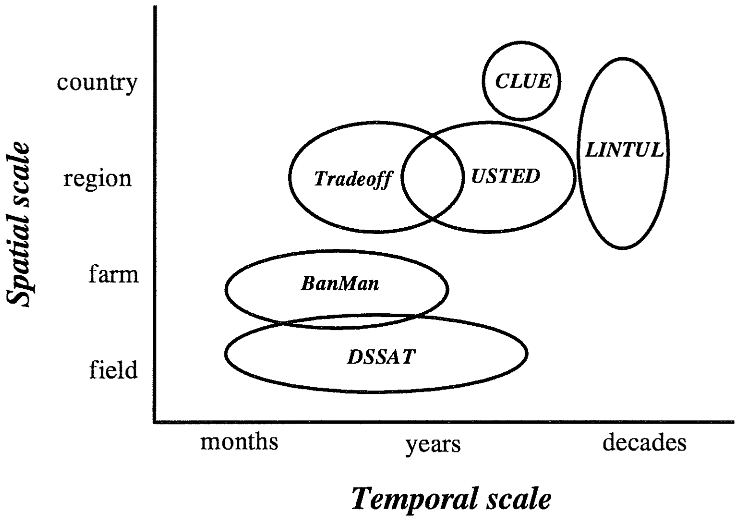

Figure 1.4 The different tools and the spatial and temporal scales at which they are applied in the workshop.

During the workshop we focused on a number of specific questions:

- How were the various studies initiated? How can this process be affected? What is the ideal mix of supply and demand?
- Did the reported studies answer the problem being raised or could other procedures have been used? Should they have been used?
- Can gaps be identified in the research areas being presented, *i.e.* important issues/problems in land use for which no tool is available? How should we cope with those gaps?
- How do we identify pro-active exploratory studies on future land use, its management and development?
- How do we tackle the data crisis? Increasingly complex models are being developed. With increasing complexity, data requirements similarly rise. Do we reach a point where our models can only be applied at extremely well studied research sites? Do we need more focus on data collection and procedures to extrapolate our tools to conditions of low data availability?

References

Bouma J 1993 Soil behaviour under field conditions: Differences in perception and their effects on research. Geoderma 60: 1-15

Bouma J 1994 Sustainable land use as a future focus of pedology. Guest Editorial Soil Sci. Soc. Amer. J. 58: 645-646

Bouma J 1997[a] Soil environmental quality: a European perspective. J. of Environmental Quality 26: 26-31

Bouma J 1997[b] Role of quantitative approaches in soil science when interacting with stakeholders. Geoderma 78: 1-12

Bouma J, Finke PA, Hoosbeek MR, Breeuwsma A 1997 Soil and water quality at different scales: concepts, challenges, conclusions and recommendations. Nutrient Cycling in Agro-ecosystems (in press)

Bouma J, Hoosbeek MR 1995 The contribution and importance of soil scientists in interdisciplinary projects dealing with land. *In* Wagenet, R.J. *et al.* (ed.). The role of soil science in interdisciplinary research. SSSA Spec. Publ. 45. ASA and SSSA, Madison, WI: 1-15

De Vries W, Posch M, Reinds GJ, Kamari J 1992 Critical loads and their exceedance on forest soils in Europe. Report 58. Winand Staring Centre, Wageningen, The Netherlands and Water and Env. Res. Institute, Helsinki, Finland

Droogers P, Bouma J 1997 Soil Survey Input in exploratory modeling of sustainable soil management practices. Soil Sci. Soc. Am. J. 61: 1704-1710

Dumanski J, Craswell E 1997 Resource management domains for evaluation and management of agroecological systems. *In*: J.K.Syers and J.Bouma (Eds.). Resource Management Domains. Proc. International Workshop, 26-19 August 1996. Kuala Lumpur. Maleisia. IBSRAM, Bangkok (in press)

FAO 1976 A framework for land evaluation. FAO Soils Bulletin 32. Rome.

Hoosbeek MR, Bryant R 1992 Towards quantitative modeling of pedogenesis - a review. Geoderma 55: 183-210

Jansen DM, Schipper RA 1995 A static, descriptive approach to quantify land use systems. Netherlands Journal of Agricultural Sciences 43: 31-46

Jansen HGP, Stoorvogel JJ, Bouma J, Nieuwenhuyse A, van Ittersum M, Veldkamp T, Ibrahim M, Nibbering J-W, Efdé S, Eppink L, Boerrigter B 1996. The 1996-1998 phase of REPOSA: report of a research planning exercise. Report 106, Working Document 27, REPOSA, Guápiles, Costa Rica

Kruseman G, Ruben R, Hengsdijk H, van Ittersum MK 1995 Farm household modelling for estimating the effectiveness of price instruments in land use policy. Netherlands J. of Agr. Science 43: 111-123

Rossiter DG 1990 ALES: A framework for land evaluation using a microcomputer. Soil Use and Management 6: 7-20

Sys C, van Ranst E, Debaveye J 1991 Land evaluation. Part 1: Principles in land evaluation and crop production calculations; Part II Methods in land evaluation. Int. Training Center for post graduate soil scientists. Univ. Gent. Belgium

Van Lanen HAJ, Bannink MH, Bouma J 1987 Use of simulation to assess the effect of different tillage practices on land qualities of a sandy loam. Soil and Tillage Research 10: 347-361

Van Lanen HAJ, Reinds GJ, Boersma OH, Bouma J 1992 Impact of soil management systems on soil structure and physical properties in a clay loam soil and the simulated effects on water deficits, soil aeration and workability. Soil and Tillage Research 10: 203-220

Van Latesteijn HC, Rabbinge R 1994 *In*: Sustainable land use planning, H.N. van Lier *et al.* (eds.). Elsevier Sci. Publ., Amsterdam: 31-45

Veldkamp A., Fresco LO 1996 CLUE: a conceptual framework to study the Conversion of Land Use and its Effects. Ecological modelling, 85: 253-270

2. BanMan: a decision support system for banana management

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2.1. Introduction

Decision support systems are developed to support decisions of stakeholders. This Chapter discusses the development and application of a decision support system for agricultural management of banana plantations. In other chapters of these proceedings, decision support systems at other spatial and temporal scales are presented (*e.g.* DSSAT in chapter 3 and tools for application at the regional level in Chapters 6 and 7). One of the principal characteristics of decision support systems is that they are demand driven. Farmers experience specific problems and look for a system that helps them in the evaluation of different decisions. Note that the systems <u>support</u> management decisions and do not <u>take</u> the decisions.

BanMan, the decision support system that is presented in this case study, is developed as a decision support system for the cultivation of bananas. This Chapter will explain the rationale behind the development of the system, the different steps that were taken during the development and the current operation of the system.

2.2. The rationale of the development

Besides pastures, banana is the dominant crop in the perhumid coastal plains in the northeast of Costa Rica. The perennial crop is cultivated on large farms of over 100 ha and covers approximately 52,000 has (1994 figure, Corbana) or 10% of the area. Within Costa Rica, a country proud on its nature management and with a very strong environmental movement, the banana plantations are increasingly seen in relation to the pollution of the environment. One of the problems is the location of the plantations most of which drain into a unique marsh area and National Park in the north east of the Atlantic Zone (Figure 2.1). The location of the plantations in combination with the high average annual rainfall of 3600-4000 mm and high use of external inputs, results in an overall picture that the plantations contaminate the environment. At the same time, however, banana plantations contribute significantly to the national income of Costa Rica, making it extremely difficult for politics to strongly regulate the farming system. Due to the strong international competition in the world banana market, regulations in Costa Rica could easily lead to a decision of the multinational companies (owning over 50% of the plantations) to leave Costa Rica.

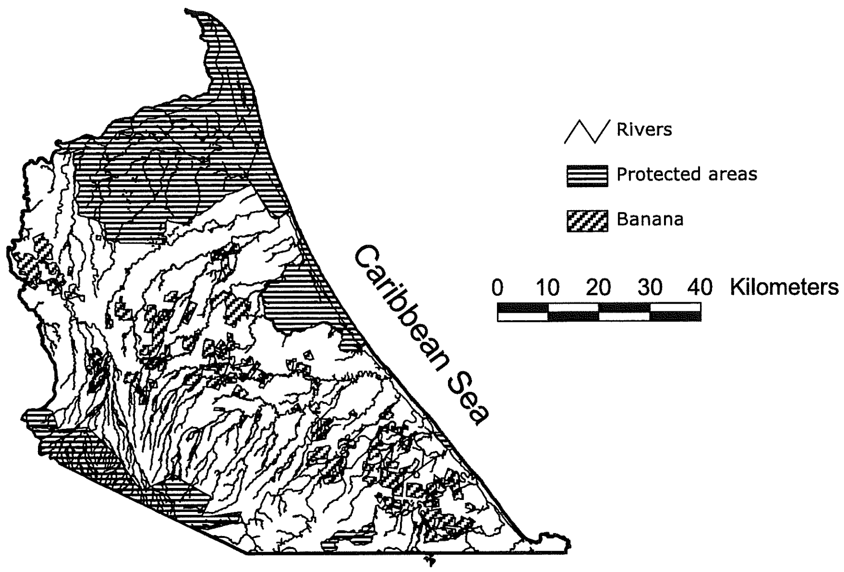

Figure 2.1 The location of banana plantations and protected marsh areas in the Atlantic Zone of Costa Rica

In close cooperation with CORBANA[1] and REPOSA[2] research was started to deal with two main questions:

1. Can we quantify the amount of pesticides and fertilizer lost to the environment as a result of the cultivation of bananas?
2. Can we find options to improve management in such a way that pesticides and fertilizers are used more efficiently leading to increased profits and a reduction in losses to the environment?

Note that researchers on the basis of a public discussion going on in Costa Rica at that time formulated the above two questions. Whereas regulations at a national level were not considered to provide a practical solution, it was decided to try to develop a system that would be interesting for farmers (mainly in terms of farm economics) and at the same time would change the farming system towards a more environmental friendly one. A regional problem was redefined to a problem at farm level. The research line as such was pro-active, where researchers approached the farmer with a system that would lead to a more cost effective way of farming and probably would lead to a more environmental friendly management.

The decision support system that would lead to changes in banana management has been developed in close cooperation with the Rebusca farm. The Rebusca farm (84°01' E, 10°28'N; Figure 2.2) covers an area of 107 ha. The farm was established in 1991, during the expansion of banana in the Atlantic zone of Costa Rica. Similar to other farms in the Atlantic Zone, Rebusca used high external inputs: annually 1800 kg/ha of mineral fertilizer, 6000 kg/ha of organic fertilizer, two applications of nematicides and 15 applications with fungicides. Although nutrient removal by the crop and climatic conditions explain the inputs, increased efficiency in their use may cut down the costs and increase their effect. One of the main reasons why researchers thought that efficiency in farm management could increase was the high soil variability in combination with inputs applied as one single dressing.

[1] *Corporación Bananera Nacional*, San José, Costa Rica

[2] Research Program on Sustainability in Agriculture, Guápiles, Costa Rica

Although farmers were aware of large differences in production, they do not have the tools available for the registration of these differences and thus to adapt management according to the differences.

2.3. Spatial variability at field level

The decision support system for banana management, denominated BanMan, has been developed to allow farmers a better understanding of the spatial variability on their farm. The decision support system is based on a description of spatial variability of his farm through a detailed soil survey of the farm and through site specific yield monitoring. During the development of the decision support system it was realized that data requirements and possible investments in equipment should be kept as low as low as possible to gain interest of the farmer. In a later stadium when the farmer has become interested, it may be possible to include additional observations.

Soil variability is described through a detailed 1:5,000 soil survey of the plantation (Figure 2.2). Six different soil types have been identified (Table 2.1 and 2.2). Although some of the soils (*e.g.* soil Hill) are recognized to be not suitable for the cultivation, bananas has been planted on all the soil types. The biggest investment in the establishment of the plantation is the infrastructure (packing plant, cables, and trucks). This investment is economically interesting whereas a large area of the plantation has soils that are very suitable for the cultivation of bananas. This area justifies the economic investment. Planting bananas in small adjacent areas with less favorable soils requires a small additional investment and is, therefore economically interesting. As a result, however, soil variability occurs and management should be adapted accordingly. Nevertheless, we see that the plantations are managed as if no soil variability occurs.

To make site-specific management recommendations, soil resources as well as yield maps are required. Yield maps are generated through site specific yield monitoring which is the core of the decision support system. Yield monitoring is increasingly being applied in grain crops where continuous grain flow monitors in conjunction with global positioning systems are installed on combines resulting in detailed yield maps (see *e.g.* Robert *et al.* 1995). In other crops, however, yield monitoring is not being applied because efficient register systems are lacking. Experiments revealed, however, that yields in other crops are similarly variable (e.g. Brouwer and Bouma 1997, Verhagen 1997). Site specific yield monitoring will only be worthwhile when differences in yields are suspected. In the case of better-developed banana plantations, yields are registered per cable and, although the cables cover relatively large areas and include a lot of soil variability, yields were found to be highly variable. A methodology for site-specific monitoring was not available and had to be developed.

In Costa Rica, bananas are cultivated in a continuous cropping system. This is possible as there are relatively small differences in weather throughout the year. Depending on weather conditions each area is harvested approximately 2 times per week. The area is checked for bunches with bananas with the proper grades which are harvested and transported manually to a grid of cables running throughout the plantation (Figure 2.3). When 20-30 bunches have been harvested, the 'train' is pulled to the packing plant where the bananas are processed and packed.

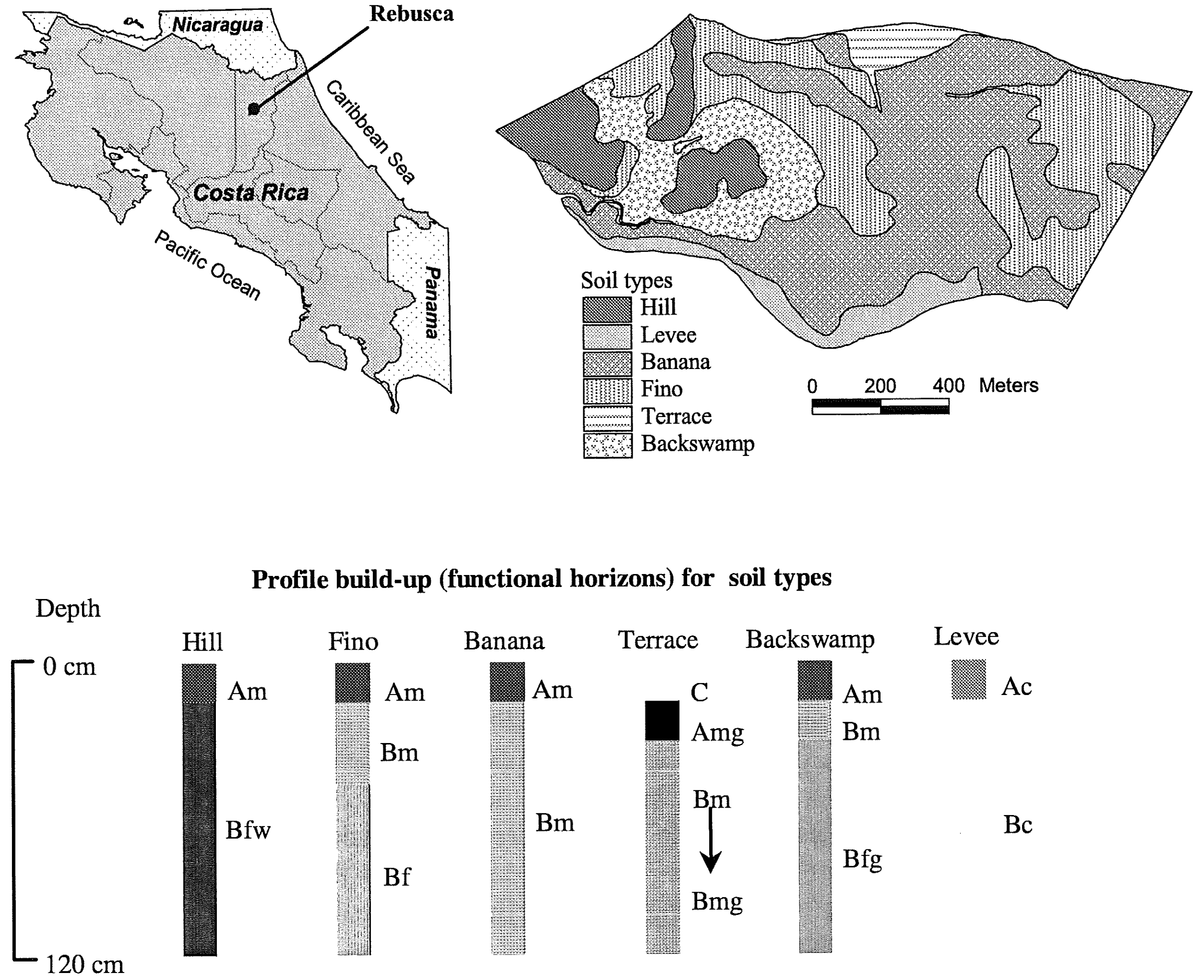

Figure 2.2 The location of the Rebusca banana plantation and the soil distribution within the plantation.

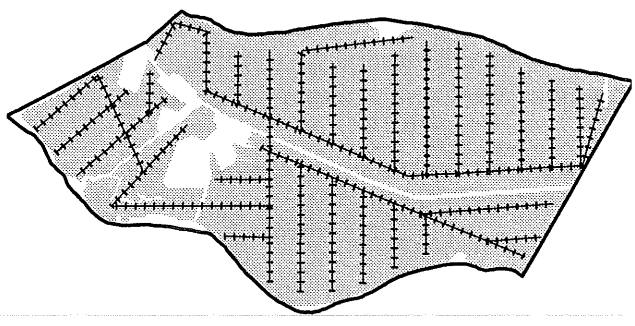

Figure 2.3 Cable infrastructure in the banana plantation

Table 2.1 Legend for the 1:5,000 soil map of the Rebusca farm

Well drained soils	
Soil Hill	A moderately deep, very fine textured soil. Grayish brown A horizon (bb 11), 10-15 cm thick and rock fragments in the brown, clayey B (bb 26) with a depth deeper than 120 cm. Positioned on hill.
Soil Levee	A moderately deep, coarse textured soil. Grayish (yellow) brown A horizon (bb 11 or 12), 10-15 cm thick occasionally with mottling overlying a (dark) brown coarse textured B horizon (bb 20) with a depth deeper than 120 cm. Positioned on levees.
Moderately well drained soils	
Soil Banana	A moderately deep to deep, medium textured soil. Grayish (yellow) brown A horizon (bb 11 or 12), 15-20 cm thick occasionally with mottling overlying a dark to yellowish brown B horizon (bb 21 or 22) with a (sandy) loam texture with a depth deeper than 120 cm. Sometimes mottled below 40 cm.
Soil Fino	A moderately deep to deep, medium to fine textured soil. Grayish (yellow) brown A horizon (bb 11 or 12), 15-20 cm thick occasionally with mottling, overlying a (dark) brown medium textured B horizon (bb 21), 20-40 cm thick followed by a (grayish) yellowish brown B horizon (bb 23 or 24) with a clay loam texture with a depth deeper than 120 cm, sometimes mottled below 40 cm.
Poorly drained soils	
Soil Terrace	A moderately deep, coarse to medium textured soil. A top layer of grayish yellow brown coarse textured C material and/or brownish gray fine textured C material (bb 30 and/or 31), 5-60 cm thick overlying a grayish (yellow) brown medium textured A horizon (bb 12), 10-15 cm thick followed by a layered profile of coarse and/or medium textured B horizons (bb 20, 21 and 22) with a depth till 130 cm. Reduced below 130 cm. Mottling occurs within 40 cm depth, recently sedimented horizon(s) not taken into account. Positioned on the terrace.
Soil Backswamp	A moderately deep, medium to fine textured soil. Grayish (yellow) brown A horizon (bb 11 or 12), 10-15 cm thick sometimes mottled overlying a (dark) brown medium textured B horizont (bb 21 or 22), 20-40 cm thick followed by a dull yellowish brown B horizon (bb 24) with a clay loam texture and a depth deeper than 120 cm. Occasionally the whole B horizon consists only of fine textured material. Mottling occurs within 40 cm of the profile. Positioned in backswamps.
Soil Swampo	A moderately deep medium to fine textured soil. Brown humic A horizon (bb 11 or 12), 10-15 cm thick overlying a brownish black B horizon (bb 60) high in organic matter, 60-100 cm thick followed by a reduced horizont (bb 25) deeper than 120 cm. Occasionally mottled.

Table 2.2 Chemical analysis of the different soil horizons identified in the soil survey of the Rebusca farm

Code	PH	Extr acid	Ca	Mg	K	P	Fe	Cu	Zn	Mn	O.M.	CIC	Ca	Mg	K	Amorf %	
		cmol/l				mg/l					%	meq/100g de suelo				Fe	Al
A-Horizons																	
bb 10	6.3	0.08	7	2.6	1.6	22	163	15	4.2	10	2.7	14	6.1	2.6	2.3		
bb 11	5.2	0.88	8	2.5	1.2	62	460	20	5.8	16	8.2	26	9.0	2.8	1.9		
bb 12	5.5	1.03	6	2.0	1.8	29	445	21	6.0	20	6.9	33	6.6	2.3	3.2		
B-horizons																	
bb 20	6.7	0.06	10	2.5	0.3	22	83	11	3.6	3	0.4	12	9.1	2.5	0.4	0.6	1.1
bb 21	5.9	0.05	8	2.2	0.3	13	122	15	3.1	6	1.5	16	9.5	2.5	0.4	2.4	1.2
bb 22	6.2	0.53	10	3.0	0.3	21	193	17	2.7	9	1.8	18	11.5	3.5	0.5	1.5	1.3
bb 23	6.2	0.07	12	2.3	0.3	39	161	17	2.5	5	1.3	19	15.0	2.9	0.5	0.9	1.2
bb 24	6.7	0.06	12	4.3	0.2	24	126	19	2.5	4	1.0	25	14.6	5.0	0.3	0.9	1.3
bb 26	5.5	0.05	5	1.1	0.2	4	76	17	1.6	9	1.7	14	4.5	1.1	0.3		
C-horizons																	
bb 30	4.8	7.76	5	0.8	0.2	26	356	13	2.0	29	0.5	15	4.0	0.6	0.3		
bb 31	5.2	1.56	12	3.4	0.6	31	378	16	2.5	138	2.5	13	13.7	3.9	0.7		

For site specific yield monitoring the area along the cable is harvested sequentially and as a result by registering the point where the trains leave, we can contribute that train to a specific area, *i.e.* the area between the point of the previous train and the actual one. By registering the origin of the trains and weighing the bunches of each train (by using a balance in the cable) yields are monitored. The balance provides us with the following kind of files:

```
SCALE ID# 1
 2:31 PM  9/11/96

"0101   "
   527.6 KG  TOTAL,  20 SAMPLE
    26.4 KG  AVG
    18.4 KG  MIN
    38.6 KG  MAX
     5.6 KG  STDDEV
   21.03 %   CO.VAR

"0105   "
   517.6 KG  TOTAL,  20 SAMPLE
    25.8 KG  AVG
    19.2 KG  MIN
    32.6 KG  MAX
     4.0 KG  STDDEV
   15.20 %   CO.VAR

"0109   "
   340.6 KG  TOTAL,  12 SAMPLE
    28.4 KG  AVG
    18.8 KG  MIN
    38.4 KG  MAX
     6.2 KG  STDDEV
   21.86 %   CO.VAR
```

Every train that entered the packing plant is described by its code, *e.g.*0109 (cable 1, tower 9[3]). A balance is placed in the cable where the bananas enter the packing plant registering for each train:

- number of bunches,
- average weight of the bunches,
- minimum and maximum weight, and
- standard deviation of the weight of the bunches.

As the cables are harvested sequentially, we know that bunches of this particular train come from the area between tower[3] 6 and 9. This corresponds with an area of 40 by 100 meter. Note that during a next harvest the spatial units may be different. So it may be that next time a train covers the area between tower 8 and 10. The farm is subdivided in 418 units for which yield is determined. BanMan combines the data of all the trains and creates a yield map (Figure 2.4).

[3] Cables are supported every 10 m by a ∩-shaped support denominated ‘tower’. Cables and towers are numbered and are used as a geo-reference.

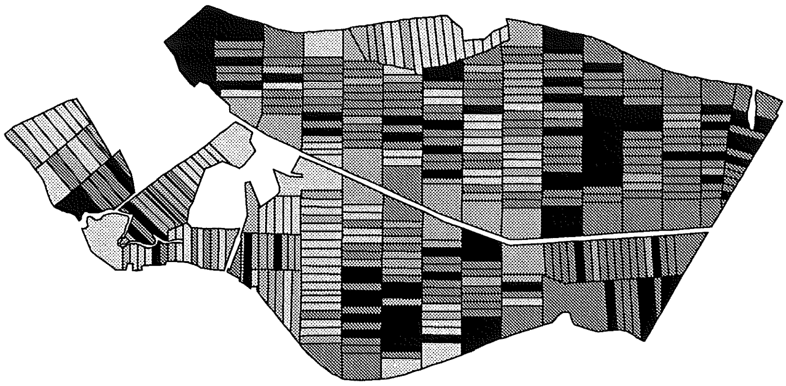

Figure 2.4 **Yield map for the Rebusca plantation**

2.4. From spatial variability to site specific management

Yield maps in combination with soil maps enable farm management a better analysis of the production (backward looking!). However, it is likely that a large part of the observed differences are the result of soil variability. Although some soil properties can be influenced by management (*e.g.* pH through liming, organic matter content through organic fertilizer), several characteristics a farmer has to take for granted (*e.g.* soil texture). A first step in the interpretation of the yield maps is therefore the correction for the different soil types, *i.e.* identify areas that have a relatively low production compared to the average for that soil type. In other words, by overlaying soil survey data with production maps, one may filter for differences in soil type (typically static properties, which can only be changed on the long term). Other differences, *i.e.* differences within the soil units, are likely to be the result of planting material, diseases and/or management. Additional field observations and chemical analysis of crop and soil may be used to explain the differences. Through the identification of site specific problems, farm management may improve these local limitations, improving the performance of the farm and at the same time reducing the costs.

2.5. Yield prognoses

Additionally BanMan allows for yield prognoses. Yield prognoses are required for the reservation of transport capacity. Farmers have to inform the shipping company three months in advance on the number of containers they will need. Yield prognoses in BanMan are based on the hypothesis that the expected harvest $Y_{t=3}$ in three months time equals the maximum obtained yield at that particular soil type (Y_{max}) minus a constant C times the number of stress days in the past 6 months. Stress days are defined as the total number of days d where the soil is extremely wet ($\theta > \theta_{max}$) or extremely dry ($\theta < \theta_{min}$). In short:

$$\overline{Y}_{(t=0)} = Y_{max} - C * \left(\sum_{t=-6}^{t=0} (d | \theta > \theta_{max}) + \sum_{t=-6}^{t=0} (d | \theta < \theta_{min}) \right)$$

The daily estimates of the soil moisture content are based on daily rainfall and the LEACHM model (Wagenet and Hutson 1989). The regression parameters Y_{max}, C, θ_{min} and θ_{max} are estimated for each management unit in the plantation on the basis of specific model runs and production figures. After each harvest, an optimization model re-estimates the different parameters for the different management units. The estimates will improve by using the system, whereas the database is increasingly expanded.

2.6. Data Requirements

The decision support system does not require specific data except the soil map and information on the farm infrastructure (mainly location of cables and support towers). These data can be digitized using Arc/Info or Idrisi after which they are exported to BanMan. BanMan supports 4 different formats for grid maps and 2 different formats for point and line information. Yield data are generated through site specific yield monitoring which is an integral part of the system. The banana crop is harvested almost continuously with 2-3 harvests per week. The banana bunches are harvested and transported to the packing plant by trains using a intensive cable system throughout the plantation. Each train comprises 25-30 bunches and originates from a specific location in the plantation. By registering the origin of the trains and weighing the bunches of each train (using a balance in the cable) yields are monitored. The yields are presented per basic unit, which is defined by the area that is harvested towards the cable of length between 3 supporting towers. In the case of the Rebusca plantation this corresponds with units of approximately 20 x100 meters. The total plantation is subdivided in approximately 500 of these units.

2.7. Pesticide leaching

Without the application of nematicides production will reduce significantly (Robinson, 1996). Whereas it is difficult to rehabilitate production in a plantation seriously damaged by high nematode concentrations, farmers typically do not want to take any risk with decreasing the frequency of nematicide application. There is no real economic incentive to reduce nematicide use as the application of nematicides comprises only 5.9% of the total maintenance costs of the crop (1995 figure for Rebusca). Off-site effects as pollution of surface waters are normally not considered in farmers' management decisions. However, a decrease in leaching implies a longer residence of nematicides in the root zone. This may lead to an increase in the effectiveness of the nematicide application. Soil characteristics like organic matter content, bulk density, layering of the soil profile as well as weather conditions govern the vertical movement of nematicides in the soil. Changes in those properties will negatively or positively change nematicide leaching. Modelling can be used to explore the effects of alternative management. For illustrative purposes one alternative management measure will be explored.

Weather conditions may influence significantly leaching of Ethoprop. Rainfall in the Banana plantation has a bimodal pattern with high rainfall in June/July and in September. Ethoprop leaching was simulated with varying application dates to check the influence of timing on leaching. Figure 2.5 indicates the spatial variation in nematicide leaching as a result of soil differences. Especially soil Hill has a high leaching, whereas the other soils show almost no leaching of nematicides. Figure 2.6 shows nematicide leaching in soil Banana and soil Levee as a function of the application date. It is clear that nematicide leaching can be reduced by proper timing of the application. However, future weather conditions are normally not known. To a certain extent, it remains, therefore, uncertain how much pesticide will leach when the farmer applies.

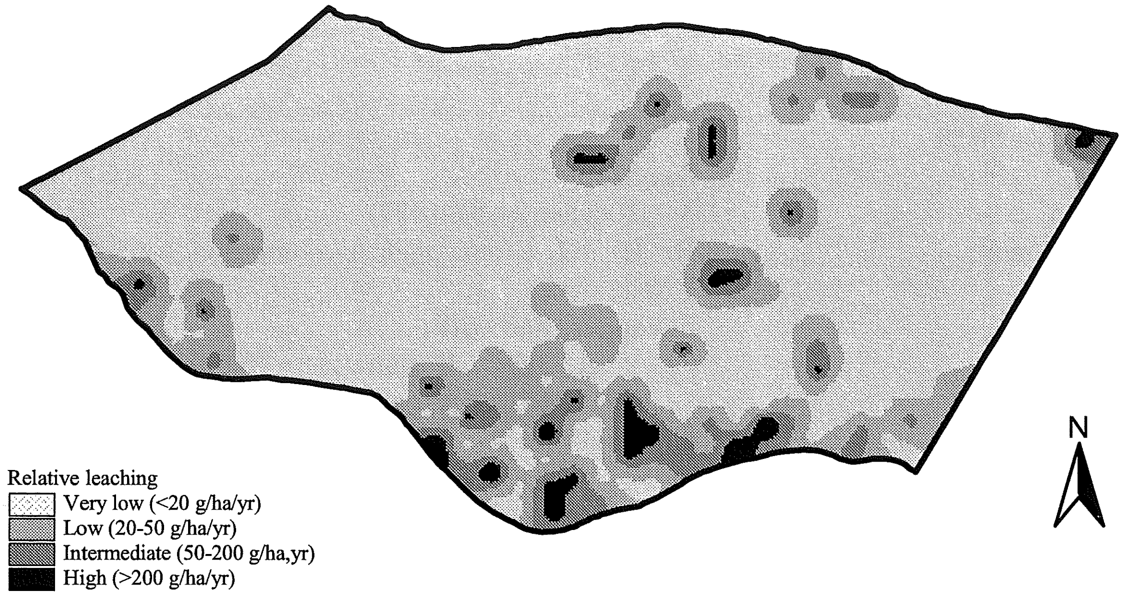

Figure 2.5: Nematicide leaching for 1996 under current management (two homogenous applications) as modelled using LEACHP

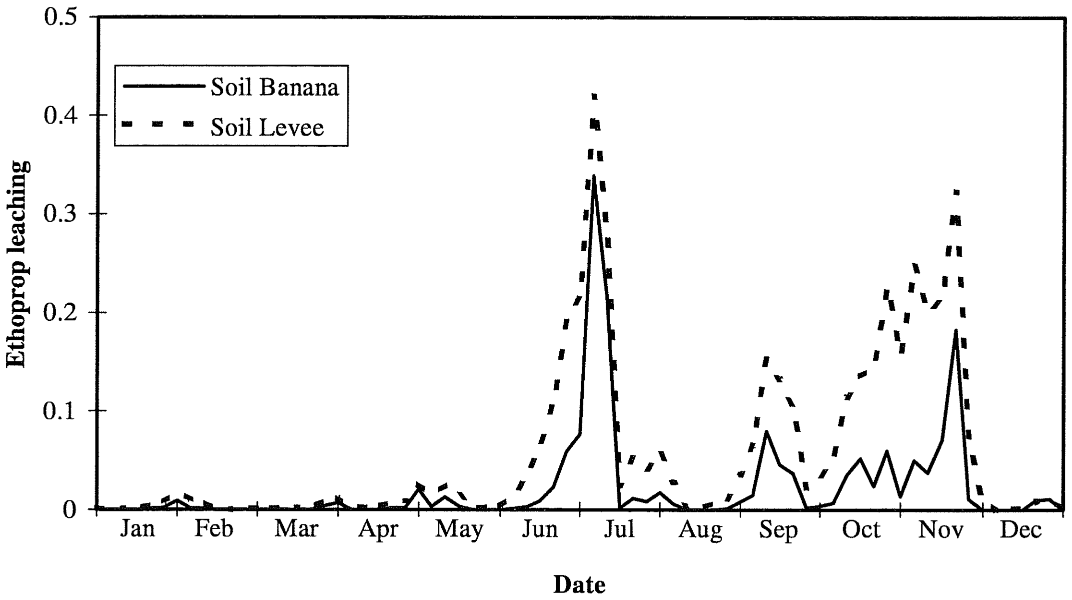

Figure 2.6 Pesticide leaching as a function of the application date.

2.8. Summary of the tool

Tools Fact Sheet	
Name	**BanMan**
Version	**3.2 (Release 24-07-1997)**
Development	**Dr Ir. J.J. Stoorvogel, Wageningen Agricultural University** **in cooperation with:** **R. Orlich, Bananera La Rebusca** **CORBANA**
Status (freeware/shareware/ commercial)	**Commercial**
System requirements	**MS Windows (3.1 or 95)**
Links with commercial software	**Spatial data can be imported from Idrisi and Arc/Info**
Objectives	**BanMan has been developed to support banana management**
Data Requirements	**Soil survey, sampling of soil and crop, registration of crop production**
Boundary conditions	**Currently BanMan can only be used to support the cultivation of bananas. For other crops yield monitoring requires adaptations of the DSS**

References

Barrientos E, Páez R 1994 Costa Rica Exportación bananera durante el primer semestre 94. Corbana 42: 5-10

Brouwer J, Bouma J 1997 Soil and crop growth variability in the Sahel : highlights of research (1990 - 95) at ICRISAT Sahelian Center. ICRISAT Information bulletin no. 49 ICRISAT, Niamey

Robinson, J.C. 1996. Bananas and plantains. Crop production science in horticulture 5, CAB International, Wallingford, UK.

Robert PC, Rust RH, Larson WE (eds.) 1995 Site–specific management for agricultural systems. Proceedings of the second international conference. ASA-CSSA-SSSA, Madison WI

Verhagen J 1997 Spatial soil variability as a guiding principle in nitrogen management. PhD Thesis, Wageningen Agricultural University, Wageningen

Wagenet, R.J. and J.L. Hutson, 1989. Leaching Estimation and Chemistry Model: A process-based model of water and solute movement, transformations, plant uptake and chemical reactions in the unsaturated zone. Continuum Water Resources Institute, Cornell University.

3. Application of a Decision Support System (DSSAT) at the Field Level: Nitrogen Management in Variable-Charged Soils

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3.1. The Need to Link Experimental and Modelling Activities

Agricultural science today is facing a critical dilemma. At the same time that it is expected to help achieve a sustainable growth in food production, it is also being asked to conduct research with a dwindling allocation of resources. To confront this challenge, agricultural scientists need to place a greater emphasis on the efficient organization of research and the knowledge that it generates. One approach to gaining improved efficiency is through the integration of research activities with the construction and application of dynamic simulation models.

Following advances in computer technology and accessibility, models of soil and plant systems have become increasingly valuable instruments for assimilating knowledge gained from experimentation. Their use within a research program has the potential to increase efficiency by emphasizing process-based research, rather than the study of site-specific net effects. Consequently, a modelling approach lends structure to a research program, helping to focus on the quantitative description of soil and plant processes. This information can then be used to predict how the system might respond to different environmental and management factors. A modelling approach also provides a dynamic, quantitative framework for multidisciplinary input.

If it is to increase the efficiency of research, the modelling process must become a truly integrated part of the research process. Experimentation and model development need to proceed jointly; whereas new knowledge is used to refine and improve models, models are used to identify gaps in knowledge, thereby helping to set research priorities. To be most effective, the modelling approach requires a regular evaluation of progress and continual refinement of objectives and priorities. It also requires a commitment to the development of software and data standards that facilitate a functional understanding of how soil and plant systems work.

The case study described in this chapter is intended to show how experimental and modelling activities were linked to obtain a better understanding of N dynamics in tropical soils in central Brazil. Specifically, we will see how experimental data were used together with a simulation model to demonstrate the significance of retarded nitrate leaching due to net-positive charge in the subsoil.

3.2. The Need for Improved N Management

In modern agriculture, N fertilizer is applied more frequently and in greater amounts than any other nutrient. Concerns, however, about the negative impacts the overuse of N fertilizers can have on the environment have led to calls for better management of N inputs. These concerns have also led to a renewed interest in the use of organic sources of N, particularly leguminous green manures. Although legumes managed as green manure may provide all or part of the N needed by a succeeding non-legume crop, their use demands as much skill and understanding as the use of manufactured N sources. Inorganic N released from a decomposing legume has the same potential as any manufactured source of N to leach nitrate to groundwater or to increase runoff of nitrate into surface waters. Therefore, when we discuss N management options, we should keep the following points in mind.

- Plants use inorganic N (NH_4^+, NO_3^-).
- Mineralization means loss of organic N as it is converted to inorganic N.
- Mineralization is independent of plant need (it is a microbiological process).
- Inorganic N is inorganic N, no matter what its original source.
- Inorganic N not used by plants can be lost from the system, e.g. leaching, denitrification, volatilization.

Because N is a dynamic and mobile nutrient in the soil, and because crop N demand can vary according to soil and weather conditions, the effect of added N on crop production is rarely the same from year to year or site to site. This variability in N dynamics makes it difficult to prescribe the management of N inputs to the same degree of accuracy often achieved with other plant nutrients. Nevertheless, there has been much learned about the major processes that govern N supply and demand, and much of this knowledge has been incorporated into comprehensive crop growth simulation models. Such models have the potential to help both researchers and farmers better understand how soil, crop, weather, and management factors interact to affect crop N demand, soil N supply, and N input efficiency.

The model of N processes to be examined in this case study is one that was originally developed as a submodel of the CERES-Maize model (Jones and Kiniry, 1986; Godwin and Jones, 1991). The same N submodel has been added to several other crop growth models that are included in the Decision Support System for Agrotechnology Transfer (DSSAT). The DSSAT will serve as the simulation platform for this case study.

3.3. A Decision Support System for Agrotechnology Transfer (DSSAT)

The crop growth model used in this case study, CERES-Maize, can be run as a stand-alone model, or it can be run from within the shell of the DSSAT version 3.1. The DSSAT is a software package that contains crop growth models, database management programs, utility programs, and analysis programs, each easily executed from within the shell or capable of being run alone. Within the DSSAT shell, a user can (i) input, organize, and store data on weather, soils, crops, experiments, and prices, (ii) run simulations with as many as 16 different crops in single-season, multi-season, or crop-sequencing modes, (iii) retrieve, analyze, and graphically display data, and (iv) evaluate different management practices at a site (Jones, 1993).

The DSSAT contains six separate models for simulating the growth of 16 different crops (Table 3.1). Although these models have been developed by different groups of researchers and institutions, there has been a coordinated effort to standardize input and output data formats (Jones *et al.*, 1994), and to implement the same soil water and N balance in each model (Hoogenboom *et al.*,1994). Therefore, all six models contain similar subroutines for describing soil-related processes and for reading and writing data using the same variable names. They differ only in the way crop growth and development processes are simulated.

Some important utilities released as a part of DSSAT include a software package for preparing daily weather data for use with simulation models (WeatherMan; Pickering *et al.*, 1994), a software package that facilitates the calculation of cultivar-specific coefficients based on field data (GENCALC; Hunt *et al.*, 1993), an analysis program for examining biophysical and economic variables after running single-season simulations for any number of weather years (Thornton and Hoogenboom, 1994), and an analysis program for examining biophysical and economic variables after simulating long-term cropping sequences (Thornton *et al.*, 1995). The latter is a program that takes advantage of the capability to simulate crops grown in a rotation or in a continuous sequence (Bowen *et al.*, 1997). Simulated output as well as any observed data can be graphed using a special graphical package (Wingraf; Chan *et al.*, 1994). Changes in simulated nitrogen and water balance components can be viewed using the graphical package N-Show (Cabrera, 1994).

Table 3.1. Principal crop models released as part of the DSSAT version 3.1.

Crop Model	Crops Simulated
CERES-Generic	Maize, Wheat, Barley, Millet, Sorghum
CERES-Rice	Rice (upland and flooded rice)
CROPGRO	Soybean, Peanut, Dry Bean, Chickpea, Tomato, Sugarcane, Pasture
OILCROP-SUN	Sunflower
SUBSTOR-Potato	Potato
CROPSIM-Cassava	Cassava

3.4. The Case Study

The case study presented here will use data collected from one field experiment that was part of a series of legume green manure and N fertilizer experiments conducted during the 1980s in central Brazil (Bowen *et al.*, 1993). The original objective of these experiments was to evaluate the potential of leguminous green manures to furnish all or part of the N needed by a subsequent maize crop. Note that these experiments were not designed or conducted with the goal of evaluating the maize model; only after the experiments were completed and results published did we think there was sufficient information for a critical test of the N submodel. Specific components of the model for which these data were sufficient to test included the dynamic simulation of N mineralization (release of organic N during decomposition), nitrate leaching, and N uptake by maize.

As demonstrated by Bowen *et al.* (1993), the model performed well in the simulation of legume N release and N uptake, but it overpredicted nitrate leaching when rainfall was excessive. The reason nitrate leaching was overpredicted was attributed to the assumption in the model that nitrate dissolution is instantaneous and that its movement is directly proportional to the amount of water moving through the profile. In variable-charge soils, however, this assumption is not correct since many of these soils—mostly Oxisols and Ultisols—have subsoils with positive charges capable of adsorbing nitrate and delaying its downward movement. To determine if the delayed movement of nitrate could be quantified using the model, the subroutine (NFLUX) that describes nitrate movement was modified to account for subsoil retention using a retardation factor described by Wild (1981). Thus the fraction of total nitrate in a soil layer (NS_i) that is in solution and can move from one layer to the next with the downward flow of water was defined as:

$$NS_i = 1 / [1 + (K_i \rho_i / \theta_i)] \qquad [3.1]$$

where K_i is the estimated adsorption coefficient (nitrate adsorbed/nitrate in solution; $cm^3\ g^{-1}$) for layer i, ρ_i is the bulk density ($g\ cm^{-3}$) for layer i, and θ_i is the volumetric water content ($m^3\ m^{-3}$) for layer i at the drained upper limit. Except for the adsorption coefficient, each of these variables was measured and already specified as inputs for the model.

A major goal of this case study is to show how the adsorption coefficient, K_i, was estimated using nitrate measurements with depth, and how these coefficients served to accurately predict the movement of nitrate in different treatments. First, we will look at a brief description of the N submodel and the input data requirements. Next, we will see how soil, weather, management, and experimental data are assembled into the standard file formats defined for the DSSAT models. Model performance will then be evaluated for simulating nitrate leaching before and after the model was modified to account for nitrate retention in the subsoil.

3.4.1. N Model Description and General Input Requirements

The CERES-Maize model provides a quantitative tool for analyzing the effect that controlled factors (management), uncontrolled factors (weather), and site-specific soil properties can have on the major components of the N balance. The model is comprehensive in that it simulates most major processes associated with both crop N demand and soil N supply (Table 3.2). Nitrogen uptake by a growing crop is determined as the lesser of crop N demand and soil N supply. Crop N demand is driven by a critical N concentration in plant tissue that depends on growth and the stage of development. Soil N supply, which is affected by all of the processes shown in Table 3.2, is defined primarily by the amount of inorganic N, the soil water content, and the root length density in each layer of the soil. The model simulates the availability of N applied as fertilizer N or plant residue.

Operating on a daily time step, the model requires daily inputs for precipitation, solar radiation, and maximum and minimum air temperatures. To simulate the phenological development and growth of maize, the model uses five cultivar-specific coefficients which define photoperiod sensitivity, thermal time between major phenological events, potential kernal number, and potential kernal growth rate. The soil profile, which the user needs to define to at least the maximum depth of rooting, is divided into layers with a maximum thickness of 30 cm. The inputs for each layer are initial soil water content, upper and lower limits of soil water availability, initial nitrate and ammonium levels, soil pH, soil organic C content, bulk density, and a root distribution factor. Management factors such as planting date, plant density, row spacing, and planting depth need to be specified. If applied, irrigation and fertilizer N amounts and time of application need to be specified. To simulate the decomposition of plant residues, the model requires the dry weight of the residue, the depth to which it was incorporated, and the percent N in the residue.

Table 3.2. The major processes that are simulated in the nitrogen submodel of the DSSAT crop models, and the environmental factors that influence those processes.

Process Simulated	Main Factors Influencing Process
	CROP N DEMAND
Growth	Solar Radiation, Temperature
Development	Photoperiod, Temperature
	SOIL N SUPPLY
Mineralization/Immobilization	Soil Temperature, Soil Water, C/N Ratio
Nitrification	Soil Temperature, Soil Water, Soil pH, NH_4^+ Concentration
Denitrification	Soil Temperature, Soil Water, Soil pH, Soil C
NO_3^- Leaching	Drainage, Nitrate Adsorption[a]
Volatilization[b]	Soil Temperature, Soil pH, Surface Evaporation, NH_3 Concentration
Urea Hydrolysis	Soil Temperature, Soil Water, Soil pH, Soil C
Uptake	Soil Water, Inorganic N, Crop Demand, Root Length Density

[a] Effect of nitrate adsorption added only after version 3.1.

[b] Presently simulated in only CERES-Rice for flooded conditions.

3.4.2. Standard file formats for the field experiment

The field experiment used in the case study was conducted during the 1985-86 wet season at the Cerrado Agricultural Research Center (CPAC-EMBRAPA) near Brasilia, Brazil. There were two treatments, with and without legume green manure (*Mucuna aterrima*), which were applied to both cropped and uncropped plots across four replications. The cropped plots were planted to maize while the adjacent uncropped plots were maintained free of all vegetation. After incorporating similar amounts of legume green manure to cropped and uncropped plots (about 5.5 tons of dry matter per hectare containing 3.3 % N), the soil profile of all treatments was sampled periodically for inorganic N to a depth of 1.2 m in 0.15-m increments. Periodic harvests of maize plants were also made on the same sampling dates to measure N uptake with time.

The input data needed to run a simulation of this experiment requires a daily weather file, a soil profile characteristics file, a cultivar coefficient file, and an experimental details file. One also needs a file with the observed data to be able to evaluate the performance of the model. To facilitate the recognition of these different categories of data, a set of file naming conventions have been adopted to specify contents based on specific file prefixes (8 characters) and file extensions (3 characters). The file names (prefix and extension) for data included in the case study are provided in Table 3.3. The file extension indicates the category of data, with *.WTH indicating a weather data file, *.SOL containing any number of soil profile descriptions, *.CUL containing coefficients for different cultivars or varieties, and *.ccX containing the experimental details, e.g., treatments, planting dates, planting density, etc.('cc' represents a crop code which in this case is 'MZ' for maize). Observed data are usually placed in either of two files, *.ccA or *.ccT. The A file contains the means of observations that are usually made only once during a cropping season, e.g., final yield, flowering date, etc. The T file contains data (means or individual plot data) measured any number of times during the season, e.g., changes in soil moisture, nitrate levels, leaf area index, etc. The prefix of the file name is constructed from an institute code (2 characters), a site code (2 characters), the year of the experiment (2 characters), and an experiment number (2 characters).

3.4.3. Evaluating Model Performance

If the two fallow plot treatments are run using the model with the assumption of no retarded nitrate leaching in the subsoil, then a graphical comparison of simulated and measured profile inorganic N looks like that shown in Figure 3.1. Clearly the model provided an inaccurate estimate of inorganic N in the subsoil by overpredicting nitrate lost by leaching.

To account for positive charge and retarded nitrate leaching in the subsoil, the adsorption coefficient, K_i, in equation 3.1 was calculated for each layer of the soil using measured data from only the no mucuna fallow treatment. Starting with the bottom soil layer, the adsorption coefficient was adjusted progressively for each layer until the best fit between simulated and measured inorganic N in that layer was obtained. The effect of this adsorption coefficient on the simulated movement of nitrate can be determined using the sensitivity analysis option when running the model. For example, changing the adsorption coefficient value for the 60-90 cm layer from 0.0 (no adsorption) to 0.4 and then to 0.9 `would provide the result shown in Figure 3.2. Note that a value of 0.9 for *K* appears to best fit the data. When calculated for all soil layers, the adsorption coefficient that best fits the data for the first 45 cm is zero, i.e., no nitrate retention in the surface 45 cm. For the deeper layers, however, *K* values that best fit the data are 0.4 for the 45-60 cm layer, 0.9 for the 60-90 cm layer, and 1.4 for the 90-120 cm layer. This increase in nitrate retention with depth has been observed elsewhere, and is probably due to an increase in surface charge as soil organic matter content decreases (Wong *et al.*, 1990).

When these *K* values are used in the same model runs shown in Figure 3.1, then the simulated changes in inorganic N levels match much better the observed data (Figure 3.3). Note that *K* values were only calibrated for the no mucuna tops treatment, and that these same values were used for the mucuna tops treatment where they provided a reasonable estimate of inorganic N dynamics during the season following the incorporation of a legume green manure. Further comparisons with inorganic N measurements made at another site in another year showed that these same *K* values could be used to improve simulated estimates of inorganic N as well as N uptake (Bowen *et al.*, 1993).

Table 3.3. Weather, soil, cultivar, experimental details, and observed data files used in the case study.

File Name	Description
EBCH8501.WTH, EBCH8601.WTH	Yearly weather files with the daily values for solar radiation, precipitation, and minimum and maximum air temperatures.
SOIL.SOL	Soil profile data for many different soils.
MZCER960.CUL	Cultivar coefficients for different maize varieties.
EBCH8501.MZX	Files containing the experimental details for the experiment used in the case study.
EBCH8501.MZA, EBCH8501.MZT	Files with observed data (means of 4 replications).

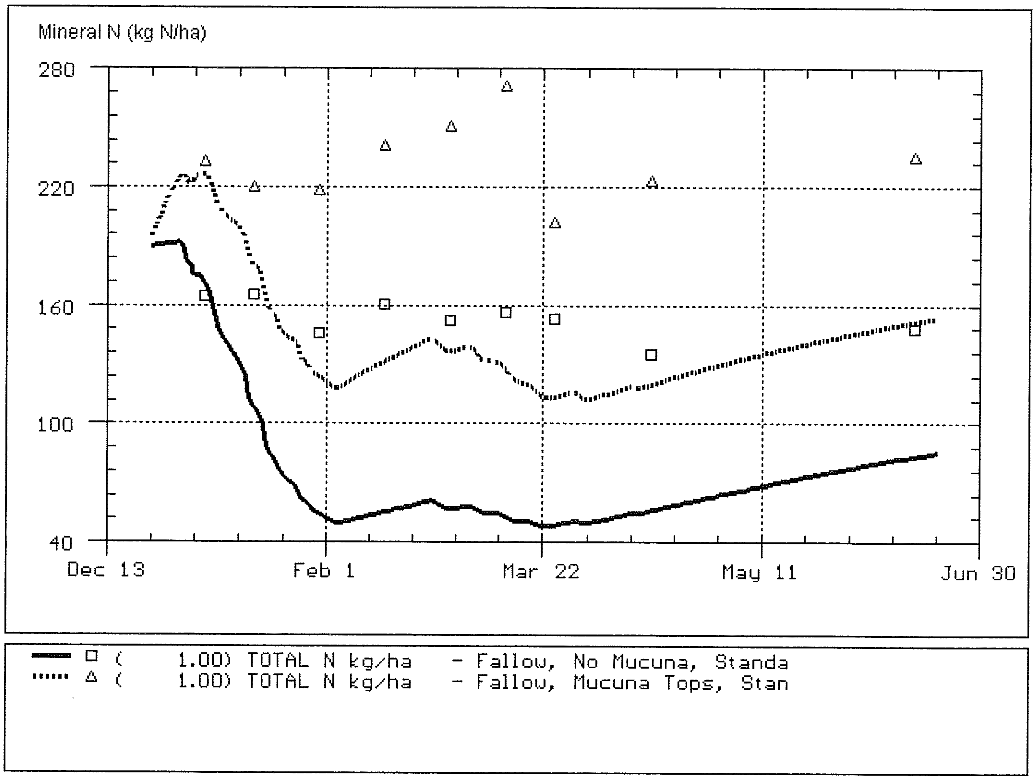

Figure 3.1. A graphical comparison of simulated (lines) and measured (marks) inorganic N in the soil profile (1.2 m depth) assuming no nitrate adsorption in the subsoil.

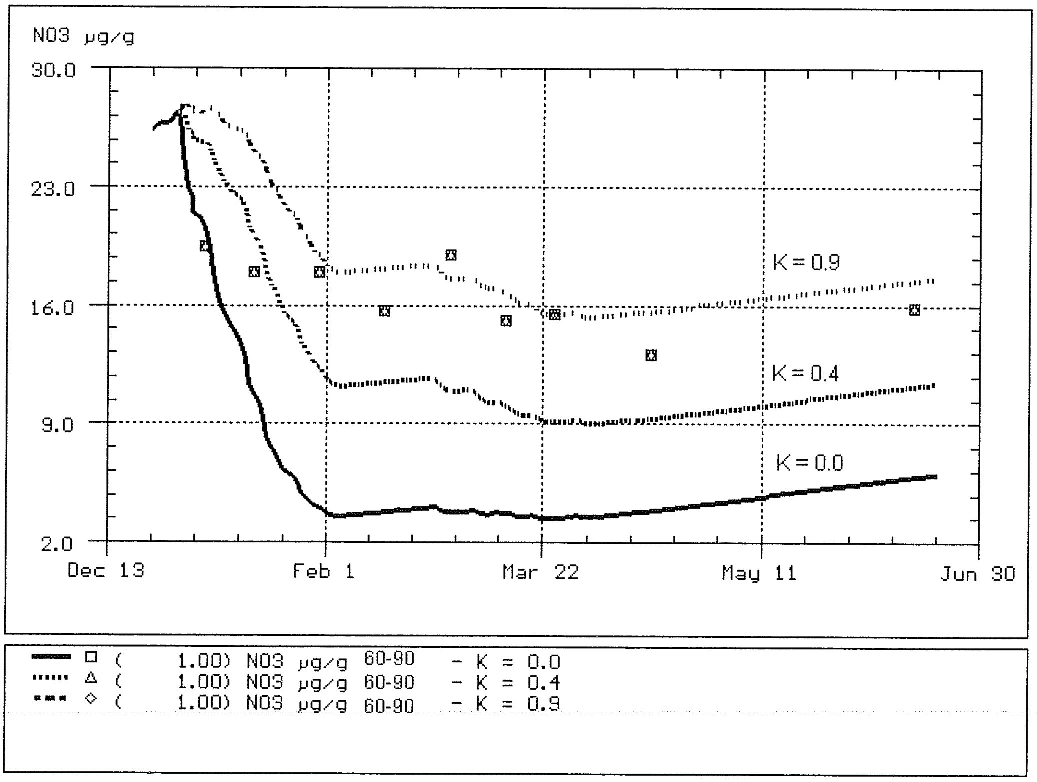

Figure 3.2. Sensitivity of simulated inorganic N in the 60-90 cm soil layer to variation in the size of the adsorption coefficient used to estimate the effect of retarded nitrate leaching.

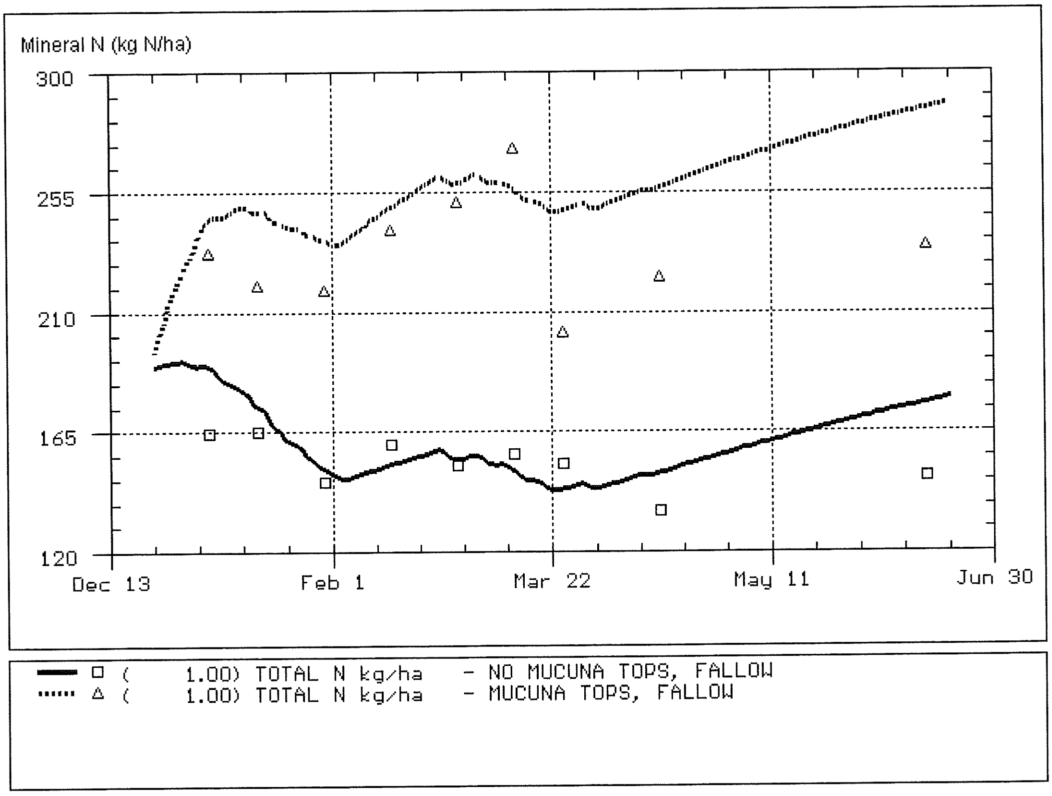

Figure 3.3. A graphical comparison of simulated (lines) and measured (marks) inorganic N in the soil profile (1.2 m depth) assuming nitrate can be adsorbed in the subsoil.

3.5 Conclusions

This case study has presented a real example of how field measurements and a model were used together to improve our understanding and capability to simulate N dynamics in tropical soils with variable charge. The latest version of the DSSAT models, version 4.0, has been modified to allow users to specify adsorption coefficient values for different soil layers. In this case study, such coefficients were estimated based on calibration to a set of field measurements. Obviously it would be better to have a more direct way of estimating these coefficients, through perhaps a measurement of anion exchange capacity or some other easily measured soil property. Research along these lines is underway.

3.6 System Requirements

The DSSAT family of models and analysis programs can be run on any 80286 processor or better, performing best on a Pentium. Although a math co-processor is not required for 286 or 386 systems, it is highly recommended. RAM requirements include a minimum of 590K free DOS RAM. The display can be EGA or VGA. Approximately 18 MB of hard disk space are needed for complete installation of the DSSAT. The operating system should be DOS 3.3 or better, or compatible.

References

Bowen WT, Jones JW, Carsky RJ, Quintana JO 1993 Evaluation of the nitrogen submodel of CERES-Maize following legume green manure incorporation. Agron. J. 85:153-159

Bowen WT, Thornton PK, Hoogenboom G. 1998 The simulation of cropping sequences using DSSAT. In Tsuji GY, Hoogenboom G, Thornton PK (eds.) Understanding options for agricultural production. Kluwer Academic Publishers. *In Press*

Cabrera ML 1994 N-Show: An educational computer program that displays dynamic graphs of nitrogen in soil. J. Nat. Resour. Life Sci. Educ. 23:43-45

Chan H, Wilkens PW, Hoogenboom GZ, Jones JW, Godwin DC 1994 Graphing simulated and experiment data. Pages 245-281. In Tsuji GY, Uehara G, Balas S (eds.) DSSAT Version 3.0. Vol. 2. University of Hawaii Press, Honolulu

Hoogenboom G, Jones JW, Wilkens PW, Batchelor WD, Bowen WT, Hunt LA *et al.* 1994 Crop model user's guide. Pages 95-244. In Tsuji GY, Uehara G, Balas S (eds.) DSSAT Version 3.0. Vol. 2. University of Hawaii Press, Honolulu

Hunt LA, Pararajasingham S, Jones JW, Hoogenboom G, Imamura DT, Ogoshi R 1993 GENCALC: Software to facilitate the use of crop models for analyzing field experiments. Agron. J. 85:1090-1094

Jones JW 1993 Decision support systems for agricultural development. Pages 459-471. In Penning de Vries FWT (ed.) Systems approaches for agricultural development. Kluwer Academic Publishers, the Netherlands

Jones JW, Hunt LA, Hoogenboom G, Godwin DC, Singh U, Tsuji GY *et al.* 1994 General input and output file structures for crop simulation models. Pages 1-94. In Tsuji GY, Uehara G, Balas S (eds.) DSSAT Version 3.0. Vol. 2. University of Hawaii Press, Honolulu

Pickering NB, Hansen JW, Jones JW, Wells CM, Chan CK, Godwin DC 1994 WeatherMan: a utility for managing and generating daily weather data. Agron. J. 86:332-337

Thornton PK, Hoogenboom G 1994 A computer program to analyze single-season crop model outputs. Agron J 86:860-868

Thornton PK, Hoogenboom G, Wilkens PW, Bowen WT 1995 A computer program to analyze multiple-season crop model outputs. Agron. J. 87:131-136

Wild A 1981 Mass flow and diffusion. Pages 37-80. In Greenland DJ, Hayes MHB (eds.) The chemistry of soil processes. John Wiley & Sons, Chicester, England

Wong MTF, Hughes R, Rowell DL 1990 Retarded leaching of nitrate in acid soils from the tropics: measurement of the effective anion exchange capacity. J. Soil Sci. 41:655-663

4. SISDA: A Decision Support System for Agriculture in Brazil

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4.1. Introduction

Even with the great industrialisation of the last three decades, most of the Brazilian economy is still driven by agricultural activities. At the same time, due to the country's dimensions and the geographical diversity, Brazilian agriculture is subject to highly variable weather conditions. As a result, recommendations are very specific for different agro-ecological zones and not valid at the national level. Brazilian farmers have problems in managing the adverse weather or adverse environmental conditions. Most of this incapacity is due to a lack of real time information services that support farmers in their decision making. That was the main reason for the development of the Decision Support System for agriculture management in Brazil SISDA.

The development of SISDA is based on:

1. an integration of available knowledge for different areas in order to provide an objective tool to evaluate the resource management at the field level, and
2. the generalization of knowledge into a comprehensive but understandable knowledge base without loosing scientific rigor (Bouma, 1997; Jones *et al.*, 1997).

SISDA is a user friendly system in both inputs and outputs. It integrates a broad spatial database on weather, water, soil, plant and irrigation (Figure 4.1) and allows for the support and evaluation of agricultural decisions.

During its development, SISDA had the participation of experts from different disciplines: agricultural meteorology, irrigation management, irrigation engineering, soil science, agronomy, plant pathology and computer science. The main purpose of SISDA is to support farmers with their day-to-day management decisions. However, it also allows the exploration of expected crop behaviour, based on historical climate data and soil data (Figure 4.2).

4.2. The rationale of the development

After the green revolution, it has been essential that discussions involving agricultural practices in Brazil (or in any other developing country) consider food security for growing populations, as well as the need for a reduction in agricultural land area, water use and soil degradation. These demands are often conflicting. Nevertheless, crop scientists have to aim at a perspective of increasing food productivity based on sustainable resource management. It was towards this end that SISDA was conceived.

Figure 4.1 The easy-to-use interface of SISDA

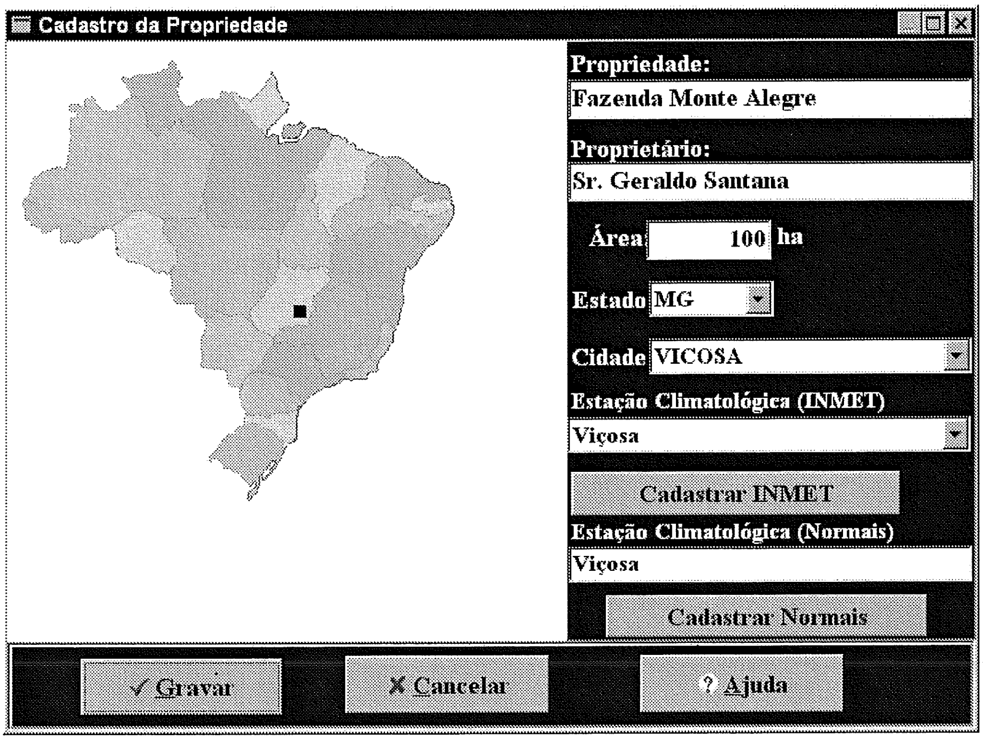

Figure 4.2 SISDA allows the management of a farm anywhere in Brazil. Information on climate and soil can be accessed just by pointing the mouse in the county of interest.

The first step towards the implementation of rational strategies in agricultural management is to find the way to give the farmer, direct or indirectly, the technical inputs needed for the decision-making process. Due to the plethora of factors determining crop productivity (and the complex interactions between them), the concept of systems approaches, including modelling, is needed to provide an objective tool for the evaluation of crop management at field, farm and regional scale levels.

As a result of government policies and incentives in Brazil, there was a big change in agricultural practices in the 80's. The productivity of the 1896/87 growing season is a good example of its effect. By that time, 4% of the agricultural area was irrigated. However, it was responsible for 16% of the total yield and 25% of the economic returns. Irrigation is one of the greatest water consumers in Brazil (around 60 % of all water used) and water use in irrigation practices. Water use by the Brazilian farmers has been growing exponentially in the last years and unfortunately most of the irrigation management is still made based on the farmers empirical judgement. They try to strive for good yield and risk aversion. As a result they tend to over-irrigate. There is great concern that current water consumption will lead to water shortage in some areas in Brazil.

Considering water requirements of the society as a whole, the Brazilian government has put aside funds and scientific resources for the development of a Decision Support System which would supply the farmer with the required technical support to make proper choices on its crop and water management.

4.3. Main characteristics of SISDA

Taking into account the great diversity in technology and education level of Brazilian farmers and also on their environment, the first challenge was the development of a country-wide decision support system. The use of traditional agricultural research was not found adequate to provide the necessary understanding to address the broad issues outlined above, nor for packing the information in a way that a wide variety of users would easily access and interpret.

Following this line, the first step in the development of SISDA was to deal with three main questions:

1. What information is the farmer willing to supply to a system like this?
2. What should be the output to the farmer?
3. In which format should the output of the system be structured?

After several months of discussion with Brazilian researchers and farmers, it became clear that the main point was the answer to the first question. The farmers had sent us a clear message: they were not willing to give us any information at all! They were fed up with scientific research and with the traditional way of doing research. In their mind, we had been asking them, for a long time, for more and more information without showing any practical results for them. So we decide that our system would be a self-given system, or in others words, it would ask for less and give more information. Also it should be a user's friendly system.

SISDA has in its file information on soil characteristics and climate, daily information, of around 600 weather station and over 8800 cities in Brazil. It also has information on disease and crop characteristics (degree-day, crop development, water use) of 6 crops: Soybean, Potato, Banana, Pineapple, Coffee and Tomato. The database is spatially structured and will provide for any particular location in Brazil data on climate conditions, soils and crops plus their interactions (Monteith, 1981; Brady, 1989; Soares *et al.,*1993; Costa, 1983; Costa *et al.*, 1996; Costa *et al.*, 1997).

4.4. Specific features of SISDA

SISDA output comprises: length of the growing season, potential evapotranspiration, rainfall probability, dry spell probability, probability of disease occurrence, availability of water in the soil. In other to attend the demands of Brazilian agriculture, SISDA was developed considering two main modules: management and simulation.

Management has to do with day-to-day decision at farm level. After the specification of soil and climatic characteristics, SISDA supports the farmer's decisions related to timing and amount of required irrigation as well as other crop management practices like fertilization (Dorenbos and Pruitt, 1977; Keller and Bliesner, 1990; Mantovani *et al.*, 1994; Mantovani *et al.*, 1995; Mateos, *et al.*, 1977*;* Allen *et al.*, 1994; Bernardo, 1996).

Simulation has to do with the analyses of management scenarios. On the basis of historical weather data and soil and crop characteristics (*e.g.* crop length, crop water use, rainfall, dry spell and disease probability), SISDA estimates crop performance for different sowing dates. On the basis of alternative runs, the farmer can select the most appropriate sowing date for his specific conditions. Daily output of SISDA can be presented as graph or table (Figures 4.3 and 4.4).

Additionally SISDA allows linkage with the Brazilian Weather Centre via internet, so the user can consider both climatic probabilities as well as weather forecasts. The database of SISDA includes data on disease, irrigation, climate and soil including images and technical information (Figure 4.5). As a result SISDA can support the decisions of farms but may function also as an educational tool. Information on Brazilian soil laboratories is made available in order to give the farmer an indication of the nearest lab for soil analysis.

All the technical and scientific concepts (including the equations) that are used for the calculations within SISDA can be consulted in the help section. SISDA was developed using DELPHI 2.0 (Borland, 1996) for Windows 95/NT. The full version is presented in CD-ROM. For its best performance it requires a Pentium 133 Mhz with 16 Mb RAM and at least 80 Mb of disk space. There is a compacted version for those who only require regional crop and climate information from the system. This version comes in four diskettes and can be used on a 286 computer

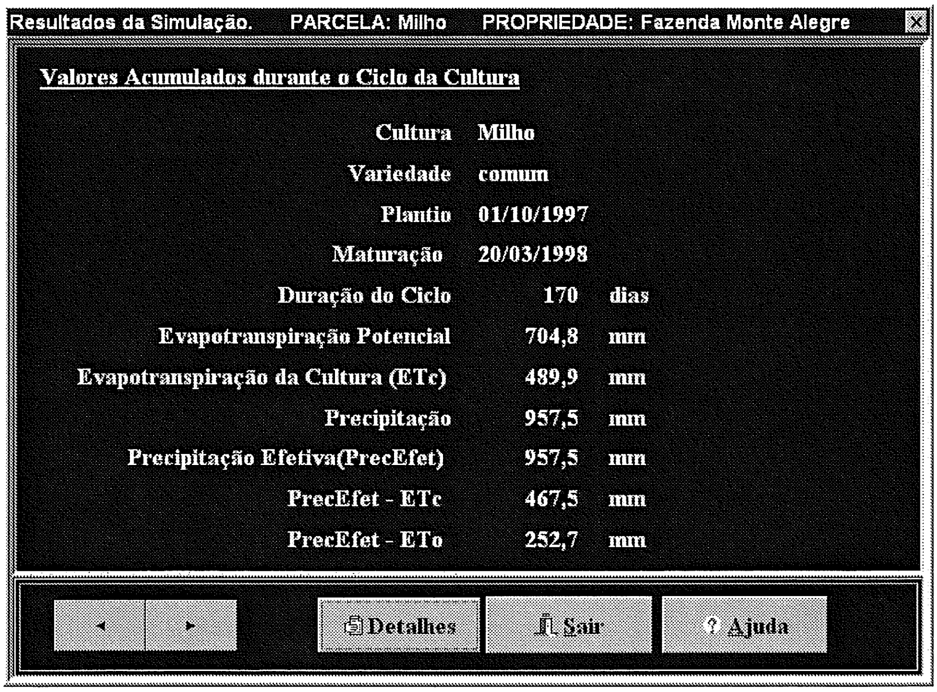

Figure 4.3 SISDA output from a simulation of a growing season of Maize crop. The results shows the length of the growing season, the potential and crop evapotranspiration, precipitation and the difference between precipitation and evapotranspiration.

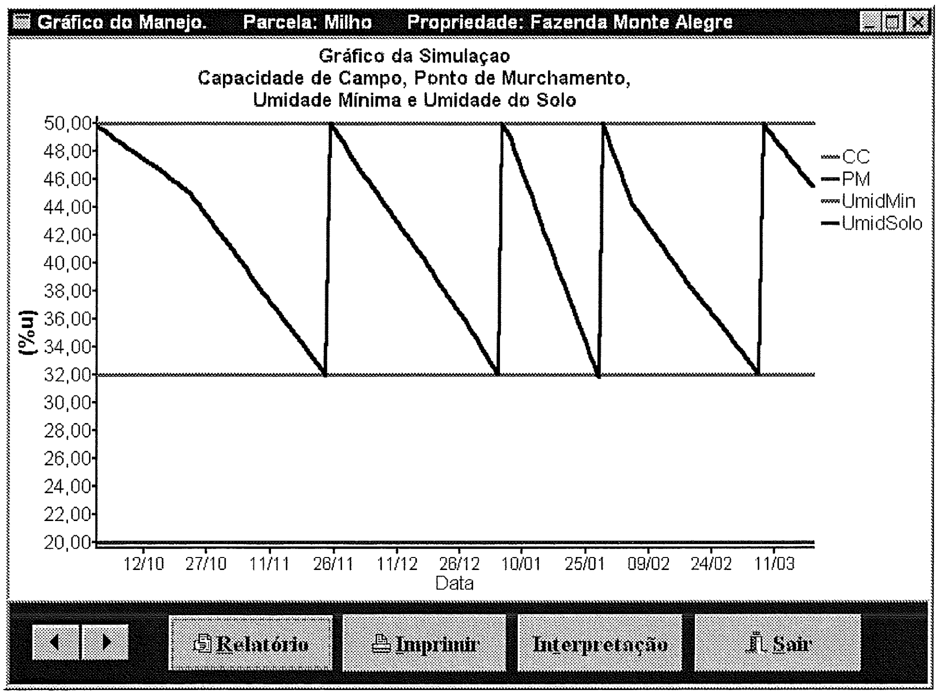

Figure 4.4 An example of a SISDA graphic output. The example shows the timing and the depths of irrigation that would be needed during the growing season of maize crop.

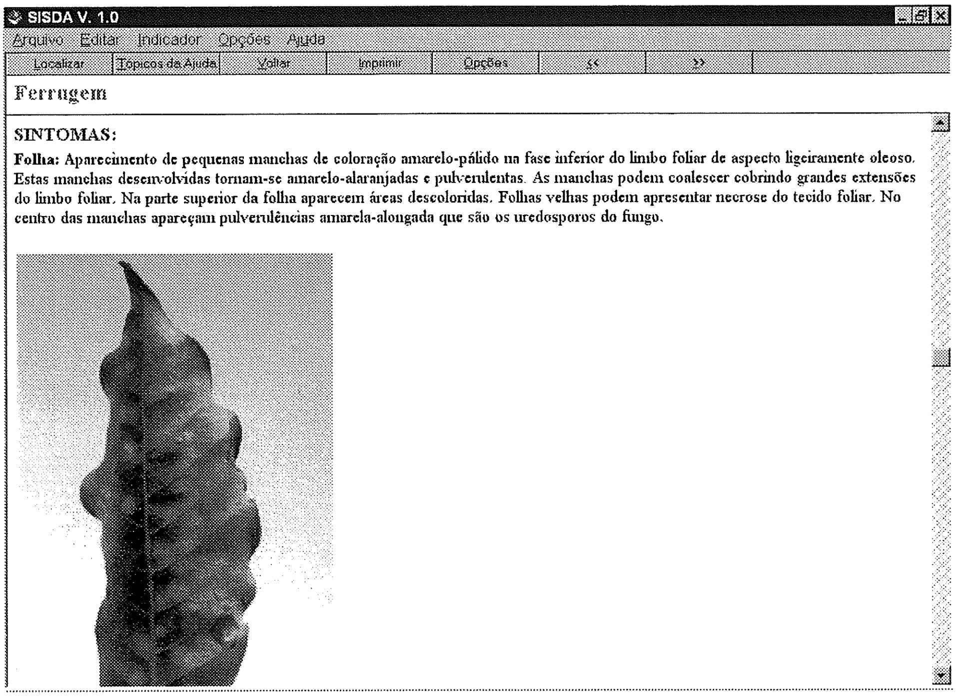

Figure 4.5 An example of a SISD help outputs. In this example it shows some information on a coffee crop disease.

4.6. Data requirement

To make SISDA in line with Brazilian reality, its first version was planned to have a minimum data requirement. For both simulation and management the user needs to give information on its soil, water and irrigation equipment. The user will pickup from the system data set. For the analysis of management scenarios additional weather data are required.

4.7. Concluding Remarks

The development of the first version of SISDA took around 18 months. Since then the program has been a success in Brazil. As part of the SISDA PROJECT more that 300 farmers, extensionists, scientists and other users from different parts of Brazil have been trained in using the System. The next step, already in development, is to scale down the system, which means to adapt the system for different regions in Brazil. For version 2.0 users requested a module on yield prognoses and economic aspects.

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References

Allen R, Smith M, Perrier A 1994 An update for the definition of reference evapotranspiration. ICID Bulletin. 43(2):1-34

Bernardo S 1996 Manual de irrigação. 6th ed. Viçosa, MG: UFV

Borland 1996. Delphi 2.0: manual do usuário

Bouma J 1977 The role of quantitative approaches in soil science when interacting with stakeholders. Geoderma 78: 1-12.

Brady NC 1989 Natureza e propriedade dos solos. 7th ed. Rio de Janeiro, Freitas Bastos

Costa LC 1993 Análise climática para fins de irrigação da região de Paracatu, Minas Gerais. Ceres 40(227): 1-7

Costa LC, Morison J, Dennett 1996 Carbon balance of growing Faba bean and its effect on crop growth: experimental and modelling approaches. RBA. 4(2): 11-17

Costa LC, Morison J, Dennett MD 1977 Effects of the weather on growth and radiation intercepted by faba bean. Pesq. agropec.bras., Brasília, 32: 277-281

Doorenbos J, Pruitt JO 1977 Guidelines for predicting crop water requirements. FAO Irrigation and Drainage 24, Rome: FAO

Jensen ME, Burman RD, Allen RG 1990 Evapotranspiration and irrigation water requirements. New York: American Society of Civil Engineers

Jones JW, Thorton PK, Hansen JW 1997 Opportunities for systems approaches at the farm scale. Pages 1-18 In: Teng PS, Kropff MJ, ten Berge HFM, Dent JB, Lansigan FP, van Laar HH Applications of Systems Approaches at the Farm and Regional Level. Kluwer Academic Publishers, London

Keller J, Bliesner RD 1990 Sprinkle and trickle irrigation. New York: Van Nostrand Reinhold

Mantovani EC, Ramos MM 1994 Sistemas de irrigação e seus componentes. In: Costa EF, Vieira RF, Viana PA (eds) Quimigação: aplicação de produtos químicos e biológicos via irrigação. Brasília, DF: EMBRAPA-SPI

Mantovani EC, Villalobos F, Orgaz F, Fereres E 1995 Effects of irrigation uniformity and accuracy of evapotranspiration estimates in crop yield. Agricultural Water Management 27:243-245

Mateos L, Mantovani EC, Villalobos F 1997 Cotton responses to nonuniformity of conventional srinkler irrigation. Irrig. Sci 17: 47-52

Monteith JL 1978 Climate variation and the growth of crops. Quart.J.R.Met. Soc. 107: 749-774

Souza EF, Soares AA, Sediyama GC, Bernardo S 1993 Modelo de computação aplicado ao manejo de irrigação. Pages 2678-2687 In: Anais do XXII Congresso Brasileiro de Engenharia Agrícola. Ilheus, Bahia

5. Description and application of the LINTUL-POTATO crop growth model

5.1. Agro-ecological description of LINTUL-POTATO

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5.1.1. Introduction

The specific environment for potato growth and production is mainly determined by temperature. Potato is not cultivated in environments with mean monthly temperatures below 5°C or above 28°C. The growing season should exceed a minimum duration, equivalent to an accumulated temperature requirement of about 1250 degree days, Cd with a base temperature of 2°C. Degree days are calculated as the accumulated number of days with a positive difference between the daily average temperature and the base temperature. This means that potato requires a minimum growing season of about 100 days when the daily mean temperature is 14.5°C and 50 days when the daily mean temperature is around 27°C. The maximum duration of potato crop growth is equivalent to an accumulated temperature requirement of 2000 degree days, °Cd. A spatial and temporal distribution of potato production throughout the world can be made just by using temperature and the above mentioned crop characteristics, see Figure 5.1. Approximate cropping management characteristics as planting and harvesting can be also estimated by using these crop specific temperatures. Beside temperature, other factors may determine the length of the cropping season such as timing of the rainy seasons and market requirements. Different potato cultivars possess different properties which makes them suitable for a specific abiotic, biotic and economic environment. These cultivars can be classified according to their environmental requirements into ideotypes.

Ideotypes have a length of the growth cycle characterized by a green leaf area that intercepts solar radiation for as long as possible during the available growing season to accumulate as much dry matter as possible. Earlier genotypes, too early divert dry matter to the harvestable parts (grains, tubers) so that not sufficient assimilates are available for the foliage that then senesces and dies. Genotypes that are too late still have full ground cover with green leaves at the end of the available growing season indicative of an unfavorable distribution of dry matter to the foliage and to the harvestable parts of the crop. Figure 5.2 schematically represents the three situations of a potato crop under northern European conditions.

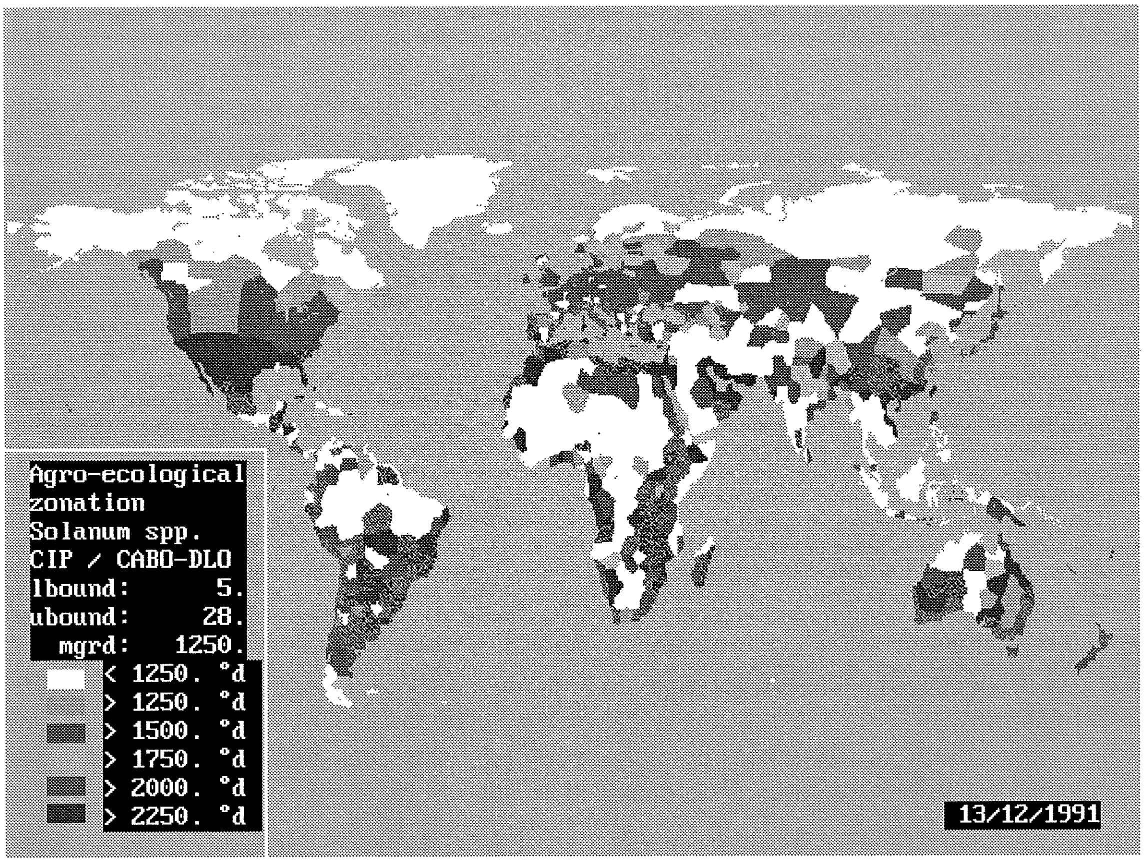

Figure 5.1 Lengths of the growing seasons (Van Keulen and Stol, 1996)

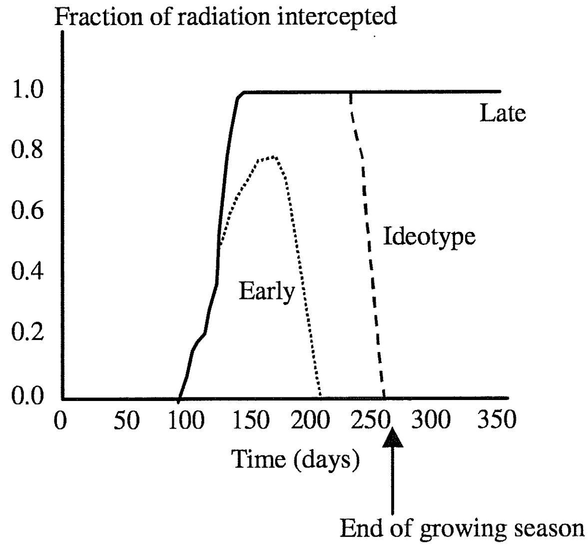

Figure 5.2. Schematical representation of the course of light interception by green crop foliage of ideotypes versus early and late genotypes. Planting is on day 75, emergence on day 100 and harvest on day 260.

To describe ideotypes with the desired length of the growth cycle one needs firstly to determine the length of the available growing season as it is delimited by growing conditions or market demands. Secondly, an assessment is needed of the yield determining factors (temperature, radiation, daylength) that cannot be changed nor influenced by the farmer once the crop is planted, with emphasis on the influence of such factors on the length of the growth cycle. Thirdly, the presence of yield limiting factors such as water and nutrients need to be studied. What is the influence of drought and lack of nutrients on the length of the growth cycle? Finally, it should be evaluated and quantified whether there is a risk of crop yield reducing factors such as pests, diseases and weeds.

The influence of the yield defining, limiting and reducing factors on crop growth parameters and their repercussions on the length of the growth cycle and how to match the length of the cycle with that of the season is important in crop production. To that end we'll discuss an appropriate model of potato growth and development with temperature and solar radiation as driving forces and we'll show how daylength and water availability may influence development and growth as well.

5.1.2 Modelling approach

Three types of crop yields are currently simulated with dedicated models. These models differ in their ranking with respect to the number of limiting factors to simulate crop production. The first type of models simulates the potential yield. Potential yield is the theoretical upper limit of crop yield and is based upon the limitations of available radiation and temperature. Attainable yield is simulated by taking the limiting factors of water and nutrients (nitrogen and phosphorus) into account. The actual yield is simulated by taking limiting biotic factors as weeds pests and diseases into account. The simulated actual yield has the most correspondence with the on-farm harvested yield.

A simple model describing growth and development of crops is based on light interception, utilization of light to produce dry matter, allocation of dry matter to the harvestable parts and of the percentage of water in the harvestable parts. Schematically this is represented in Figure 5.3. The growth cycle is shown in the graph (Figure 5.3) of which the abscissa (thermal) time) starts at planting. Then the course of light interception or ground cover from planting until crop senescence is shown. Cumulation of the amount of daily intercepted radiation over time versus total and tuber dry matter yields the efficiency coefficients for total and tuber dry matter production. The simplest potato growth model that can be derived from the observation of light interception and dry matter accumulation over time is:

$$Y = \frac{R * E * H}{D}$$

where: **Y = tuber fresh yield, R = the amount of intercepted radiation, E = conversion efficiency, H = the harvest index and D = the dry matter concentration of the freshly harvested tubers.**

These parameters can easily be derived from potato experiments in which periodic harvests are taken and fresh and dry matter of haulm and tubers is determined, where the percentage ground cover is measured weekly and where daily solar radiation is recorded. Figure 5.4 illustrates the effect of (a combination of) a yield reducing factor (potato cyst nematodes) and a yield limiting factor (drought) on ground cover, thus light interception, and on the conversion efficiency of intercepted light into total and tuber dry matter.

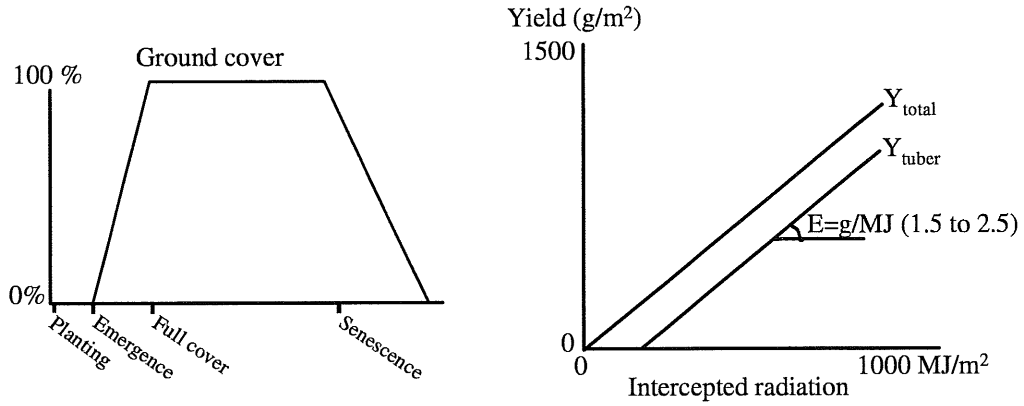

Figure 5.3 Schematical representation of tuber production in potato based on ground cover (and) light interception and conversion of intercepted into total and tuber dry matter

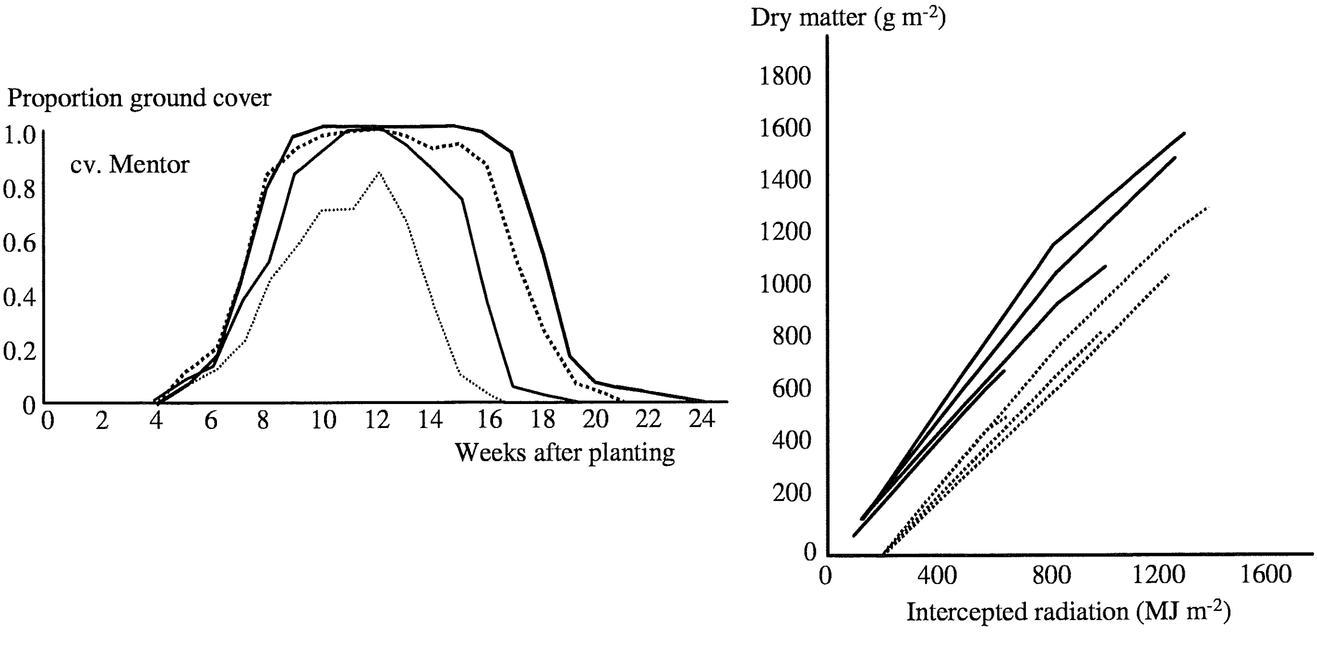

Figure 5.4 The effect of drought and potato cyst nematodes on light interception and dry matter production (bold lines: treatment with nematicides (soil fumigation), regular lines: no treatment with nematicides, drawn lines: irrigated, broken lines unirrigated. Dry matter production: continuous lines indicate total dry matter of the first three harvests, dashed lines indicate tuber dry matter of the last 3 harvests. (Haverkort *et al.*, 1992)

Van Keulen and Stol (1995), used this model approach to calculate potential yields at about 1000 meteorological sites. They assumed that no potato crop grows below 5° nor above 28°C and that the conversion rate is 2.5 g MJ^{-1} · They also assumed that each site is grown with a cultivar of the appropriate length of the cycle fitting the length of the season. This means that for each site a harvest index of 0.75 at crop senescence was assumed. Thus they calculated potential yields as shown in Figure 5.5. Around the equator at sea level potato production does not take place because it is too warm year round. At higher latitudes than about 55° no potatoes are grown because not sufficient thermal time is accumulated to allow one growth cycle. Yields are highest in the tropical highlands where potato production is feasible year round, followed by Mediterranean climates where two cropping seasons are possible followed by the temperate areas with one long single growth cycle.

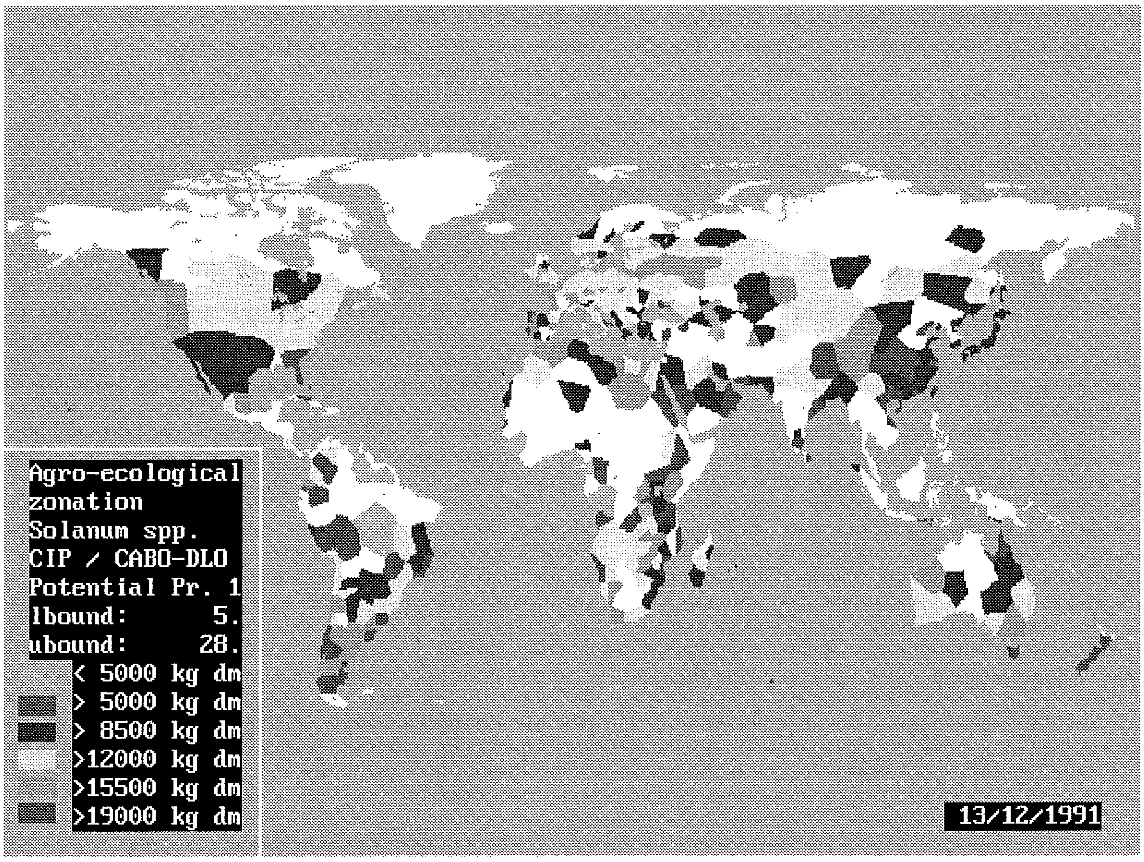

Figure 5.5 Calculated potential potato dry matter yields (Van Keulen and Stol, 1995)

5.1.3. Yield defining factors: temperature and daylength

In Figure 5.5 potential yields are shown globally assuming that cultivars exist that fit the local conditions regarding temperature and daylength responses. Potato is known to react to shorter days and lower temperatures: such conditions hasten tuber formation and favour tuber growth at the expense of haulm growth. LINTUL-POTATO (Kooman and Haverkort, 1995) was developed to quantify the effect of temperature and daylength on tuber initiation and subsequent dry matter partitioning over tubers and haulms. The main features of the LINTUL-POTATO model are shown in Figure 5.6
The model subsequently contains routines describing:

Phase 0 between planting and emergence assuming a sprout growth rate of 1 mm per daydegree. This means that a tuber planted at 12 cm depth with a sprout length of 2 cm emerges after 10 days when the average soil temperature is 10 °C. Once emerged (defined when the initial leaf area per plant is 0.0155 m^{-2} m^{-2} x the number of plants per plants per m^2) the relative leaf extension rate is 0.012 m^2 per m^2 per day degree and the leaf area is formed to build up the leaf area index. Light is extinguished according to Beer's Law with an extinction coefficient of 1. Leaf classes that are formed have a temperature dependent longevity.

Other temperature dependent rates, but with an optimum around 20° are the sprout growth rate, light use efficiency (see Figure 5.4, optimally 2.5 g MJ^{-1}) and most importantly the tuber initiation and tuber growth rates. The latter optimally is assumed to be 0.37 g g^{-1} d^{-1}. Most crucial in this model approach is the moment of tuber initiation and subsequent tuber growth rate. The tuber initiation rate (inverse of the number of days between emergence and tuber initiation (defined as the presence of 1 g of tuber dry matter per m^2) also depends on the daylength: longer days reduce the relative effect of optimal temperatures, so plants continue to grow for a longer period.

When tubers are initiated early (with an early cultivar) and when conditions for tuber growth are optimal, soon all daily accumulated assimilated will be allocated to the tubers and the crop will die early. Figure 5.7 shows the different phases of a crop: 0 is between planting and emergence (the sprout growth rate is temperature dependent), 1 is between emergence and tuber initiation (the tuber initiation rate is temperature and daylength dependent), phase 2 is between tuber initiation and the moment when 90 % of all daily produced assimilates are partitioned to the tubers (the tuber growth rate is temperature and daylength dependent) and phase 3 is between the moment when 90 % of the assimilates are partitioned to the tubers and crop senescence (the leaf senescence rate is temperature dependent).

With LINTUL-POTATO it is possible to explore what happens to a standard cultivar when grown under different temperature and daylength conditions. For model parameterization experimental results were obtained of 8 cultivars varying in lateness from very early to very late were grown under various temperature and daylength conditions in Rwanda (two altitudes), Tunisia (spring, autumn and winter seasons) and in the Netherlands (summer season). Figure 5.8. shows the expected tuber yields of a standard genotype of medium lateness with average temperature and daylength effects on tuber initiation rate. Potato crops have a considerably broader optimal temperature range at longer days. This phenomenon may explain the wide adaptability of the crop which is grown in a wide range of environments.

A second use of LINTUL-POTATO is to identify genotypes adapted to the climatical conditions at any site in the world. Figure 5.5 showed the potential yields of 1000 meteorological sites. To find out how late a cultivar should be so that the length of the growth cycle matches the length of the growing season, LINTUL-POTATO is able to calculate the ideal moment of tuber initiation for each site. If for a particular site tuber initiation takes place before the optimal moment, plants are still too small and too early all assimilates will be allocated to the tubers leaving none to the foliage that will die too early to match the length of the potential growing season (when temperatures are between 5 and 25°C). When tuber initiation takes place too late, much foliage is formed and the allocation pattern is unfavorable for tuber growth resulting in too low harvest indices. This is shown in Figure 5.9 for two sites: a spring and an autumn season in Tunisia and a s single summer season in the Netherlands.

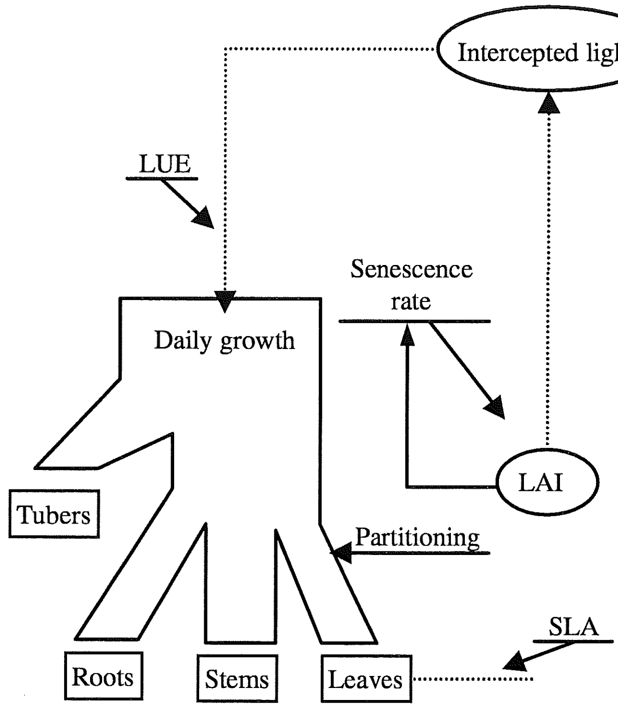

Figure 5.6 LINTUL-POTATO, Schematical representation of the modelling approach

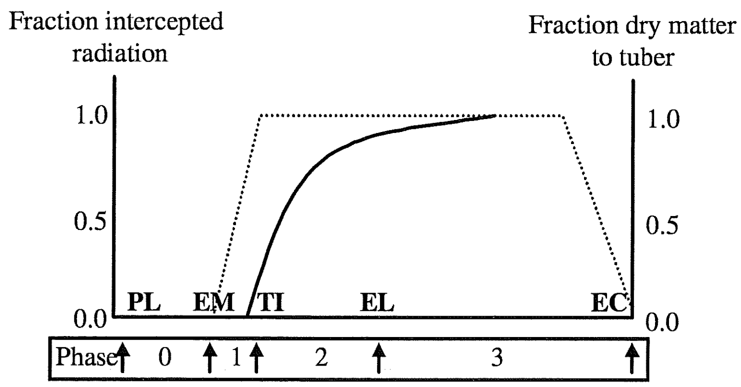

Figure 5.7 The phases of crop growth and development of potato (PL = planting, EM = emergence, TI = tuber initiation, EL = end of leaf growth, EC = end of crop growth, f_{int} = fraction of incoming solar radiation intercepted by the crop (broken line) and f_{tub} = fraction of daily accumulated dry matter allocated to the tubers (unbroken line))

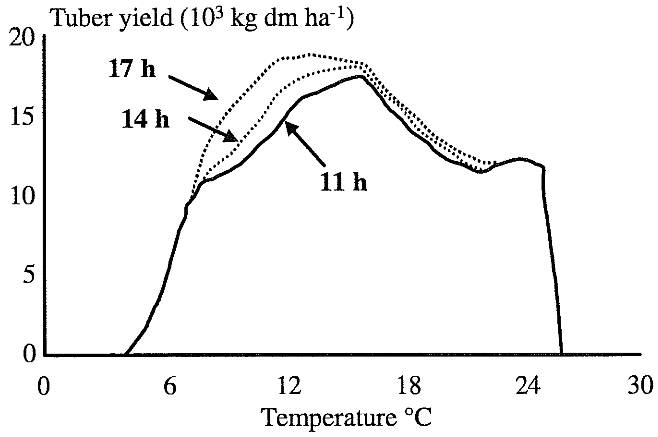

Figure 5.8 Tuber yields of a standard genotype of potato grown at different temperature and daylength combinations (Kooman and Haverkort, 1995)

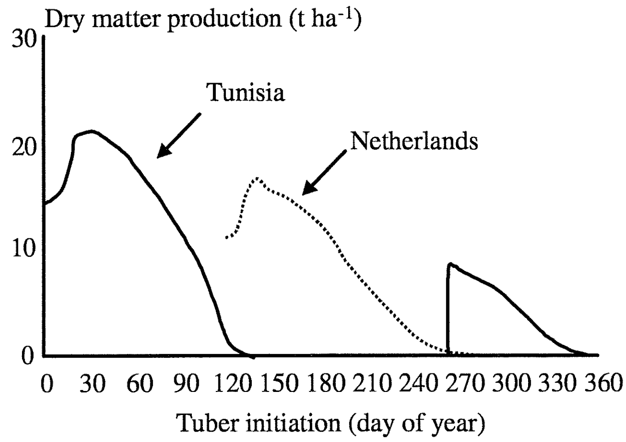

Figure 5.9 Expected potential dry matter production (30 year average temperature data) at varying moments of tuber initiation) in three varying seasons, calculated with LINTUL-POTATO (Kooman and Haverkort, 1995)

5.1.4. Yield limiting factor (water) and yield reducing factor (nematodes)

Water probably is the most yield limiting factor of most crops. The kind of drought which is expected is crucial in the strategy to increase the efficient use of water. Crops may react in different ways (and so do their producers) to limit the extent of damage. Yield analysis following the basic principles of LINTUL-POTATO (periodic observation of fresh and dry total and tuber mass and cumulative intercepted radiation by the crop) showed (Haverkort *et al.*, 1992) that yield losses are mainly due to reduced amounts of intercepted radiation by the crop and for less than 10% due to reduced conversion efficiencies (Table 5.1) or to reduced harvest indices. Also long-term effects of potato cyst nematodes are similar to those of drought: both mainly reduce yields through reduced light interception by green foliage (27 to

52 % reduction; Table 5.2) whereas the conversion efficiency is reduced by 14 % at the most but usually less than 10 %. As with drought, the harvest index is decreased slightly and the tuber dry matter increased by a few percentage points.

Table 5.1 Relative values of yield components of unirrigated versus irrigated plots (mean values of two years, after Haverkort *et al.*, 1992)

Cultivar	Y=	R x	E x	H :	D
Darwina	55	62	99	94	105
Desiree	77	88	99	94	105
Elles	80	93	90	95	101
Mentor	73	87	97	97	111

Table 5.2 Relative values of yield components of unfumigated versus fumigated plots (mean values of 3 years, after Haverkort *et al.*, 1992)

Cultivar	Y=	R x	E x	H :	D
Darwina	48	61	90	94	105
Desiree	52	71	86	93	102
Elles	73	86	95	102	107
Mentor	49	57	92	100	101

Cultivar Elles was most tolerant of both drought and of potato cyst nematodes which is not surprising. Elles was the latest cultivar tested, and when subjected to a yield limiting or a yield reducing factor made best use of the available growing season. Elles is a cultivar that initiates its tubers late allowing the plant to allocate much dry matter the foliage. When subjected to stress such a genotype makes better use of the available growing season because its length of the growth cycle better matches the length of the growing season than an earlier genotype.

Incorporation of the effect of drought stress in LINTUL was done by van Keulen and Stol (1995). The level of drought stress (S_d) is then calculated as:

$$S_d = \left(1 - \frac{T_A}{T_P}\right) - 0.2$$

where T_A (actual transpiration) falls short of potential transpiration (T_P) under limited soil moisture availability. T_A/T_P decreases linearly with soil moisture content from unity at the critical soil moisture content to zero at wilting point. The reduction by 0.2 accounts for the tolerance of leaves to low degrees of stress.

The growth rate is multiplied with increasing S_d from 1 at 0, via 0.5 at o.5 to 0 at 0.75. The effect on leaf senescence is dependent on cumulative drought stress (i.e. the integrated value of S_d) in such a way that, due to accelerated leaf senescence, the crop canopy does not expand any further beyond a cumulative drought stress value of 10. At still higher values, light interception decreases irreversibly. Beside worldwide potential yields as shown in Figure 5.5, Van Keulen and Stol in the same paper reported the water limited yields and by subtracting the two, the benefit of irrigation. This approach is know as yield gap analysis. Yield gaps are defined as the difference between the potential production and the attainable and/or actual crop production. Yield gaps illustrates the possibilities of crop and or management improvement.

5.2. Description of the LINTUL-POTATO crop growth model

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5.2.1. Introduction

Crop growth under favourable conditions is observed to be often proportional to the amount of intercepted light. The **L**ight **IN**terception and **U**ti**L**isation model LINTUL1 is based upon this observation. The model simulates potential growth of a crop, i.e. its dry matter accumulation under ample supply of water and nutrients in a pest-, disease and weed free environment, under the prevailing weather conditions. The rate of dry matter accumulation is a function of irradiation and crop characteristics. Dry matter production is modelled as the product of light interception and a constant light use efficiency. The dry matter produced is partitioned among the various plant organs, using partitioning factors defined as a measured function of the phenological development stage of the crop. The dry weights of the plant organs are obtained by integration of their growth rates over time. LINTUL1 requires as input physiological properties of the crop and the actual weather conditions at the site, characterised by its geographical latitude, i.e. daily maximum and minimum temperatures and irradiation for each day of the year during the cropping season.

Crop growth under water limited conditions is simulated by the LINTUL2 model by including a water balance of crop and soil in the LINTUL1 model. Conditions are still optimal with respect to other growth factors, i.e. nutrients are ample available and the environment is pest-, disease- and weed-free. The effect of altered water relations is transmitted through two variables, one acting on total crop growth and the other one acting on root-shoot partitioning of dry matter. Additional environmental input data are vapour pressure, wind speed, precipitation and soil characteristics as soil water content at wilting point, field capacity, full saturation etc.. These characteristics can be estimated from soil physical properties which are documented in soil maps.

The objective of this section is to give a detailed description of the model for potential potato production and to show the possibility to apply this model in ecoregional research. LINTUL1 is written in FST, the FORTRAN Simulation Translator (van Kraalingen *et al.*, 1994), which runs on various computer platforms, e.g. VAX-mainframe, IBM-PC or compatible, and Apple-Macintosh.

The explanatory text follows as closely as possible the computer listing of the model. Each section starts with a number of lines copied from this listing. In the following text, the inevitably awkward abbreviative terminology so typical for computer modelling, is then explained. Units of all variables and data are specified.

```
DEFINE_CALL GLA(INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT,INPUT, ...
                INPUT,INPUT,OUTPUT)
TITLE LINTUL1
```

FST requires, before the program starts, a definition of the calls for subroutines that are used in the program. All variables in the subroutine-call have to be defined as INPUT or

OUTPUT variables. These definitions will be used by FST for sorting the program lines. After the definition of the subroutine-call the program starts with the TITLE of the program.

5.2.2. *Initial conditions and run control*

```
*  Initial conditions
INCON ZERO = 0.
*  Initial leaf area index (LAII: m2/m2)
   LAII = NPL * LA0
```

FST requires the name of a constant as initial value for an integration. In case this integration starts at zero (e.g. summation of temperature) the initial constant ZERO is used.

The initial leaf area index crop emergence (LAII, $m^2_{leaf}\ m^{-2}_{ground}$) is calculated as the product of initial Leaf Area per plant (LA0, m^2_{leaf} $plant^{-1}$) and the Number of PLants per surface area (NPL, #plants.m^{-2}_{ground}).

```
*  Run control
TIMER STTIME = 1.; FINTIM = 200.; DELT = 1.; PRDEL = 5.
TRANSLATION_GENERAL DRIVER='EUDRIV'
PRINT LAI, WSOTHA, WSO, WST, WLV, WRT, TSUM, DAVTMP, DTR
```

Simulation may start earlier than emergence. This is specified in the TIMER statement (STTIME = 1 means: 1 January). Simulation is executed with time steps of one day (DELT=1.), with rectilinear integration (Euler) of the rates (DRIVER='EUDRIV'). Output is produced every fifth day (PRDEL=5.). To make sure that the simulation does not continue endlessly, the finish time (FINTIM) is set at day 200. The simulation will also stop when the FIN statement is greater than 0.

In the PRINT line any variable can be specified. Values are written to the output file at every print interval (PRDEL).

```
FINISH FIN > 0.
DYNAMIC
FIN  = INTGRL(ZERO,RFIN)
RFIN = REAAND(TSUM-100.,0.01-LAI)
```

The simulation stops also if the crop is mature. This occurs if the Leaf Area Index (LAI) is smaller than 0.01 $m^2.m^{-2}$. In order to prevent that the simulation stops when the leaves have just emerged, the temperature sum (TSUM) has to be greater than 100 °Cd (TSUM>100). This means that simulation stops at the end of the growing season when the leaves have become detoriated (LAI<0.01).). For explanation of the INTGRL and REAAND functions, see the description of FST (van Kraalingen *et al.*, 1994)

5.2.3. Environmental data and temperature sum

```
WEATHER WTRDIR='C:\SYS\WEATHER\'; CNTR='PER'; ISTN=3; IYEAR=1985
*      Reading weather data from weather file:
*      RDD     Daily global radiation        J/(m2*d)
*      TMMN    Daily minimum temperature     degree C
*      TMMX    Daily maximum temperature     degree C
       DTR     = RDD/1.E+6
       DAVTMP  = 0.5 * (TMMN + TMMX)
       DTEFF   = MAX ( 0., DAVTMP-TBASE )
       EMERG   = MAX( INSW(TIME-DOYEM, 0., 1.), INSW(-LAI,1.,0.) )
       TSUM    = INTGRL(ZERO, RTSUM)
       RTSUM   = DTEFF*EMERG
```

Actual daily total global radiation (RDD, J m^{-2} d^{-1}) is read from the weather data file, which contains measured values for solar radiation (400 - 2000 nm) for all days of the year. RDD is converted into other units by division by 10^6, to give DTR in MJ m^{-2} d^{-1}.

Daily maximum and minimum temperatures (TMMX and TMMN, respectively, °C) are also read from the weather data file, containing measured values for all days of the year. DAVTMP is the daily average temperature. Since many growth processes are temperature dependent above a certain threshold temperature, an effective temperature (DTEFF) is calculated. For potato, the threshold value (TBASE) is 2 °C. The variable EMERG equals 0 before emergence, and 1 after emergence, when DOY is equal or larger than the daynumber of emergence (DOYEM) is or when there are leaves, LAI>0. For explanation of the MAX and INSW functions, see the description of FST (van Kraalingen *et al.*, 1994). Note that TIME may become larger than 365, in case the simulation runs from one calendar year into the next year.

Phenological development of crops is more closely related to thermal time, i.e. the accumulated number of degree-days after emergence, than to the age of the crop in days. Therefore, the model calculates the temperature sum (TSUM, °Cd) by accumulating the daily values of effective temperature after emergence (RTSUM, °C).

5.2.4. Leaf growth and senescence

```
***    3. Leaf growth and senescence
       CALL GLA(
TIME,DOYEM,DTEFF,TSUM,LAII,RGRL,DELT,SLA,LAI,GLV,GLAI)
*      dry matter leaf growth rate
       GLV    = FLV * GTOTAL
*      death rate of leaf area index
       DLAI    = MIN(DRDV+DRSH, LAI/DELT + GLAI)
*      death rate leaves due to ageing
       DRDV    = INSW(TSUM-725., 0., DRDV0 * DTEFF)
*      death leaves due to self-shading
       DRSH    = LIMIT(0., DRSH0, DRSH0 * (LAI-LAICR) / LAICR)
*      death rate of leaves
       DLV    = WLVG * DLAI/NOTNUL(LAI)
*      growth rate of LAI
       RLAI   = GLAI - DLAI
       LAI    = INTGRL(ZERO, RLAI)
```

The area of green leaves is the major determinant for light interception and utilisation. The leaf area index (LAI, m^2 (leaf) m^{-2} (ground)) is obtained by integrating the net result (RLAI, $m^2\ m^{-2}\ d^{-1}$) of the leaf growth rate (GLAI, $m^2\ m^{-2}\ d^{-1}$), and the leaf senescence rate (DLAI, $m^2\ m^{-2}\ d^{-1}$).

GLAI is calculated, depending on the phenological development stage, in the Subroutine GLA. Before seedling emergence (TIME < DOYEM), GLAI equals zero. At emergence, GLAI = LAII/DELT. After emergence, light intensity and temperature are the environmental factors influencing the rate of leaf area expansion.

During juvenile growth, temperature is the overriding factor, as the rate of leaf appearance and final leaf size are constrained by temperature through its effect on cell division and extension, rather than by the supply of assimilates. In these early stages, leaf area increases approximately exponentially over time. Examination of unpublished field data suggests that a safe approximation is to restrict the exponential phase to the situation where LAI < 0.75 $m^2\ m^{-2}$ and TSUM < 330 °Cd. This is programmed in the Subroutine GLA, which is reproduced at the last page of this program description. Exponential leaf area development is described analytically by:

```
LAI(t+DELT) = LAI(t) * EXP(RGRL * DTEFF * DELT)
```

so that the rate of increase in leaf area during juvenile growth is:

```
GLAI = (LAI(t + DELT) - LAI(t)) / DELT
     = LAI(t) * (EXP(RGRL * DTEFF * DELT) - 1.) / DELT
```

in which LAI(t) is the current leaf area ($m^2\ m^{-2}$), RGRL is the relative growth rate of leaf area, expressed per degree-day ($(°Cd)^{-1}$), DELT is the time step of integration (d) and DTEFF is the daily effective temperature (°C).

In later development stages, leaf area expansion is increasingly restricted by assimilate supply. Branching and tillering generate an increasing number of sites per plant where leaf initiation can take place and mutual shading of plants further reduces the assimilate supply per growing point. During this stage (LAI > 0.75 or TSUM > 330 °Cd), the model calculates the growth of leaf area by multiplying the simulated increase in leaf weight (GLV, $g\ m^{-2}\ d^{-1}$) by the specific leaf area of new leaves (SLA, $m^2\ g^{-1}$).

The senescence rate of LAI (DLAI, d^{-1}) is set at the minimum of either a relative death rate due to ageing (DRDV) and self-shading, DRSH, or either due to developmental ageing. The relative death rate due to shading equals zero for LAI smaller than 4 (= LAICR), and above that value increases linearly with increasing LAI till a maximum value of 0.03 (= DRSHO) at LAI = 8. For the meaning of the LIMIT function, see the description of FST, van Kraalingen *et al.*, 1994.

DRDV equals zero as long as TSUM < 725 and is a function of the average daily temperature (DAVTMP, °C) for TSUM > 725.

The death rate of leaves in terms of weight (DLV, $g\ m^{-2}\ d^{-1}$) is defined using the same relative senescence rate (DLAI) that also applies to LAI, but now multiplied with the weight of the green leaves (WLVG, $g\ m^{-2}$).

5.2.5 Light interception and total crop growth rate

```
PARINT = 0.5 * DTR    * (1. - EXP(-KDF*LAI))
GTOTAL = LUE * PARINT
```

Photosynthetically active radiation (PAR), wavelengths between 400 and 700 nm, is about 50% of the incoming global radiation (0.5*DTR). The daily values of intercepted Photosynthetically active radiation (PARINT, MJ $m^{-2}\ d^{-1}$) are derived by assuming that light interception increases with LAI according to a negative exponential function of leaf area index, characterised by a crop-specific light extinction coefficient (KDF, $m^2_{ground}\ m^{-2}_{leaf}$).

The overall daily growth rate of the crop (GTOTAL, g $m^{-2}\ d^{-1}$) is then calculated by multiplying the amount of light intercepted by a constant light use efficiency (LUE, g MJ^{-1}).

5.2.6. *Growth rates and dry matter production of plant organs*

```
FRT    = AFGEN( FRTTB, TSUM )
FLV    = AFGEN( FLVTB, TSUM )
FST    = AFGEN( FSTTB, TSUM )
FSO    = AFGEN( FSOTB, TSUM )
* state variable integration
WLVG   = INTGRL( ZERO, RWLVG)
WLVD   = INTGRL( ZERO, DLV  )
WST    = INTGRL( ZERO, RWST )
WSO    = INTGRL( ZERO, RWSO )
WRT    = INTGRL( ZERO, RWRT )
WLV    = WLVG + WLVD
* rate calculation
RWLVG  = GTOTAL * FLV - DLV
RWST   = GTOTAL * FST
RWSO   = GTOTAL * FSO
RWRT   = GTOTAL * FRT
* conversion from WSO,g/m2 to WSOTHA tons/ha
WSOTHA = WSO / 100.
```

Partitioning of biomass over the various plant organs is described by fixed distribution factors, defined as functions of the temperature sum. Before tuber initiation (TSUM < 142) the highest distribution factors are those for roots (FRT), leaves (FLV) and stems (FST), thereafter most of the biomass is allocated to the storage organs, i.e. tubers (FSO). This allocation-pattern is embodied in the FUNCTION-statements given in the next section.

Dry weights of the various plant organs (roots (WRT, g m^{-2}), green leaves (WLVG, g m^{-2}), dead leaves (WLVD, g m^{-2}), stems (WST, g m^{-2}), storage organs (WSO, g m^{-2})) are obtained through integration of the respective growth rates. For convenience, the program calculates yield in tons/ha as well (WSOTHA, t ha^{-1}).

5.2.7. *Functions and parameters for potato*

```
*      Section 1
* number plants and initial leaf area
* NPL: plants/m2 soil ; LA0: m2 leaf/plant
PARAM NPL = 3.8; LA0 = 0.0155

*      Section 2
* base temperature,
* TBASE: oC
PARAM TBASE = 2.
```

```
*     Section 3
* day number of crop emergence and relative LAI growth rate
* DOYEM: day ; RGRL: 1/Cd
PARAM DOYEM = 132.  ; RGRL  = 0.012
* specific leaf area and critical leaf area for death due to
* selfshading
* SLA: m2/g dm; LAICR: m2 leaf/m2 soil
PARAM SLA   = 0.03 ; LAICR = 4.

* initial death rates of leaves due to ageing and shading
* DRDV0: 1/d, DRSH0: 1/d
PARAM DRDV0 = 0.004; DRSH0 = 0.05

*     Section 4
* light use efficiency and extinction coefficient
* LUE: g/MJ(PAR); KDF: m2soil/m2 leaf
PARAM LUE = 2.7; KDF = 1.0

*     Section 5
*     Partitioning tables for leaves (LV), stems (ST),
*     storage organs (SO) and roots (RT):
FUNCTION FLVTB  = 0.,0.6, 142.,0.6, 465.,0.0 , 572.,0.0, 2500.,0.0
FUNCTION FSTTB  = 0.,0.2, 142.,0.2, 465.,0.2 , 572.,0.0, 2500.,0.0
FUNCTION FSOTB  = 0.,0.0, 142.,0.0, 465.,0.75, 572.,1.0, 2500.,1.0
FUNCTION FRTTB  = 0.,0.2, 142.,0.2, 465.,0.05, 572.,0.0, 2500.,0.0

END

* Start of rerun section

PARAM DOYEM = 60.
END

STOP
* Start of Subroutine section (see Section 3)
* -----------------------------------------------------------------
*
*SUBROUTINE                                                     GLA
*
*Purpose:This subroutine computes daily increase of leaf area index
*
*                           (m2     leaf/    m2    ground/     d)
*
* -----------------------------------------------------------------
*
      SUBROUTINE
GLA(TIME,DOYEM,DTEFF,TSUM,LAII,RGRL,DELT,SLA,LAI,GLV,
     $               GLAI)
      IMPLICIT REAL (A-Z)
```

```
*---- Growth during maturation stage:
      GLAI = SLA * GLV

*---- Growth during juvenile stage:
      IF ((TSUM.LT.330.).AND.(LAI.LT.0.75))
     $   GLAI = LAI * (EXP(RGRL * DTEFF * DELT) - 1.) / DELT

*---- Growth at day of seedling emergence:
      IF ((TIME.GE.DOYEM).AND.(LAI.EQ.0.))
     $   GLAI = LAII / DELT

*---- Growth before seedling emergence:
      IF (TIME.LT.DOYEM) GLAI = 0.

      RETURN
      END
```

5.2.8. Definitions of the abbreviations used in de models LINTUL1

Name	Description	Units*
CNTR	Country code for weather file	-
DAVTMP	Daily average temperature	°C
DELT	Time step of integration	d
DLAI	Death rate of leaf area index	$m^2 m^{-2} d^{-1}$
DLV	Death rate of leaves	$g m^{-2} d^{-1}$
DOY	Daynumber of year	d^{-1}
DOYEM	Daynumber at crop emergence	d^{-1}
DRDV	Relative death rate of leaves due to ageing	d^{-1}
DRDV0	Initial relative death rate of leaves due to ageing	d^{-1}
DRSH	Relative death rate of leaves due to shading	d^{-1}
DRSH0	Maximum relative death rate of leaves due to shading	d^{-1}
DTEFF	Daily effective temperature	°C
DTR	Daily global radiation	$MJ m^{-2} d^{-1}$
DTRJM2	Daily global radiation	$J m^{-2} d^{-1}$
EMERG	Auxiliary variable indicating crop emergence	-
FINTIM	Finish time of simulation run	d
FLV	Fraction of dry matter allocated to the leaves	-
FLVTB	Table of FLV as a function of TSUM	-
FRT	Fraction of dry matter allocated to the roots	-
FRTMOD	Relative modification of FRT by drought	-
FRTTB	Table of FRT as a function of TSUM	-
FSO	Fraction of dry matter allocated to the storage organs	-
FSOTB	Table of FSO as a function of TSUM	-
FST	Fraction of dry matter allocated to the stems	-
FSTTB	Table of FST as a function of TSUM	-
GLA	FORTRAN subroutine to calculate GLAI	-
GLAI	Growth rate of leaf area index	$m^2 m^{-2} d^{-1}$
GLV	Growth rate of leaf dry matter	$g m^{-2} d^{-1}$
GTOTAL	Growth rate of total crop dry matter	$g m^{-2} d^{-1}$
ISTN	Weather station number	-
IYEAR	Year	-
KDF	Extinction coefficient for Photosynthetically active radiation	$m^2 m^{-2}$
LAI	Leaf area index	$m^2 m^{-2}$
LAICR	Critical LAI beyond which leaves die due to self-shading	$m^2 m^{-2}$

LAII	Initial leaf area index (at crop emergence)	$m^2 m^{-2}$
LA0	Initial leaf area per plant (at crop planting)	m^2 $plant^{-1}$
LUE	Light use efficiency (dry matter produced per unit of intercepted Photosynthetically active radiation)	$g MJ^{-1}$
PARINT	Intercepted Photosynthetically active radiation	$MJ m^{-2} d^{-1}$
PRDEL	Time interval for printing	D
RAIN	Water input through rainfall	$mm d^{-1}$
RDD	Daily global radiation (weather file)	$J m^{-2} d^{-1}$
RGRL	Relative growth rate of LAI during exponential growth	$(°C d)^{-1}$
RLAI	Growth rate of LAI	$m^2 m^{-2} d^{-1}$
RTSUM	Rate of increase of the temperature sum	°C
RWLVG	Net rate of increase weight of green leaves	$g m^{-2} d^{-1}$
RWRT	Rate of increase weight of roots	$g m^{-2} d^{-1}$
RWSO	Rate of increase weight of storage organs	$g m^{-2} d^{-1}$
RWST	Rate of increase weight of stems	$g m^{-2} d^{-1}$
SLA	Specific leaf area	$m^2 g^{-1}$
STTIME	Start time of the simulation run	d
SVP	Saturation vapour pressure	kPa
TBASE	Base temperature	°C
TIME	Time from 1 January	d
TMMN	Daily minimum temperature (weather file)	°C
TMMX	Daily maximum temperature (weather file)	°C
TSUM	Temperature sum	°C d
WLV	Dry weight of leaves	$g m^{-2}$
WLVD	Dry weight of dead leaves	$g m^{-2}$
WLVG	Dry weight of green leaves	$g m^{-2}$
WLVI	Initial dry weight of green leaves (at crop emergence)	$g m^{-2}$
WRT	Dry weight of roots	$g m^{-2}$
WSO	Dry weight of storage organs	$g m^{-2}$
WSOTHA	Dry weight of storage organs	$t ha^{-1}$
WST	Dry weight of stems	$g m^{-2}$
WTRDIR	Weather directory	-
ZERO	Initial value used in integral statements	*Same unit as state variable*

5.3. Ecoregional application of the LINTUL-POTATO model

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The potential crop production depends on the daily intercepted radiation and the ambient temperatures at a specific site. The LINTUL model is derived for prediction of crop yield at experimental plot scale and field scale. This implies that the variability at smaller scales (subplot scales) can not be reproduced by this model because some processes are lumped into more robust process-descriptions. Therefore the LINTUL model assumes a homogenous distribution of environmental variables at a specific site with plot or field size. This however has consequences for the application of this model at larger scales. The environmental variables have in first to be generated for each site with an average size of a field. When the environmental heterogeneity between sites can be ignored, these sites can be aggregated into larger ones until the variability within a site increase. The model simulates after this the expected crop yield for each site. Further aggregation of sites into larger spatial areas has to be performed with the simulated crop yield rather then with the environmental input variables. Non-linearity's in the crop growth model cause a large variability in simulated crop yields while little variability in the environmental input variables is perceptible.

An example of environmental heterogeneity in input variables is shown in Figure 5.10. The FAO long year mean climate stations are shown with the spatial extension for each station. The spatial extension for each station is calculated by using a Thiessen tessellation which is a procedure that produce the weighted average distance between separate stations. Potato crop yields for each spatial unit can be simulated by using the climate variables of each station. This approach however leads to erroneous predicted crop yields. The spatial extension of the weather stations is however large compared to the known spatial heterogeneity in soil type, elevation, etc. of the region. So in order to increase the reality of the simulated crop production more environmental variables have to be included either in the model or in the environmental data-analysis. A proper procedure is to include more climate stations in the simulations up to the level that the heterogeneity within the spatial unit becomes sufficient small.

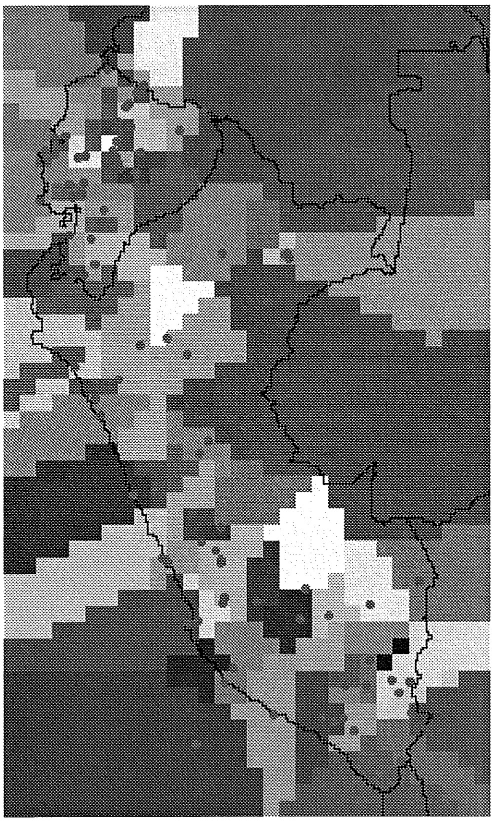

Figure 5.10 The FAO weather stations in Ecuador and Peru. The spatial coverage of each station is determined by a Thiessen tessellation procedure.

Another source of environmental heterogeneity is the soil type. The water holding capacity and the amount of available nutrients are determined by soil characteristics. The soil types for the Andean region which are derived from the FAO-soil map are shown in figure 5.11. The environmental heterogeneity increases by combining the weather station map and the soil map. The spatial influence area of each weather station might cover several soil types. So the in first spatial homogenous distributed potential crop yield for each weather station is now decomposed into several simulated crop productions in the combination station-soil type, see figure 5.11. The spatial decomposition increases further by overlaying figure 5.11 with a digital elevation map. The in first apparent spatial homogeneity of the spatial extension of each climate station in figure 5.10 becomes a mosaic of smaller spatial units. It is this mosaic which should be applied as smallest spatial unit for crop simulation studies.

The objectives of this application are to understand the basic principles of crop growth simulation and its application in an ecoregional context. The main objective is to understand the limitations of straightforward application of crop simulation models. These limitations are based on:

1) A model is only a partial description of reality
2) The result of a crop simulation model is a point prediction of crop yield. Additional methodology has to be developed before simulation results can be applied in an ecoregional context.

Especially the issue of scale where point based crop simulation results are aggregated to represent the mean simulated crop yield of a region has to be handled carefully. The DME-NOR project is aimed to develop a generic methodology with which multi-scale issues can be handled.

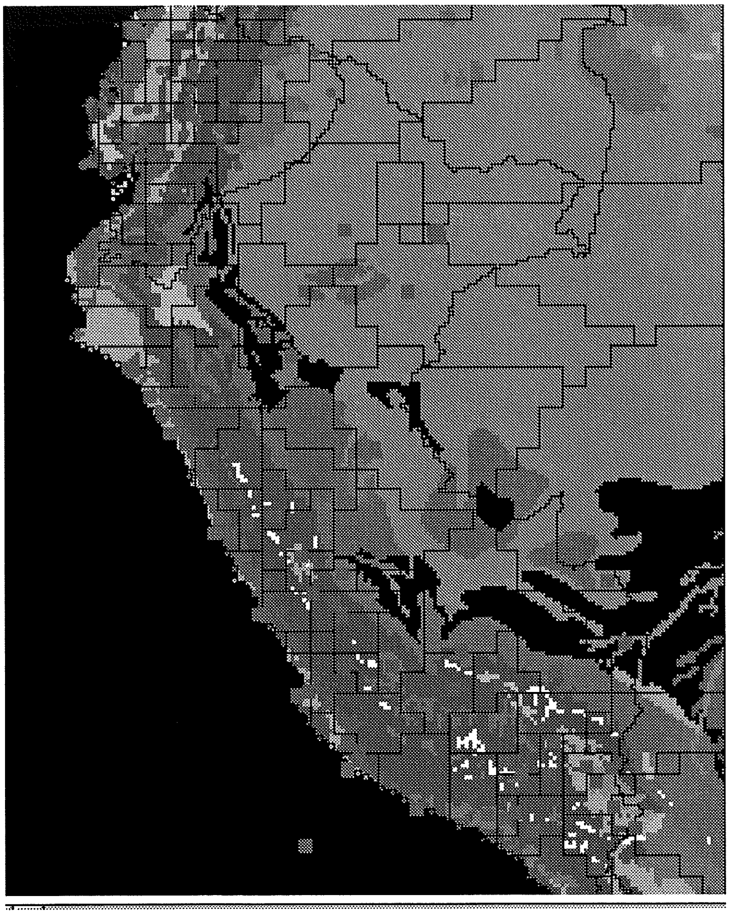

Figure 5.11 FAO soil map of Ecuador and Peru in combination with the polygons of the Thiessen tessellation of the FAO weather stations.

5.4. Summary of the tool

Tools Fact Sheet	
Name	**LINTUL1-potato and LINTUL2-potato**
Version	**FST**
Development	**Model: Spitters & Schapendonk, 1990, Plant and Soil 123:193-203** **Windows user interface: R. van Haren**
Status (freeware /shareware/ commercial)	**model: available upon request and registration (nominal cost)** **windows user interface: available upon request and registration (nominal cost)**
System requirements	**MS Windows (3.1 or 95)**
Links with commercial software	**Fortran compiler is recommendable, not necessary**
Objectives	**LINTUL has been developed for educational and application purposes**
Data Requirements	**weather (potential production) and soil data (water limited production)**

References

Haverkort AJ, Boerma M, Velema R, van de Waart M 1992 The influence of drought and cyst nematodes on potato growth. 4. Effects on crop growth under field conditions of four cultivars differing in tolerance. Netherlands Journal of Plant Pathology 98:179-191

Haverkort AJ, Goudriaan J, 1994 Perspectives of improved tolerance of drought in crops. Aspects of Applied Biology 38:79-92

Keulen H. van, Stol W 1995 Agro-ecological zonation for potato production. Pages 357-371 In: Haverkort AJ, MacKerron DKL (eds.) Potato ecology and modelling of crops under conditions limiting growth. Kluwer Academic Publishers, Dordrecht

Kooman AJ, Haverkort AJ 1995 Modelling development and growth of the potato crop influenced by temperature and daylength: LINTUL POTATO. Pages 41-60 In: Haverkort AJ MacKerron DKL (eds) Potato ecology and modelling of crops under conditions limiting growth. Kluwer Academic Publishers, Dordrecht

Kraalingen DWG van, Rappoldt C, Laar HH van 1994 Appendix 5: The FORTRAN Simulation Translator (FST), a simulation language. Pages 219-232 In: Goudriaan J, Laar HH van Modelling potential crop growth processes. Kluwer Academic Publishers, Dordrecht The Netherlands

Penning de Vries FWT, Jansen DM, Berge HFM ten, Bakema A 1989 Simulation of ecophysiological processes of growth of several annual crops. Simulation Monographs 29, Pudoc, Wageningen

Spitters CJT, Schapendonk AHCM 1990 Evaluation of breeding strategies for drought tolerance in potato by means of crop growth simulation. Plant and Soil 44:193-202

6. Tradeoff assessment as a quantitative approach to analysis of the sustainability of agricultural production systems

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6.1. Backgrounds

A reorientation of public agricultural research institutions toward sustainable agricultural practices began in the 1980s and continues today. In the United States as well as in many other countries, sustainability criteria have been used to represent public concerns about the long-term economic, environmental, and public health impacts of agricultural technologies and associated production practices (Crosson, 1993; OECD, 1992). Many national research programs and the 16 research centers that comprise the Consultative Group on International Agricultural Research (CGIAR) operate under mandates to quantify the environmental and public health impacts associated with agricultural technologies. Yet, because sustainability is a relatively new objective for research, researchers have not reached a consensus on methods to quantify the concept of sustainability and incorporate it into public policy analysis (Batie, 1989; Lynam and Herdt, 1992; Ruttan, 1992, 1994).

Making sustainability operational within the context of international agricultural research calls for new approaches to research priority setting, problem identification, and organization. Several new research initiatives are adopting an eco-regional approach to integrate information at various levels of aggregation (Rabbinge, 1995). The International Potato Center (CIP) and its fellow institutes in the CGIAR adopted an eco-regional approach as a means to operationalize the concept of sustainability. The CGIAR identifies eco-regions as agro-ecological zones and defines the role of the eco-regional approach as follows:
"The main role of the eco-regional approach is to contribute to the goal of increasing sustainability of agricultural production by providing: first, a process that identifies the right research content due to its holistic and forward looking perspective which contrasts with traditional disciplinary and commodity approaches to research. Second, a mechanism for partner-ship, among relevant actors with complementary functions, that contributes to achieving their common and individual institutional goals through applied and strategic research on the foundations of sustainable production systems. Third, a mechanism that develops, tests, and supports effective research paradigms for the sustainable improvement of productivity" (CGIAR, 1993, p. 4).

The eco-regional approach places emphasis on modeling production systems and their environmental impacts at a small scale, such as the field scale or watershed, and on how those small-scale impacts affect systems at larger scales or higher levels of aggregation. The approach is primarily a systems modeling approach which emphasizes the importance of economic decision-making models to capture changing priorities in farm households and communities.

Other tools important to the eco-regional approach include geographic information systems and crop, livestock, and soils models (Bouma *et al.*, 1995). It must be emphasized that these tools build upon the methods and data provided by the traditional experimental approach of agricultural research that is the hallmark of the CGIAR research system (CGIAR, 1995).

6.2. Model objectives

The model aims at the development of a tool that provides a decision support system for assessing tradeoffs between agricultural production and the environment for different economic, agricultural and environmental policies, and agricultural research. The model assesses linkages between farmers' cropping decisions, economics and natural resources and should be able to:

- quantify the impact of existing and proposed agricultural and environmental policies on the sustainability of selected agro-ecosystems,
- screen proposed agricultural technologies such as integrated pest management and various types of soil husbandry for their potential impact on the sustainability of selected agro-ecosystem, and
- generate results that can be utilized to develop recommendations for research priorities for national and international research systems.

The spatial variation of natural resources is recognized and the model is linked to a geographical information system to be able to deal with this variation.

6.3. The research chain for tradeoff assessment

A central theme of this approach is that quantifying tradeoffs is an essential ingredient in setting research priorities and in designing and implementing the criteria of sustainable agriculture in agricultural research programs. Tradeoff assessment provides an organizing principle and conceptual model for the design and organization of multi-disciplinary research projects to quantify and assess the sustainability of agricultural production systems. This process is illustrated in Figure 6.1. Input from the general public ("stakeholders"), policy makers, and scientists is used to identify the critical dimensions of social concern, i.e., the sustainability criteria. Based on these criteria, hypotheses are formulated as tradeoffs between possibly competing objectives, such as higher agricultural production and improved environmental quality.

Once the key tradeoffs are identified, research team leaders can proceed with project design and implementation, and can identify the appropriate scientific disciplines to further design and implement the research needed to quantify these tradeoffs. The next step, critical to quantifying tradeoffs, is the identification of disciplinary models and data needed to quantify each sustainability indicator. A key aspect of this stage of the research design is to identify the data needs for each of the disciplinary components of the analysis, and how the model outputs can be effectively linked for the construction of tradeoffs. As we discuss further below, a critical element at this stage is for all of the disciplines to agree upon basic spatial and temporal units of analysis: Will analysis be conducted at the field scale or watershed? Will time steps be daily, weekly, monthly, or yearly? Once these fundamental issues in research design have been resolved, the data collection and disciplinary research can proceed. Upon completion of the disciplinary components of research, the respective data and models can be linked to test hypotheses about tradeoffs, and the findings can be presented to policy makers and the general public.

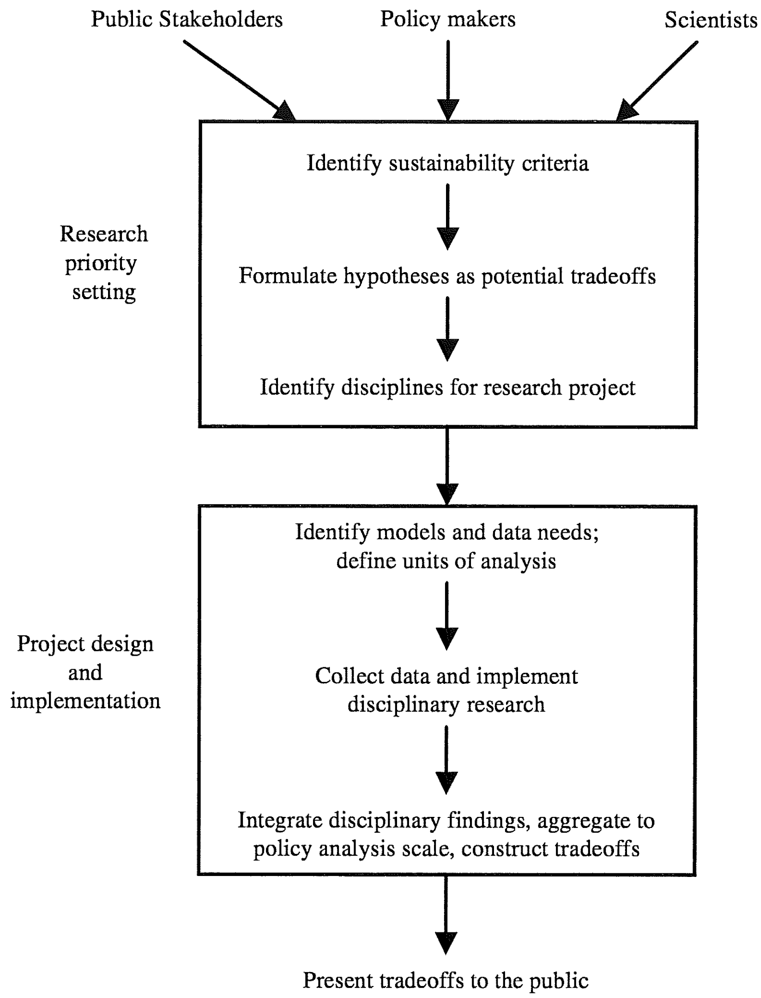

Figure 6.1 Tradeoff assessment as a priority setting and design tool for sustainability research

A number of challenges face researchers in implementing this type of research. Despite the widespread acceptance of the goal of sustainable agricultural systems, and the recognition of significant tradeoffs associated with the regulation of technologies such as pesticides, a scientific consensus is lacking on how the economic, environmental, and public health impacts of agricultural technologies can be quantified and assessed (D'Souza and Gebremedhin, forthcoming 1998). Analysis of these complex, interrelated issues raises difficult theoretical and methodological problems for researchers. Environmental, agricultural, and health characteristics of farmers, farmland, and farming technologies vary over space and time. The problems that concern the public are multi-disciplinary and thus require a multi-disciplinary approach. Overcoming disciplinary biases and establishing effective inter-disciplinary communication is a continuing challenge for a research team.

6.4. Scale issues

As noted above, one of the practical methodological challenges is the choice of the unit of analysis. Research in the biological and physical sciences typically deals with a unit of analysis—whether it is at the cellular, plant, animal, or field level—that is different from the farm or sectoral levels relevant to policy analysis. Policy analysis typically is concerned with a large unit of analysis, usually defined in relation to a geographic or political region, that contains a population of the units addressed by biological and physical sciences. The aggregation problem, *i.e.* the problem of combining heterogeneous small units into a larger unit for policy analysis, must be addressed by all researchers if their data and results are to be useful for policy analysis.

The fact that the various scientific disciplines use different units of analysis frequently means that the data and methods developed for disciplinary research are of limited value for policy research. Disciplinary research typically operates in a format dictated by disciplinary orientation and generates data intended to satisfy disciplinary objectives. This disciplinary orientation of research leads to a situation in which various pieces of the scientific puzzle are investigated without regard to the fitting together of those pieces into the larger picture that is required for policy analysis. Thus, the disciplinary component of research intended to support the assessment of tradeoffs must be planned at the beginning of the research effort to produce methods and data that are required for disciplinary analysis, but that can also be utilized across disciplines to assess tradeoffs. The planning, in advance, of *coordinated* disciplinary research is one of the key benefits of the tradeoff assessment methodology that is being proposed here.

Tradeoffs associated with agricultural production systems can be defined across several dimensions at a point in time, and can also be defined in one or more dimensions over time. In evaluating the long-term sustainability of a production system, economic and environmental indicators can be used to quantify the productivity and other attributes of a system over time. These indicators include measures of economic returns, soil erosion, chemical leaching, nitrate movement through soil profiles, and the organic content in the soil. Measuring tradeoffs in these dimensions requires site-specific data and models. Because the environmental impacts of different production systems are generally site-specific, one production system may not have the same impacts in all environmental dimensions at all sites. Thus, any attempt to rank production systems according to sustainability criteria needs to account for spatial variability in economic, environmental, and health outcomes.

The larger the spatial or temporal scale, the more complex becomes the process of quantifying tradeoffs for analysis of agricultural sustainability. Analysis at the regional or national scale is even more difficult than analysis at smaller scales, such as a watershed. Attempts to develop quantitative indicators of the sustainability of the U.S. farming sector, or the farming sectors of member countries of the Organization for Economic Cooperation and Development (OECD), have relied on aggregate data about production, input use, and resource degradation (U.S. Department of Agriculture, 1994; OECD, 1994). These data do not provide a scientifically defensible foundation for policy formation because production cannot be linked to environmental and health impacts on a site-specific basis.

The research methods applied in the model make use of an alternative approach to addressing regional policy concerns in the area of sustainable agriculture and technology evaluation that is based on solid scientific foundations. The proposed approach is to develop data and related disciplinary models which link the site-specific management decisions of producers with environmental and health impacts, and then to utilize a statistical representation of the relevant human and physical populations to statistically aggregate those impacts to a regional level for policy analysis.

Political pressure to identify a set of sustainable production technologies implies that there must be some means of ranking the importance of the various impacts. Ranking technologies according to multiple criteria requires a method of converting these criteria to a common unit of analysis. The economic approach to this problem is to convert all impacts to monetary terms and to use this information to conduct a benefit-cost analysis. However, despite decades of research on valuation of environmental and health outcomes by environmental and health economists, there is no scientific or public consensus on valuation methods or their public acceptability, and data for valuation of most environmental and health impacts are lacking. For this reason, the approach advocated in this book is that agricultural sustainability research should focus on establishing a sound scientific basis for quantifying tradeoffs between ecological and economic objectives that exist with alternative production systems, without attempting to value impacts for benefit-cost analysis.

6.5. Tradeoff Assessment

The approach described here is compatible with the eco-regional approach and provides a methodology for the implementation of research within this paradigm. In particular, the methodology developed here can be viewed as a way to operationalize the eco-regional approach by linking disciplinary models of agricultural production, environmental impact, and human health to a regional level for technology assessment and policy analysis. The methods for quantifying and assessing tradeoffs presented here provide an explicit framework for setting research priorities and organizing research within the framework of the eco-regional approach.

The conceptual framework for disciplinary integration and policy analysis developed for the application of the tradeoff model is illustrated in Figure 6.2. This framework is designed to address the methodological issues raised by disciplinary integration and aggregation from the field scale where modeling is valid, to the level appropriate for policy analysis (e.g., the watershed or larger scale). Moving from top to bottom, the framework captures the logical sequence of how macro-level policy affects farming decisions that result in micro-level impacts, and how those impacts should be aggregated back up to units useful for macro-level policy analysis. This sequence crosses several levels of analysis and, because it is statistically based, provides a basis for aggregation. The farm-level component of the model represents farmer decision making. By incorporating the decision-making process of the land manager, the model provides the link to the available set of policy instruments and regulations. The "what if " questions needed for policy analysis can be explicitly incorporated into the model.

Starting at the top of Figure 6.2, using a parcel of land as the unit of analysis, the model shows that prevailing policies and market prices, technologies, farmer characteristics, and the physical attributes of land affect farmers' management decisions in terms of both land use and input use—the extensive and intensive margin decisions. Physical relationships between the environmental attributes of the land in production and management practices then jointly determine the agricultural output, environmental impacts, and health impacts associated with a particular unit of land in production.

As the discussion later in this chapter demonstrates, farm-level decision models show that each unit of land that is in production has management and environmental characteristics which in turn are functions of prices, policies, technology, and other farm-specific variables. As indicated in the lower part of Figure 6.2, the probability distributions of technology, farmer, and environmental characteristics in the region induce a joint distribution of management practices, environmental characteristics, and health outcomes for each land unit in production, as a function of prices and policy parameters. This joint probability distribution provides a statistically valid representation of the outputs, inputs, environmental impacts, and health impacts for the population. Therefore these individual outcomes can be "added up" to produce an aggregate distribution of impacts. These aggregate outcomes—measured in terms of agricultural output, environmental quality indicators, and health indicators— are used to construct tradeoffs for policy analysis. This information can be utilized in several ways. If monetary values can be assigned to all impacts, then a benefit-cost analysis of policy alternatives can be conducted. However, since monetary values are usually available, the more useful approach is often to present information about tradeoffs directly to policy decision makers.

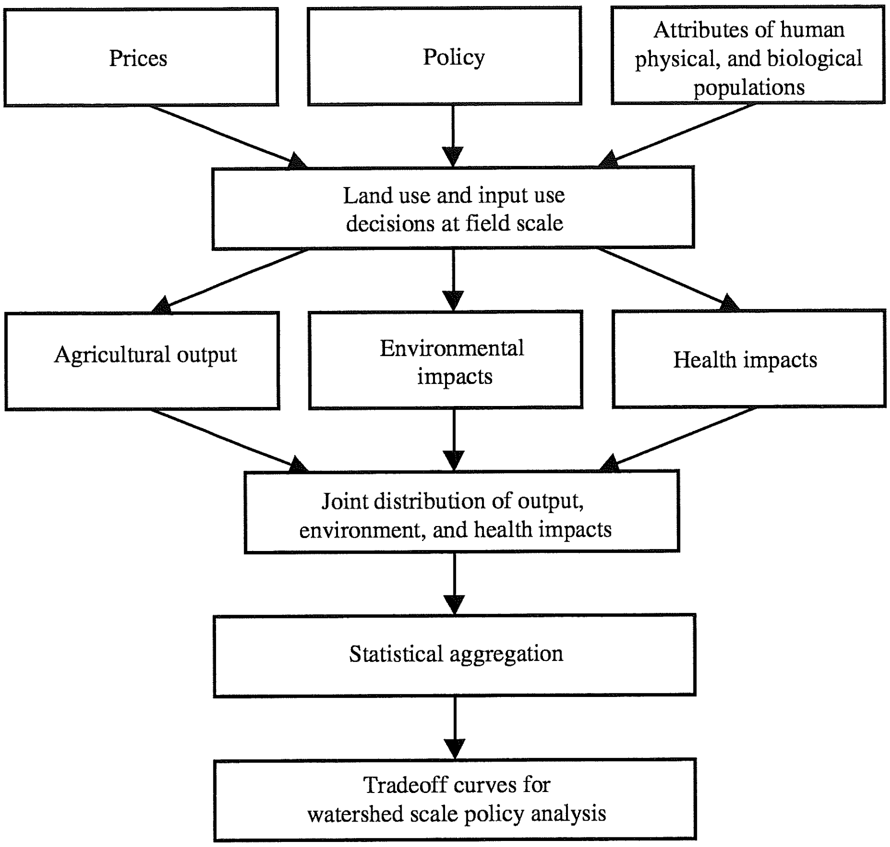

Figure 6.2 Conceptual framework for disciplinary integration and policy analysis

Starting at the top of Figure 6.2, using a parcel of land as the unit of analysis, the model shows that prevailing policies and market prices, technologies, farmer characteristics, and the physical attributes of land affect farmers' management decisions in terms of both land use and input use—the extensive and intensive margin decisions. Physical relationships between the environmental attributes of the land in production and management practices then jointly determine the agricultural output, environmental impacts, and health impacts associated with a particular unit of land in production.

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The structure of the integrated model is presented in Figure 6.3. A policy or technology scenario—e.g., alternative pesticide prices or pest management technologies—is input into the economic model. The economic model generates three types of output that are used subsequently. First, pesticide applications are generated on a daily time step by agro-ecological zone to be input into the pesticide leaching model. The pesticide leaching model generates outputs in the form of loadings into the environment (the total mass leached into groundwater) and water concentrations leached below the root zone. Second, the value of agricultural output by field is generated and saved so that it can be aggregated and used to construct aggregate tradeoffs for policy analysis. Third, numbers and quantities of pesticide applications by field are generated to be input into the health component of the simulation model. The health simulations generate estimates of the effect of pesticide exposure on the farm population in terms of mean neurobehavioral score (MNBS) averaged over the population, and in terms of the risk that the MNBS exceeds a critical value. The last step in the simulation model aggregates the economic, environmental, and health outcomes to the watershed level so that aggregate tradeoffs across those outcomes can be analyzed.

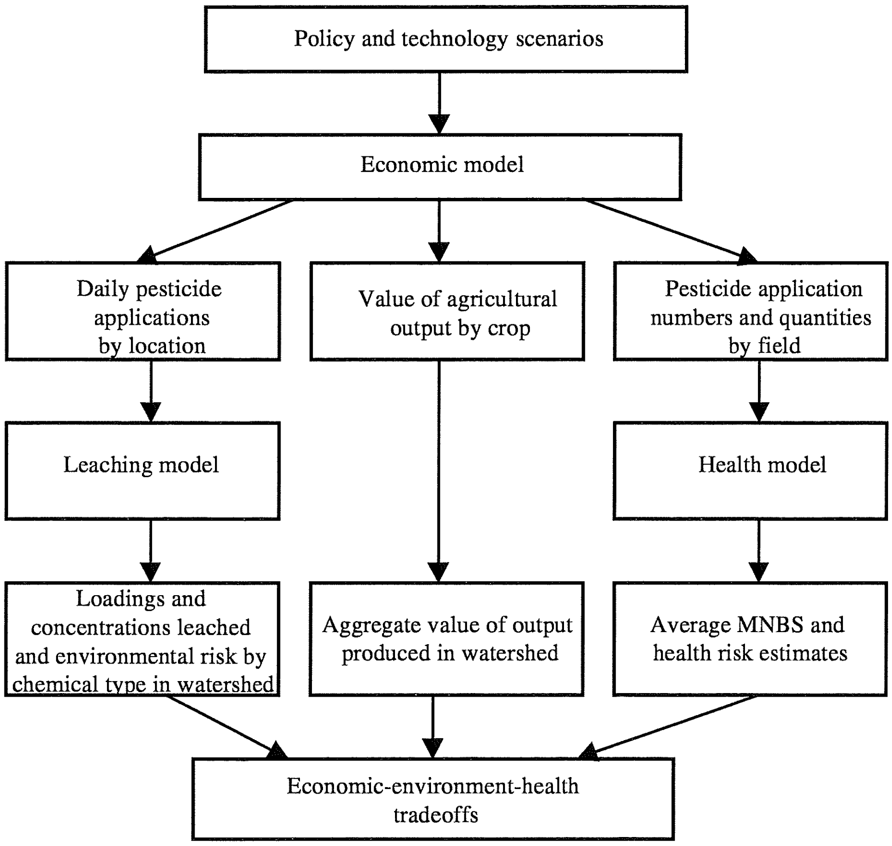

Figure 6.3. Integrated model for tradeoff analysis

6.6. The Economic Simulation Model of the Carchi Potato Production System

In the conceptual framework for agricultural-environmental analysis, farmers' land use and input use decisions provide the foundation for disciplinary integration and statistical aggregation for policy analysis. In this section, we briefly review the theoretical foundations of this model, and then describe the stochastic simulation model constructed to represent the Carchi potato production system.

The construction of the farm decision model begins by defining a population of land units (referred to henceforth as a field) in relation to an environmentally meaningful geographical unit, such as an aquifer or watershed. A vector ω^i represents the ith field's physical characteristics (e.g., soil types, climate) that affect both crop productivity and environmental impact.

The economic model is based on the allocation of land and other inputs to maximize expected economic returns at the field level (which may be adjusted for risk attitudes in a more general presentation). Let a farmer manage the ith field of a^i acres that has environmental characteristics ω^i. The indicator δ^i is defined to be equal to one if the field is in crop production, and equal to zero if the field is in a non-crop use (e.g., fallow, pasture, or conserving use). Crop production on the ith field, measured per unit area, is defined by the production function $q^i = q(x^i, \omega^i, \tau^i)$, where constant returns to scale is assumed and x^i is a vector of inputs measured per unit area. For simplicity, the production process with technology τ^i is represented as static and deterministic. If the crop is produced, the farmer's management problem is to maximize expected returns. The solution to this problem is represented by the profit function $\{\pi(p, w, \omega^i, \tau^i)\}$, and input demand functions $\{x(p, \omega^i, \tau^i) = \partial\pi(p, \omega^i, \tau^i)/\partial w^i\}$, where p is a vector of input prices normalized by the output price. Farmers allocate each field between crop and noncrop uses at the beginning of each production period according to its highest valued use. Letting c^i be the return to pasture use, farmers make land use decisions to solve:

$$\max_{\delta^i} \{ \delta^i \pi(p, \omega^i, \tau^i) + (1 - \delta^i) c^i \}.$$

The land use decision is therefore a step function of the form $\delta^i = 1$ if $\pi^i > c^i$, and $\delta^i = 0$ otherwise, implying that the land allocation decision is a function of p, ω^i, and c^i.

To model the Carchi potato production system, the preceding static production model must be generalized to represent the dynamics of the decision problem as described earlier in this chapter. Combining the extensive/intensive margin decision model with the sequential decision model, we obtain the dynamic extensive/intensive margin model use as the basis for the simulation model. We now describe each major component of the model constructed for the potato/pasture production system in Carchi.

- ***Field Selection.*** Physical characteristics of the field are drawn from empirical distributions estimated with the sample data. Field size is specified as a continuous lognormal distribution; discrete variables (planting month for first crop = 1 to 12, previous crop grown = potato or pasture) are specified as tabled probability mass functions; and altitude of the field is specified as a normally distributed random variable within each zone. At the beginning of each production cycle for each field, a set of prices is sampled from empirical lognormal price distributions estimated from sample data. Other input quantities in the model (fertilizer, land preparation labor, and animal labor) are also drawn from empirical lognormal distributions.

- ***Extensive Margin Decisions.*** For each field for each production cycle, a land use decision is made based on the comparison of net returns to the two competing uses (potato and pasture). These net returns distributions are estimated based on the econometrically estimated Cobb-Douglas profit function. When more than one potato crop is produced on a field without being rotated with pasture, the net returns distribution for potatoes is adjusted downward according to a set of declining geometric weights to reflect pest buildup and diminished soil productivity.
- ***Intensive Margin Decisions.*** When potatoes are produced, a sequence of pesticide application decisions is selected. For this purpose, pesticides are classified according to the three groups discussed above—fungicides, carbofuran, and insecticides used to treat foliage pests. For each type of pesticide, a pair of reduced-form, dynamic factor demand equations are simulated that represent the quantity of pesticide applied and the timing of the application (the days after the last application). At the beginning of the pesticide application loops, a starting time is drawn based on when the crop was planted, and a stopping time is drawn from an empirical distribution. For each application, random errors are drawn from the sample distributions estimated econometrically, quantity and timing outcomes are calculated from the estimated functions, the number of days after planting is updated, and if the date is less than the stopping date, a new set of quantity and timing outcomes is drawn until the stopping date is reached.
- ***Output Realization.*** At the end of the production cycle, the pesticide quantities are aggregated and combined with the other input quantity to estimate the realized value of crop production in that field, using an econometrically estimated Cobb-Douglas revenue function.

To validate the simulation model and to investigate its properties, the model was executed for a sample of 30 fields and five crop cycles (a cycle is a crop of either potatoes or pasture). For each of the 30 fields, these five cycles were replicated 30 times with different random draws from price, input, and other stochastic elements of the model, giving a total of 4,500 crop cycles (see Crissman *et al.*, 1998, chapter 7).

6.7. The Leaching Model Component

For linkage between the economic model and the leaching of pesticide, we note that there is a uni-directional causality from farmers' land use and management decisions to leaching. Accordingly, we assume that the leaching process can be simulated as a fraction (r_{jt}) of the quantity of pesticide applied on field j at time t as a function of soil and climate characteristics of the field where the chemical is applied. We execute the leaching model n times with random starting dates during each time period (in the Carchi study, the year was divided into 12 months) for each agro-ecological zone in the watershed with characteristics c_{it}, where $i = 1, ..., m$ classes, and time $t = 1, ..., T$. We then estimate a statistical meta-model to represent the leaching process.

The leaching data obtained from the execution of the LEACHA model (described in Crissman *et al.*, 1989: Chapter 8) show that leaching outcomes follow a highly skewed distribution with a "spike" of outcomes near zero and a "tail" of much larger positive outcomes. To represent this type of distribution, a statistical meta-model was estimated using a two-stage econometric procedure. This procedure is designed to account for data that are selected into groups according to a nonrandom process that is not independent of the data. These equations provide the basis for the leaching component of the integrated simulation model as follows:

Step 1: *Input data and units of measurement.* The simulation program reads the data files created by the economic model containing pesticide application quantity and timing data by field and crop cycle. If the pesticide input is a fungicide or foliage pest insecticide, its quantity is measured in quality-adjusted units, and these units are converted to units of the fungicide mancozeb or the insecticide methamidophos if it is a foliage pest insecticide. These two chemicals are among the most frequently applied by Carchi potato producers and are used here to represent the respective type of pesticide in the leaching simulations. In the case of carbofuran used to control the Andean weevil, no quality adjustment was made in the economic model, and so the carbofuran applications from the economic model are input directly into the leaching simulation model.

Step 2: *Select applications into zero and positive leaching groups.* Random error terms are selected and combined with the data for the model's explanatory variables to compute the conditional probability of a positive leaching event for a given agro-ecological zone and date of input application. A draw from this conditional probability distribution function then classifies applications into zero and positive leaching groups.

Step 3: *Predict mass of leaching for the positive leaching groups.* For pesticide applications in the positive leaching group, an estimated equation is used to generate a fraction leached below the root zone as a function of field characteristics and time of input application.

Step 4: *Compute the per hectare mass leached below the root zone.* For each application in the positive leaching group, the mass leached below the root zone is estimated as product of the fraction leached below the root zone and the amount of active ingredient applied per hectare.

Step 5: *Compute the concentration of pesticide in water leached below the root zone.* For each application in the positive leaching group, the mass leached below the root zone and the total water flux below the root zone are combined to estimate the concentration of active ingredient in water leached below the root zone.

Step 6: *Merge leaching outcomes with value of agricultural production to produce joint distributions of economic and environmental outcomes.* The value of agricultural output stored from the economic component of the simulation model is merged by field with the leaching outcomes by field.

6.8. The Health Model Component

Utilizing the data collected by the health component of the project, and analysis of these data (see Crissman *et al.*, 1989: Chapters 9 and 10), the health effects of pesticides are represented with an equation that predicts the mean neurobehavioral score (MNBS) for a member of the farm population as a function of pesticide use and potato intake, controlling for individual characteristics. For purposes of validating this component of the integrated model, the sample MNBS distribution was compared to the distribution generated by the base case simulation. The simulated distribution was found to resemble closely the sample distribution.

6.9. Data Requirements, Limitations

The integrated model that underlies the tradeoff analysis described here has a number of significant data requirements. These are described in detail in Crissman *et al* (1998). Here we summarize them, and then provide a discussion of some limitations.

First, the economics model requires data to estimate econometrically the behavioral relationships needed to simulate land use and management decisions. While the techniques required for collection of these data can be readily replicated, the time and expense of doing so mean that such data cannot be collected to represent extensive land areas. Clearly, a key limitation of this approach is the economic data requirements. How best to overcome this limitation remains a topic for current and future research.

Second, the bio-physical analysis (the leaching model in this particular application) also has substantial requirements in terms of soils and climate data. In the Carchi case study, for example, the limitations on the availability of soils data lead the researchers to stratify the watersheds into four agro-ecological zones. A better approach, now being implemented, is to develop a digitized soils map that can be linked with the other data in the model is a GIS format. Weather data are available for a limited number of points in proximity to the watershed. How best to interpolate these data remains a methodological challenge in all research of this type.

The Carchi study illustrates several of the current limitations to integrated agriculture-environment-health research and directions for fruitful future work. Because of the complexity of these systems, researchers are forced to limit the scale and scope of any research project to make it financially and organizationally feasible. In the Carchi study, a conscious decision was made to limit the objectives to tradeoffs associated with pesticide use in the potato-pasture production system and to limit the spatial scope of the study to a relatively small pair of watersheds. Moreover, the tradeoffs were limited to include only pesticide leaching and certain short-term health effects.

These self-imposed limitations reflect the methodological approach advocated here that focuses on quantifying the key tradeoffs identified by the public stakeholders, policy makers, and scientists (Figure 6.1). These limitations serve to impose much needed discipline on this type of research. Faced with a complex problem and stimulated by interdisciplinary interactions, a well-functioning research team naturally tends to attempt to address more questions than are feasible given the available time and resources. Keeping the project focused on the key policy questions that need to be addressed helps the research team allocate scarce resources to the project's highest priorities. It is important for team leaders to keep in mind, and to remind research team members, that it is not necessary to measure all possible health or environ-mental effects of a production system in order to assess the key tradeoffs and provide useful guidance to policy makers and the public.

6.10. Discussion

Even with all the limitations, the project took many dollars and many years to complete. Obviously, there are tradeoffs that must be considered between internal validity and generality in designing research projects. A key decision for this and other projects is the selection of the study site. Even with a limited number of impacts to be considered, the ideal site for a case study probably does not exist. The Carchi site was selected for this study based on its reputation for intensive pesticide use. A valid question for generalizing results is whether a "representative" rather than an "extreme-case" research site is more appropriate. One important area for future research is to investigate how the findings of this type of study can be generalized over space and time and across heterogeneous populations. Results of this kind of research would provide guidance on key research design questions such as site selection.

Within each of the three disciplinary efforts reported in this study, important advances also need to be made. The dynamic, site-specific economic models that provide information on a daily time step that were developed for this study represent an advance over the conventional static, representative producer models typically used by agricultural economists. Nevertheless, the stochastic simulation model that was based on the dynamic econometric production model has significant limitations for certain applications. A critical limitation is the reliance on a statistical representation of the production technology. By construction, this technology can represent only the range of behavior observed in the data from which it is estimated. Consequently, when policy simulations are needed that go outside the range of observed behavior, the model may not produce reliable results. For example, when policies are simulated that would reduce fungicide use, we know that beyond some point crop failures would occur. Our data do not provide the basis to estimate this effect, however. Future planned research will investigate the possibility of linking the economic models with crop growth models to provide a more reliable basis for conducting simulations outside the range of observed behavior.

Linking the economic production model to crop growth models also would provide a way to utilize biophysical data available in geographic information systems to generalize the economic model beyond the case study area. As noted above, the reliability of this kind of extrapolation is one of the issues that needs to be examined in future research.

An important issue addressed in this study, and related to the issue of extrapolation and generalization, is the definition of a common unit of measurement for the modeling that forms the basis of the integrated tradeoff assessment. In the Carchi study, data were collected at the field scale, and tradeoffs were assessed at the watershed scale. Adaptations of conventional economic, environmental, and health analysis models had to be made to accommodate analysis at the field scale. An important open methodological question is whether valid analysis of agricultural production systems can be conducted with data collected at larger scales. The analysis of spatial vari-ability conducted in the Carchi study cast doubt on this proposition, as it showed that aggregation to the watershed level obscured important spatial differences in both environmental and health impacts. Nevertheless, research has not fully investigated the question of the appropriate scale of analysis needed to adequately address various policy questions.

Another important methodological challenge is extrapolation of results over time and linkage of small-scale analyses of environmentally meaningful units such as watersheds to larger economic units such as a regional, national, or international economy. The Carchi case study examined the effects of policy and technology changes in the potato-pasture system in a partial equilibrium frame-work that is not suitable for longer term analyses or general equilibrium analyses. The landscape ecology literature and the regional economics literature provide important insights into the added complexities that are introduced when one attempts to model long-term changes in land use resulting from policy interventions (Fresco *et al.*, 1994; Bockstael, 1996). Linking an environmental unit to larger economic units for the analysis of environmental impacts of macroeconomic and trade policy also raises problems inherent in linking analysis conducted at different scales and levels of aggregation (Antle *et al.*, 1996).

In the environmental area, a number of issues also need to be considered to broaden the usefulness of quantitative tradeoff assessment. One critical problem (also relevant to the health area) is resolving how to deal with multiple outcomes. The tradeoff analysis considers the trade-offs between agricultural production and leaching of several chemicals and neurobehavioral risk, but generally a number of other economic, environmental, and health outcomes could be examined, such as income distribution, soil erosion, wildlife impacts, and longer term health risks such as cancer. Although the issue of aggregation has been addressed formally in economics, there does not appear to be a comparable literature in the environmental field, and so researchers are left with the choice of dealing with a large number of dimen-sions or arbitrarily combining outcomes into indices that have no theoretical basis or rationale.

Another important limitation of the environmental analysis was that the LEACHA model represents leaching below the root zone. The eventual fate of the pesticides was not modeled or quantified. Consequently, the environmental analysis quantified loadings into the environment but did not provide the basis to estimate actual environmental damages. Future work needs to go beyond loadings and make the connection to changes in environmental quality that are valued by people so that meaningful estimates of costs or damages can be made.

In the health area, alternative approaches to epidemiological design, expo-sure assessment, adverse health outcomes, health benefits, and perceptions of barriers to safer practices should be explored in future work. Consideration should be given to a prospective cohort design with intensive monitoring of symptoms and work absences compatible with pesticide poisonings parallel to the documentation of pesticide use. Included in this should be better documentation of diet and nutritional status combined with residue analysis of potatoes to document benefits of potato production and to sort out any role potatoes may play as a route of exposure to pesticides. This would permit a more direct linking of pesticide use to positive and adverse health outcomes that are more easily measured in field settings and more readily understood by the farm members themselves. The challenges of aggregation across organ system-specific outcomes would be reduced by focusing on common impacts such as disability days. Qualitative work to better understand the perception of health risks from pesticide use and the perceived barriers to implementation of safer use practices would further assist the modeling of tradeoff options and the implementation of policy changes.

Future integrated impact assessments also could more effectively integrate the disciplinary models. This study makes use of a simple format for model integration. Because of this limitation, for example, the economic and environmental models were not linked on a daily time step in a way that would fully utilize the information contained in the two models. A true integration of the models would utilize all of the information on timing of input use in relation to weather events; in some cases, this could have an impact on the results, especially when the environ-mental processes are sensitive to the intensity of daily weather events. In the case of leaching that occurs over long periods of time, this may not be as important as in processes such as erosion and the surface transport of chemicals that are greatly affected by rainfall intensity.

References

Antle JM, Crissman CC, Wagenet RJ, Hutson JL 1996 Empirical foundations of environment-trade linkages: evidence from an Andean study. Chapter 12 in: Bredahl ME, Ballinger N, Dunmore JC, Roe TL (eds) Agricultural trade and the environment: understanding and measuring the critical linkages, Boulder, CO: Westview Press

Antle JM, Pingali P 1995 Pesticides, productivity, and farmer health: A Philippine case study Pages 361-387 in: Pingali PL, Roger PA (eds) Impact of pesticides on farmer health and the rice environment, Boston, MA: Kluwer Academic Publishers

Batie SS 1989 Sustainable Development: Challenges to the agricultural economics profession. American Journal of Agricultural Economics 71: 1083-1101

Bockstael N 1996 Modeling economics and ecology: the importance of a spatial perspective American Journal of Agricultural Economics 78: 1168-1180

Bouma J, Kuyvenhoven A, Bouman BAM, Luyten JC, Zandstra HG (eds) 1995 Eco-Regional Approaches for Sustainable Land Use and Food Production. Dordrecht, The Netherlands: Kluwer Academic Publishers

Consultative Group on International Agricultural Research (CGIAR) 1993 The eco-regional approach to research in the CGIAR. Report of the TAC/Center Directors Working Group, Technical Advisory Committee Secretariat, Food and Agriculture Organization (FAO), Rome

Consultative Group on International Agricultural Research (CGIAR) 1995 Report of the task force on eco-regional approaches to research." Mid-term meeting, Nairobi, Kenya, 22-26 May 1995.

Crissman CC, Antle JM, Capalbo SM 1998 Economic, Environmental and Health Tradeoffs in Agriculture: Pesticides and the Sustainability of Andean Potato Production. Boston: Kluwer Academic Publishers

Crosson P 1993 Sustainable agriculture: a global perspective. Choices: 38-42.

D'Souza GE, Gebremedhin TG (eds) 1998. Sustainability in agricultural and rural development. Hampshire, England: Dartmouth Publishing Co.

Food and Agriculture Organization 1976 A framework for land evaluation. FAO Soils Bulletin No. 32, Rome

Fresco LO, Stroosnijder L ,Bouma J, van Keulen H (eds) 1994 The Future of the Land: Mobilizing and Integrating Knowledge for Land Use Options. Chichester, U.K.: John Wiley and Sons, Ltd.

Lynam JK, Herdt RW Sense and sustainability: sustainability as an objective in international agricultural research Pages 205-224 in: Moock JL, Rhoades RE (eds) Diversity, farmer knowledge, and sustainability. Food Systems and Agrarian Change Series. Ithaca, NY/London: Cornell University Press

Organization for Economic Cooperation and Development (OECD) 1992 Agents for change: summary report from the OECD workshop on sustainable technologies and practices, 11-13 February 1992. Pub. No. OECD/GD 92-49, Paris

Organization for Economic Cooperation and Development (OECD) 1994 The use of environmental indicators for agricultural policy analysis. OECD Joint Working Party of the Committee for Agriculture and the Environment Policy Committee, Paris

Pingali PL, Roger PA (eds) 1995 Impact of pesticides on farmer health and the rice environment. Boston, MA: Kluwer Academic Publishers

Rabbinge R 1995 Eco-regional approaches: why, what, and how. Pages 3-11 in: Bouma J, Kuyvenhoven A, Bouman BAM, Luyten JC, Zandstra HG (eds) Eco-Regional Approaches for Sustainable Land Use and Food Production. Dordrecht, The Netherlands: Kluwer Academic Publishers

Ruttan V 1994 Constraints on the design of sustainable systems of agricultural production. Ecological Economics 10: 209-219

Ruttan V (ed) 1992 Sustainable agriculture and the environment. Boulder, CO: Westview Press

U.S. Department of Agriculture (USDA) 1994 Agricultural resources and environment indicators. Agricultural Handbook No. 705, USDA, Economic Research Service, Natural Resources and Environment Division, Washington, DC

U.S. Environmental Protection Agency 1988 Pesticides in groundwater data base, 1988 Interim Report EPA, Washington, DC

7. A methodology for sustainable land use exploration at the regional level: application to the Atlantic Zone of Costa Rica

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7.1. Introduction

This workshop is about land use analysis methodologies and the role of information technology in their development and application. As evidenced by the various presentations, the term land use analysis is commonly used for a wide variety of modelling exercises with significantly different objectives, methods, and scale levels of analysis. At the two extreme levels as far as scale is concerned, there now exist tools for national level projection of future land use through interpolation and extrapolation of trends at the national level (Veldkamp and Fresco, 1996; de Koning this workshop); while at the level of the farm the long-familiar concept of site-specific farming has been made operational through the development of tools geared towards optimizing and supporting production and input use (Bouma *et al.*, 1995; Stoorvogel, Bowen, and Antle and Stoorvogel, all this workshop). Between these two extreme scale levels there exists the regional level for which three types of land use analysis methodologies have been developed thus far. There is the agro-ecological zoning approach which was explained by van Haren and Haverkort (this workshop). Another approach which has not received any attention in this workshop is the so-called farm household modelling approach, developed by the sustainable land use and food security program of the Dutch Research Institute for Agrobiology and Soil Fertility (AB-DLO) and the Department of Development Economics of Wageningen Agricultural University. This approach is aimed at identification and evaluation of policy instruments to achieve a desired land use (Singh *et al.*, 1986; Kruseman *et al.*, 1995; Kuyvenhoven *et al.*, 1997). The third regional land use modelling approach, and the one with which this paper is concerned, aims at exploration of land use options making use of linear programming (LP) techniques. The methodology described in this paper is called *USTED* (*Uso Sostenible de Tierras En el Desarrollo*; Sustainable Land Use in Development) (Stoorvogel, 1995; Stoorvogel *et al.*, 1995) and is developed by the Research Program on Sustainability in Agriculture (REPOSA), beginning at the level of the settlement (Schipper *et al.*, 1995) and gradually upscaling via the district level (Jansen *et al.*, 1997) towards the level of an entire region (in this case the northern Atlantic Zone (NAZ) of Costa Rica). Even though LP models are often used in exploratory land use studies (van Keulen, 1990; Veeneklaas, 1990; Rabbinge and van Latesteijn, 1992; WRR, 1992), a salient characteristic of USTED is that it integrates knowledge on biophysical and socio-economic processes while optimizing for the various dimensions of sustainability and environmental impact at the regional level.

7.2. Justification

In most countries, issues surrounding the debate about the development of the agricultural sector, while of concern to both individual farmers as well as policy makers at the national level, center around the main question of how to achieve a certain level of food security while at the same time providing sufficient income for food producers and a certain degree of environmental protection. At the same time, however, there exists a lack of tools and models which can be effectively used to evaluate the effects of alternative policies on regional land use. Land use has obvious implications for farm income and the various dimensions of sustainability and environmental impact. The latter mainly involve the various environmental effects of agricultural production (*e.g.,* soil nutrient leaching, environmental effects of pesticides, gas emissions) but also may include such aspects of human health effects of pesticide use and gender division of agricultural labor requirements. There exists a particular need for methodologies that are capable of quantifying the trade-offs that occur between various objectives in general and those between income-related and sustainability-related objectives in particular. The main challenge in the development of such methodologies consists of the integration of bio-physical with socio-economic information.

7.3. Methodology

The USTED methodology developed to explore land use options at the regional level involves the integration of a number of techniques and models (Figure 7.1). The core of the methodology consists of a LP model and two so-called Technical Coefficient Generators (TCGs), one for cropping activities called CROPTCG (CROP Technical Coefficient Generator) and one for livestock activities called PASTOR (PASture and livestock Technical coefficient generatOR). These TCGs generate technical coefficients (TCs) that serve as input data for the LP model. TCs are inputs and outputs of alternative production systems such as yields, costs, labor use, and sustainability and environmental indicators (Hengsdijk *et al.*, 1996). GIS plays an important role in archiving and manipulating geo-referenced input data and, to a lesser extent, in presenting spatial output results. There is a semi-automated flow of data between the GIS, the TCGs, and the LP model.

The LP model is used to select alternative land use activities (*i.e.*, crops and livestock options) per sub-area and per soil type by maximizing a certain goal given specific boundary conditions and a set of other restrictions. The goal (objective function) normally is to maximize regional value added, while restrictions are related to the amount of resources available (mainly land and labor), marketable volumes of products, and sustainability and environmental considerations. The optimization of the LP model, given a coherent set of restrictions and given a certain data input, is called a scenario. Alternative land use activities for the plot level are generated by CROPTCG and PASTOR. Crop options as defined by CROPTCG are defined as combinations of a land unit (soil group) and a land use type with a specified technology, called LUSTs (Land Use Systems with a defined Technology; Jansen and Schipper, 1995). In the livestock sector, three systems are defined; PASture production systems at a defined Technology (PASTs), Animal Production Systems (*i.e.*, herds) at a defined Technology (APSTs), and Feed Acquisition Systems at a defined Technology (*i.e.*, feed supplements) (FASTs)[1]. Only LUSTs and PASTs are truly land-based production systems. Whereas LUSTs and APSTs generate marketable products, PASTs and FASTs generate nutritive values to feed the cattle in the APSTs and are, in this sense, 'intermediate' systems. All systems describe specific quantitative combinations of physical inputs and outputs, thus representing fixed input-output technologies.

In the next sections, the various steps in the methodology as given in Figure 7.1 are discussed in greater detail.

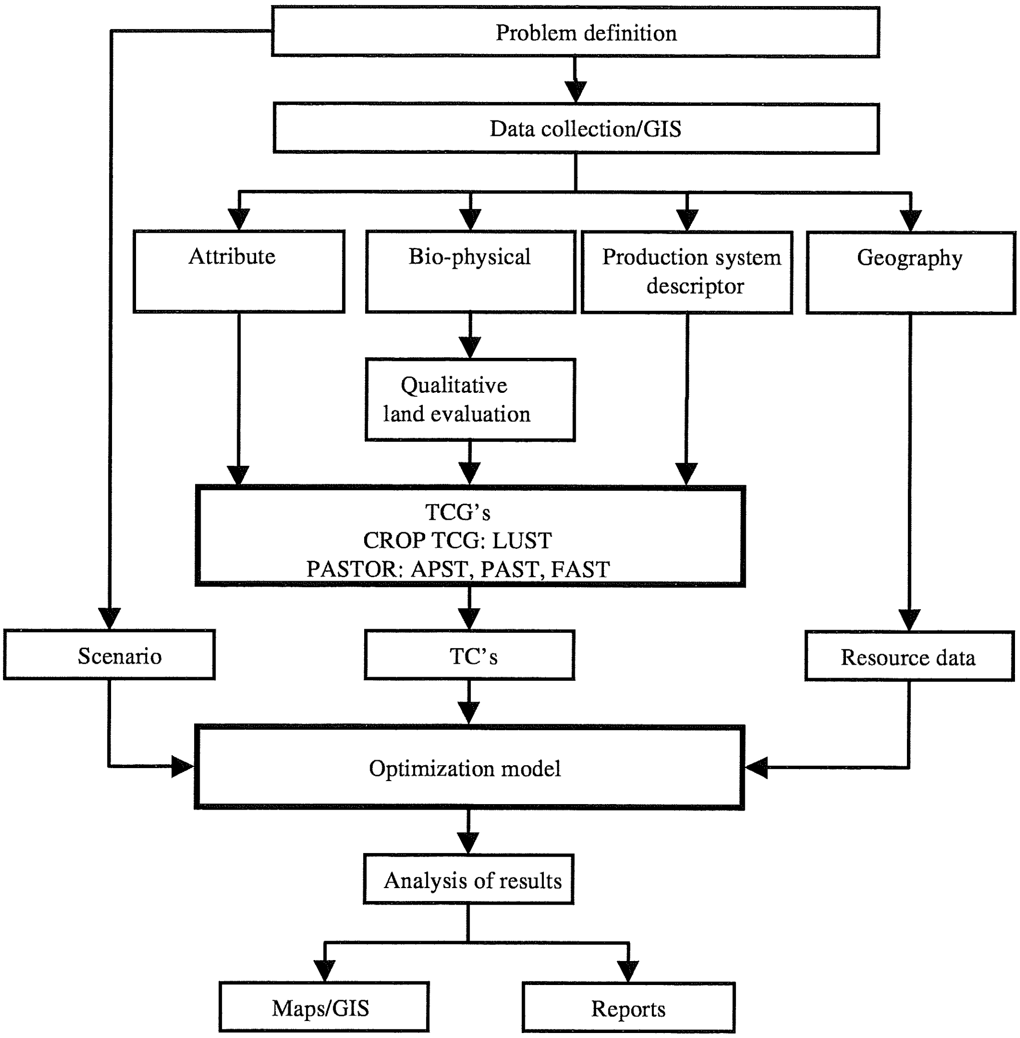

Figure 7.1 Diagram of the main steps in the USTED methodology. Though the arrows indicate a top-down approach, in reality the execution of the methodology is an interaction procedure among the various steps. *E.g.* the results of the qualitative land evaluation may require the collection of new base data.

[1] Names as suggested by D.M. Jansen (unpublished)

7.3.1. Problem definition

Studies to explore regional land use options should start with an analysis of the current and expected future situation regarding sustainable land use:

- Bio-physical and socio-economic constraints to sustainable land use
- Conflicts in land use
- Policy views of stakeholders in the field of land use and land use planning; such stakeholders may include farmers, farm managers, and regional and national planners and interest groups.

The process of problem analysis should be an interactive one in which stakeholders, while experiencing the benefits of interaction among different disciplines involved in the methodology, are involved in defining scenarios to be explored with the methodology, the spatial detail of the study, the type of alternative land use systems to be modelled, and the type and detail of base data to be collected. The inventory of relevant actors in the field of land use (planning) and their policy views is an important step in 'guiding' the design and execution of the land use exploration exercise.

7.3.2. Base data and GIS

Basic data requirements of the USTED methodology include the following:

- Attribute data: prices of inputs in the production systems (*e.g.,* fertilizers, pesticides, materials, labor); prices of products (crop products, meat, milk); transportation costs; chemical composition of fertilizers (organic and non-organic); chemical composition and toxicity of pesticides.
- Bio-physical data: crop and livestock production potentials; soil properties; weather characteristics.
- Geographical data: digitized maps of road infrastructure; administrative boundaries; topographical data; labor availability by sub-region.
- Description of land use systems (*i.e.,* crop and livestock options): system input-output data differentiated by soil group, target yield level, and level of technology.

The exact nature of the data (*e.g.,* which crops and livestock systems to include) as well as its detail depend on the results of the problem definition above (as well as on the results of the qualitative land evaluation, see below). Regarding the data collection process, while the efforts required and corresponding costs involved generally will depend on what is already available (*e.g.,* the existence of a good digitized soil map saves expensive and time-consuming field work), some general remarks can nevertheless be made. Whereas the acquisition of some base data involves normally only secondary data collection (*e.g.,* attribute data such as prices of inputs and outputs; weather data; or many types of geographical data), other data bases require a larger effort to assemble. For example, collection of input-output data for land use systems that actually occur in the field normally involves farm surveys. Data on alternatives to such actual land use systems can be acquired via simulation modelling, expert systems and literature review. Transportation cost data can be generated by estimating transportation cost models (Jansen and Stoorvogel, forthcoming).

Attribute data, bio-physical data and data describing land use systems are mainly used in the TCGs (*i.e.,* CROPTCG and PASTOR). Besides as TCs, attribute data are also used in the LP model (normally in the objective function) to enable calculation of value added; farm gate prices are calculated by subtracting transportation costs from wholesale prices, and as such are geo-referenced. Geographical data, stored and manipulated in a Geographic

Information System (GIS), are used to formulate sub-zones; in the calculation of transportation costs (based on distances and road characteristics); and, where appropriate, for the incorporation of soil erosion effects. Regarding sub-zonation, the regional area under consideration may have to be subdivided into homogeneous zones on the basis of bio-physical and socio-economic data. For the NAZ, this sub-zonation was mainly based on differences in transportation costs, since both soil types and climate do not differ much between sub-zones. Based on transportation costs for crops and animals on various road types to their respective market outlets, an automatic procedure within the GIS was developed to stratify the area along the road infrastructure into homogeneous transportation cost zones. For each zone, resource availabilities such as soil types and labor availabilities were calculated by map overlaying. Labor availability per sub-zone was derived from overlays with administrative boundaries linked to population census data. Moreover, labor mobility costs between sub-zones were calculated from mean bus fares between centres of the sub-zones. Product transportation costs, labor mobility costs, hectares per soil group, and labor availability data are all used in the LP model.

7.3.3. Qualitative land evaluation

To determine bio-physical growth potential for crops and pastures, the USTED methodology makes use of a qualitative land use evaluation which may also be used to identify promising (new) alternatives for incorporation in PASTOR (in the case of pastures) or CROPTCG (in the case of all other crops). Such a qualitative land evaluation may vary from sound expert knowledge to formalized computation schemes such as the FAO guidelines for land evaluation (FAO, 1976). In USTED, use is made of the PLANTGRO model developed by Hackett (1991). PLANTGRO allows a coarse prediction of plant growth potential on the basis of weather characteristics, soil properties and crop requirements. The output consists of a qualitative suitability ratings for 22 climate/soil factors. PLANTGRO currently contains data for 123 plant species, but more data can be created and added by the user. In the USTED methodology, PLANTGRO is applied to all weather/soil combinations that exist in the area under study. GIS is used to retrieve the weather and soil input data and to create maps of the PLANTGRO results. Completely unsuitable land use types are discarded from further analyses.

7.3.4. Technical coefficient generators

TCs are generated using the so-called 'target oriented' approach (Rabbinge and van Latesteijn, 1992; WRR, 1992; Hengsdijk *et al.*, 1996). This approach entails that, for alternative production systems, a target production level is set by the user and that subsequently the amount of required inputs is calculated by a TCG. Inputs are calculated on the basis of systems-analytical knowledge on input-output relations for the production system under consideration. For crops and pastures, target production levels may vary from maximum (*i.e.,* potential) to very low yields, resulting in simulated high and low external input levels (*e.g.,* fertilizers, crop protection agencies), respectively. Next to target production levels, the technology employed in the production can be specified. For example, certain operations may be performed either with machines or manually (or using a combination of the two). Target production levels, technologies and the relationships between inputs and outputs all are soil type specific and therefore are defined by soil type as defined in the geographical data base (see above). In the case of animal production systems (*i.e.,* APSTs), target production levels are operationalized via target live weight gains and/or target milk production levels. Animal production technologies vary with respect to herd maintenance (*e.g.,* degree of health care given) and marketing (*i.e.*, selling/buying) strategies. By combining various target production levels with different technologies, the TCGs generate TCs for alternative production systems at a defined technology. All TCGs are generic in the sense that the user can add or remove crop/pasture/feed supplement types and change target production levels and technologies.

Table 7.1 lists the TCs generated for the four production systems. There exist three groups of TCs: economic TCs (*e.g.,* costs of production and labor use); production TCs (*i.e.,* crop yield and cattle nutritive value); sustainability indicators; as well as a number of so-called environmental effect indicators.

Sustainability indicators are the soil nutrient balances for the three main elements nitrogen (N), phosphorus (P) and potassium (K). Soil nutrient balances for N, P and K are calculated by keeping track of inputs (*i.e.,* natural deposition, fixation, weathering, and organic and inorganic fertilizer) and outputs (nutrients removed through harvest plus losses by, *e.g.,* leaching and volatilization). Negative balances cause soil mining, implying that the simulated crop or pasture production system is likely to be unsustainable (*i.e.,* target yield levels cannot be maintained on the long run). Actually occurring production systems are often unsustainable (see description of the NAZ below). Alternative (*i.e.,* sustainable) production systems are modelled by imposing zero soil nutrient balances for N, P and K; the TCGs then calculate the required amount of fertilizer needed to maintain such zero nutrient balances. For all crop and pasture land use types under consideration, both unsustainable (*i.e.,* actual) and sustainable (*i.e.,* alternative) systems are modelled.

The environmental effect indicators consist of two groups. The first group is related to the use of pesticides and consists of a pesticide input use indicator via an ordinal so-called Pesticide Environmental Impact Index (PEII; Jansen *et al.*, 1995), and the total amount of active ingredients used. Even though the latter is relatively easy to monitor and much used, it is not a particularly appropriate indicator as pesticides differ considerably with regard to their environmental impact. Therefore, the PEII takes into account not only pesticide quantities used but also their percentage active ingredients, their degree of toxicity, and their persistence in the environment. The second group of environmental indicators consist of total N losses to the environment via leaching, volatilization and denitrification/nitrification. Whereas volatilization of N via ammoniac results in acid rain, leaching of N potentially pollutes soil water. Denitrification/nitrification losses of N via N_2O and NO add to the greenhouse gas effect. The simulated losses of N, P and K are largely based on generalized measures and expert estimates, even though efforts are currently being made to link the TCGs to more process-based simulation models.

Economic yields are only generated for LUSTs and APSTs (Table 7.1). PASTs and FASTs generate intermediate yields in the form of nutritive value available for cattle consumption, consisting of metabolizable energy, crude protein, and phosphorus. Each modelled APST is characterized by its nutritive feed requirements, where the latter must be matched by the supply from the PAST and FAST systems included in the LP model.

Table 7.1. TCs per cropping and livestock production system. For explanation of LUST, PAST, APST and FAST see text. NBAL = soil nitrogen balance, PBAL = soil phosphorus balance, KBAL = soil potassium balance, NLEA = amount of nitrogen leached, NVOL = amount of nitrogen volatilized, NDEN = amount of nitrogen lost by denitrification/nitrification, PEII = Pesticide Environmental Impact Index and PAI = amount of active Pesticide Ingredients Applied (see text). TCs for LUSTs and PASTs are expressed per hectare per year, TCs for APST are per herd per year, and TCs for FASTS are per kg of applied feed supplement.

	LUST	PAST	APST	FAST
Cost	X	X	X	X
Labor use	X	X	X	X
Production	Crop yield	APST nutrition	Meat, milk	APST nutrition
APST nutrition required		X		
NBAL	X	X		
PBAL	X	X		
KBAL	X	X		
NLEA	X	X		
NVOL	X	X		
NDEN	X	X		
PAI	X	X		
PEEI	X	X		

7.3.5. LP model

LP is virtually the only approach available that allows explorations of changes in regional land use outside the range of past experiences (*e.g.,* as a result of technological developments or policy measures). The basic input into a regional LP land use model is a large number of agricultural production activities (representing different crop and livestock activities), each of which can be performed with a range of technologies per activity, and where each technology has its own specific economic value as well as sustainability and environmental implications. These differences are embodied in TCs (as generated by CROPTCG and PASTOR) of a large number of different LUSTs, APSTs, PASTs and APSTs. With such a range of variants it becomes possible to investigate the effects of several policy instruments on the regional land use pattern, income, and sustainability and environmental effects. The LP model selects the optimal combination of LUSTs, APSTs, PASTs and FASTs, given a certain objective function and set of restrictions. APSTs, PASTs and FASTs are linked in the LP model via a nutrient balance equation that imposes an exact balance between the nutrition requirements of the selected APSTs (*i.e.,* herds) and the nutrition resulting from the selected PASTs (*i.e.,* pastures) and FASTs (*i.e.,* feed supplements).

TCs are averages per month (*e.g.,* land use and labor requirements) or per year (*e.g.,* soil nutrient losses and the PEII and PAI) or annuities based on the present value calculated over the life-span of a LUST, APST, PAST or FAST (*e.g.,* production, input costs). The latter procedure is needed because even though the LP model is a one-period model, the various LUSTs, APSTs, PASTs and FASTs are defined for different periods of time (*e.g.,* maize 4 months, palm heart 15 years) (Schipper, 1996). In order to obtain an average value for, *e.g.,* physical production or input cost, values over different years need to be discounted back to the present (using a real discount rate of 10% in the NAZ model in which nominal prices are kept constant) and added, after which the resulting value is transformed into an annuity. From the angle of land use at the level of the region, this procedure can be justified by arguing that at any given time one can expect a wide range of stages to exist for a given land use type.

In its most conventional form, the LP model maximizes regional value added (which is the sum of the value added over the different sub-zones). Value added is defined as the sum of output value (*i.e.,* quantities of crop and livestock products times their corresponding farm-gate prices) minus production costs where the latter consist of current input costs (*i.e.,* costs of fertilizers and pesticides, annualized costs of capital items such as machinery, corals etc.) and labor costs.

In the NAZ model, each of the sub-zones has its own submatrix. The TCs generated by CROPTCG and PASTOR apply to each of the sub-zones since costs of inputs (except labor) were assumed to be identical in each sub-zone (see below). However, the LP tableaus (*i.e.,* input-output matrices) are different for each of the sub-zones since the latter differ in the following respects:

- Output prices (*i.e.,* farm-gate prices of crop outputs and livestock products) are geographically differentiated, depending on transportation costs to the nearest market.
- Labor costs (*i.e.*, wages) which depend on geographical distribution of labor demand and supply.
- Each sub-zone has its own resource endowment in terms of soil distribution and available labor pool.

Transportation costs were assumed to depend on geographical distances between markets and the geographical center of each sub-zone, and quality of the road infrastructure. To empirically estimate transportation cost models for the NAZ, farm level data was collected on transportation costs of crops from farms to farmers' markets or to the national wholesale market. Data on transportation costs of cattle was collected among transporters at the cattle auction in the NAZ. Since field experience learned that input costs do not differ significantly within the NAZ, no transportation cost models were estimated for agricultural inputs. Using a GIS, these survey data were combined with geographical data on the approximate location of sample farms and distances specified for four road types, and used to econometrically estimate a number of alternative models to assess the influence of road type on transportation costs. Separate transportation cost models were estimated for crops and cattle, resulting in the following preferred specifications:

- Crop transportation: $UC = 0.50 + 0.04*(Dis_1+Dis_2)+ 0.10*(Dis_3+Dis_4)$
- Cattle transportation: $UC = 357 + 12.4*(Dis_1+Dis_2) + 15.0*(Dis_3+Dis_4)$

where: UC = unit transportation cost (in Colon (¢) kg^{-1} for crop products, and ¢ $animal^{-1}$ for cattle)

Dis_n = distance on road type n (in kilometers).

The cost of labor depends on the quantity demanded insofar as the latter exceeds the labor pool that already resides in a sub-zone; once this situation has been reached, increasingly higher wages must be paid in order to attract labor from outside the sub-zone. In this way, labor mobility does exist but is not costless; rather, the cost of labor in excess of that already existing in the sub-zone depends on the cost of moving humans (approximated by the bus fare structure) between sub-zones and from the capital of San Jose to each of the sub-zones (movement of labor within each sub-zone is assumed to occur at no cost). Initial labor availabilities by sub-zone were estimated using data from the 1984 population census and zone-specific population growth rates available from the Costa Rican Bureau of Statistics (DGEC).

During the course of the development of the USTED methodology, beginning at the level of the settlement (some 5,000 ha) via the district level (some 50,000 ha) to the regional level (some 450,000 ha), a number of aggregation issues have been identified (Jansen and Stoorvogel, 1998). Aggregation issues are particularly relevant for regional agricultural land use models aimed at policy exploration (Rabbinge and van Ittersum, 1994; Schipper *et al.*, 1995; Hijmans and van Ittersum, 1996). While the previously described sub-zoning tackles the issue of geographically varying prices given a certain regional land use pattern, the issue of changes in output prices as a result of changes in land use becomes important at scale levels where the shares of the region modelled in domestic and/or export markets of certain crops are sufficiently large to influence prices in those markets. For the NAZ of Costa Rica, this is the case for, *e.g.*, banana (while Costa Rica is responsible for around 15% of world banana exports, virtually all banana plantations in Costa Rica are located in the NAZ) and palm heart of which Costa Rica is one of the largest suppliers as well. For such crops, prices can no longer be assumed endogenous, pointing to the need to incorporate demand factors in the LP model (Hazell and Norton, 1986). The required price elasticity estimates were obtained from Geurts *et al.* (1997) who estimated both price and expenditure elasticities with data from the latest household budgeting survey. With the exception of rice and beans (Stewart, 1987), supply elasticity estimates for Costa Rica do not exist. Consequently, supply elasticities in the LP model were based on assumed values.

7.3.6. Software

TCs resulting from definition of LUSTs are generated with CROPTCG developed in Microsoft Excel 5.0; TCs based on PASTs, APSTs and FASTs are generated by PASTOR which was developed in standard FORTAN77. The LP model is written in GAMS 2.25. PC ArcInfo 3.5.1 and ArcView 3.0a are used to manage the GIS. The model PLANTGRO was used as incorporated in the software package MPSC which was produced by Agro Data Services International and Larenstein International Agricultural College in The Netherlands (unpublished). All software runs on PCs under DOS or Windows environments (with the exception of some ArcView options which only run under Windows 95).

7.4. The northern Atlantic Zone of Costa Rica

The NAZ is located in the Caribbean lowlands of Costa Rica. Our case study area covers the major part of the province of Limón (Figure 7.2). The NAZ is characterized by a humid tropical climate, with mean daily temperature of 26 °C (variation through the year of only 2°C), mean annual rainfall of 3000 to 6000 mm, and average relative humidity of 85-90% (Herrera and Gómez, 1993). Even though the January-March period is relatively dry, all months of the year have a precipitation surplus. Elevation varies from sea level to +400 m. Climate is assumed to be homogenous throughout the region. The 21 different soil series of the original soil map in the area (Wielemaker and Vogel, 1993) have been grouped into three major categories, based on the most important diagnostic characteristics of fertility and drainage (Stoorvogel *et al.*, 1995): (1) young alluvial, well drained volcanic soils of relatively high fertility (Inceptisols and Andisols), classified as fertile well drained (SFW), (2) old, well drained soils developed on fluvio-laharic sediments of relatively low fertility (Oxisols and Inceptisols), classified as infertile, well drained (SIW), and (3) young, poorly drained volcanic soils of relatively high fertility (Entisols and Inceptisols), classified as fertile, poorly drained (SFP).

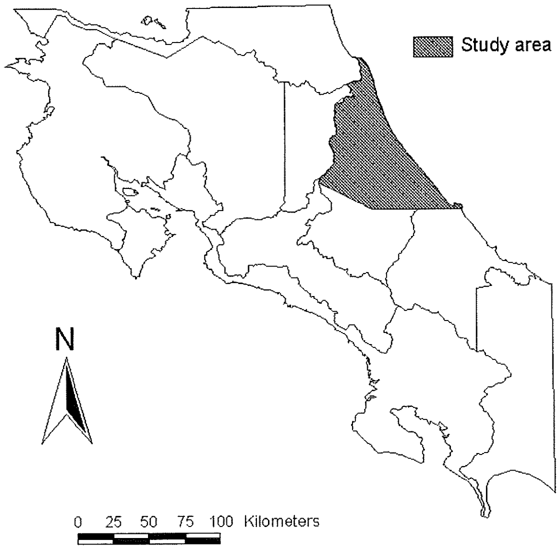

Figure 7.2. Case study area in the Atlantic Zone of Costa Rica.

The total surface area of the case study is some 447,000 ha, 334,000 ha of which is suitable for agriculture. From this 334,000 ha, about 59,000 ha is national protected area for nature conservation, so that 275,000 ha is available for agriculture (about 62% of total surface area). Table 7.2 presents an estimation of current (1992) land use based on satellite imagery, aerial photographs and field observations. Land use is dominated by cattle keeping and banana plantations. Main crops include plantain, palm heart (together some estimated 65% of all crops), cassava, beans, papaya and ornamentals. However, crops only play a minor role in the land use pattern in the NAZ.

Table 7.2. Estimated actual land use (1992) in the case study area in the northern Atlantic Zone of Costa Rica (based on Belder, 1994). Surface areas of roads, rivers and villages implicitly included in all land use types.

Land use	Ha	%
Primary & secondary forest	214,054	48
Pasture/cattle	174,928	39
Banana plantation	42,300	10
Crops	15,510	3
Total:	446,792	100

Colonization of the NAZ started in the late 19th century, with a major 'colonization push' in the second half of this century. Substantial deforestation has taken place after which soils were generally used for extensive cattle ranging and for large-scale plantation banana cultivation (Kaimowitz, n.d.). Due to the extensive nature of cattle ranging with low to zero external inputs, pasture degradation has become a serious problem in the area. Carrying capacity of most natural pastures continues to decline as fields are becoming more and more infested by weeds, resulting in decreasing returns to livestock keeping. During the past few years, low beef prices have aggravated this situation. While current practices of cattle ranging in the NAZ are unsustainable, since 1987 small crop farmers have been faced with a drastic change in agricultural policy by the Costa Rican government as a result of the introduction of the structural adjustment program (SAP) (*agricultura de cambio*). Both consumer subsidies and producer support prices on basic food staples such as rice, maize and beans were abolished. At the same time, increased emphasis was put on the cultivation of non-traditional export crops such as palm heart, root and tuber crops, and ornamental plants. These policy changes have put heavy pressure on farmers to change their (traditional) ways of farming (*e.g.,* commercial maize cultivation has virtually disappeared from the area). Another concern in the NAZ is raised by environmentalists who signaled various threats to the remaining natural forests and protected areas in the area. The large-scale conversion of primary forest into extensive pastures has increased the emission of greenhouse gasses such as CO_2 and N_2O, and of NO, which is a precursor to the greenhouse gas ozone (Keller *et al.*, 1993). In addition, the relatively large amounts of pesticides used in the area, especially in the cultivation of bananas, ornamentals and some field crops (Jansen *et al.*, 1997), may pose a threat to the 'health' of the ecosystem in general (Castillo *et al.*, 1997), and of humans in particular (Wesseling *et al.*, 1996). Finally, expansion of agricultural land - especially the extensive range land systems - causes land use conflicts in buffer-zones around protected areas and natural parks (de Vries, 1992).

7.5. Preliminary model results

7.5.1. Base data and TC generation

The stratification of the area resulted in 12 sub zones (Figure 7.3). Resource endowments and transportation costs of products are summarized in Tables 7.3 and 7.4, respectively.

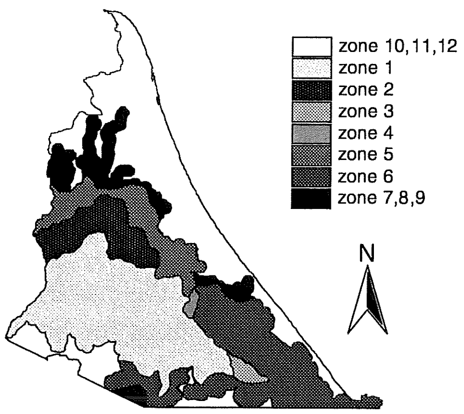

Figure 7.3. Subzones in the Atlantic Zone case study area based on transport cost differentiation (see text for explanation).

Table 7.3. Area available for agriculture (i.e., not having a protected status) per soil type (in ha), and agricultural labor pool (in number of persons) per sub zone.

Zone	Code	SFW	SFP	SIW	Labor
1	R111	68,214	13,369	28,862	16,288
2	R112	14,666	9,516	7,264	5,168
3	R121	2,515	621	804	430
4	R211	467	616	726	220
5	R212	8,185	14,004	10,410	3,794
6	R221	27,069	24,162	9,546	13,377
7	R2221	2,662	3,799	3,429	2,136
8	R2222	1,215	2,080	141	720
9	R2223	666	0	960	300
10	R9991	5,765	10,038	559	2,179
11	R9992	434	69	39	755
12	R9993	1,640	0	368	1,576
Sum		133,498	78,274	63,108	46,943

Table 7.4. Transport costs (in colon per kg product) of product per sub zone. Crop products are divided into products for the domestic and the export market; timber, meat and milk have the same market outlet for export and domestic use.

Zone	Crop Export	Crop Domestic	Timber	Banana Export	Meat	Milk
1	3	6.6	1	0.8	2.4	10
2	7.5	6.6	1	2.3	2.4	10
3	3	6.6	1	0.8	4.3	10
4	3	9.6	2	0.8	2.4	15
5	7.5	9.6	2	2.3	2.4	15
6	3	9.6	2	0.8	4.3	15
7	7.5	9.6	2	2.3	4.3	15
8	7.5	9.6	2	2.3	4.3	15
9	7.5	9.6	2	2.3	4.3	15
10	28.5	24.6	6	9.3	6.8	60
11	14.5	14.6	3	4.7	5.1	45
12	14.5	14.6	3	4.7	5.1	45

An example of the qualitative land use evaluation using PLANTGRO and GIS is presented for banana in Figure 7.4. In general, the suitability of the NAZ for banana is high, with the exception of swamps and very poorly drained soils in the eastern parts of the area. Low levels of solar radiation may somewhat limit the possibilities for banana cultivation in the northwestern part. Overall, water logging constitutes a main bio-physical constraint to many crops, but fortunately, this can be alleviated by drainage.

Based on the qualitative land evaluation and on expert knowledge, crop types and pastures were selected representing major crop groups that have (bio-physical) potential in the area. LUSTs were created for the following land use types: palm heart, banana, plantain, cassava, black bean, maize (grain and fresh cobs), melina tree plantation, and teak tree plantation (more/new crops may be added in the future, *e.g.*, pineapple, rubber, rice, papaya, cacao). Sixteen technology levels are defined by combining two levels of input (low (L) and high (H)) for fertilizers, insecticides, herbicides, and degree of mechanization. PAST options are modelled for five pasture types: natural grass (a mixture of indigenous species and naturalized improved varieties introduced in the 1970s), grass-clover mixture, and the improved varieties estrella (Cynodon nlemfuensis), brachiaria (Brachiaria brizantha), and tanner (Brachiaria radicans). Different technology levels are generated by varying (1) stocking rates (1-6 animal units (AU) per hectare), (2) fertilizer levels (0-100% of the amount to reach potential production levels), and (3) the type of weeding, *i.e.,* manual, chemical, or mixed.

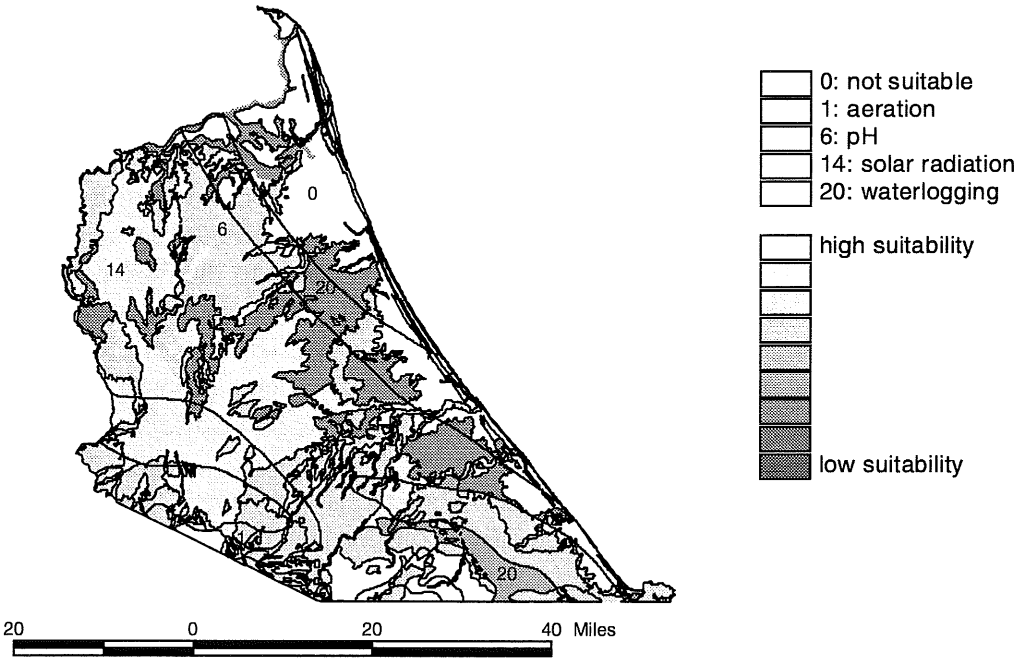

Figure 7.4. Results of qualitative land evaluation for banana. The grey scale in the map indicates the suitablility class, the numbers represent the type of limiting factor (see legend).

As far as APSTs are concerned, thus far breeding and fattening systems have been modelled (work on double-purpose systems is in progress). FASTs are feed supplements of sugar cane, molasses, green bananas (rejected for human consumption), and a number of organic and inorganic feed concentrates.

Simulated TCs were validated against field observations, literature data, and well-established knowledge on agronomic relationships. For example, simulated pasture data agreed well with data from field experiments performed in the humid tropics by Salazar (1977) and Vicentle-Chandler *et al.* (1974) (data not shown).

7.5.2. Evaluation of alternative scenarios

To demonstrate the capabilities of the USTED methodology, a number of scenarios were evaluated in comparison with a so-called base scenario. The base scenario reflects the maximization of regional value added with the only constraints included consisting of resource limitations at the level of the sub-zone in terms of soil endowments and available labor pools (even though labor is mobile between sub-zones and labor from outside the NAZ may be hired). However, no additional constraints on neither sustainability nor on the environmental parameters are included. Other possible constraints such as export quota etc. are also assumed absent. Next to the base scenario (scenario 1), four alternative scenarios were evaluated:

- a sustainability scenario (scenario 2), operationalized via a restriction that imposes a zero N balance of the soil;
- a combined sustainability and environmental scenario (scenario 3), operationalized via a zero N balance of the soil and a restriction that limits the application of pesticides (in terms of active ingredients) to 50% of that in the base run;
- an export marketing limitation scenario (*i.e.,* an export quota on banana; scenario 4), operationalized via a restriction that limits banana exports to currently prevailing quantities of about 1.44 x 10^6 tons; and
- a combined international quota and sustainability scenario (scenario 5), operationalized via the above export quota on banana and a zero N balance of the soil.

Summary results of the scenarios are presented in Table 7.5. As far as land use is concerned, it should be reminded that of the total land area, 38% cannot be used for agriculture and is permanently under forest cover. Land left unused by the model in some scenario runs is supposed to be converted to secondary forest and is added to the 38% existing forests. Land use in the base scenario is dominated by banana (38% of total area, or 60% of total agricultural land) and cattle keeping (22% of total area, or 35% of total agricultural land). Cattle is all raised on natural pastures with an average stocking rate of 1.5 AU/ha. About 60 and 40% of livestock activities consist of cattle fattening and cattle breeding, respectively, in number of herds (there is a regional balance in the model so that all animals used for fattening have been bred in the area). Banana is cultivated with low fertilizer input technologies, resulting in strongly negative soil nutrient balances, particularly for N (-270 kg/ha) and K (-494 kg/ha), with correspondingly high N leaching losses (219 kg/ha). Average pesticide use is very high at 28 kg a.i./ha (compared to about 6 kg/ha for Costa Rica as a whole; von Düszeln, 1990). Pesticide use on pastures is moderate, but very high in banana cultivation (about 45 kg a.i./ha; Castillo *et al.*, 1997). Other crops selected by the model include palmheart (some 6,400 ha) and a little plantain (about 1000 ha). All available land for agriculture is used, while the labor-intensive character of banana cultivation creates the need for hiring of additional labor from outside the NAZ.

Land use in the base scenario can be qualified as highly unsustainable, as evidenced by the substantial soil nutrient losses. Consequently, the second scenario imposes a restriction of a zero soil N balance on the model, with all other model specifications unaltered. Besides a shift in land use away from banana and towards cattle keeping, the main result is a dramatic change in technologies used in both the crop and the livestock sector. Cattle keeping (with fattening still dominating breeding) now occurs on balanced grass-clover mixtures which are self-sufficient in N, allowing stocking rates of 2.5 AU/ha. In banana cultivation, low fertilizer technologies have made way for fertilizer-intensive production methods. Together with the imposed zero soil N balance, the highly negative soil K balance of the base scenario has nearly disappeared. However, these improvements in sustainability come at a substantial cost. First, regional value added has decreased by nearly 30%. Second, environmental indicators have worsened, with N leaching, N volatilization and denitrification all gone up substantially compared to the base scenario, even though the average amount of pesticides used has decreased somewhat (to 22 kg a.i./ha). Labor use stays virtually constant, but the strict enforcement of a zero soil N balance does no longer allow all available agricultural land to be cultivated.

The main effect of a constraint on pesticide use in the third scenario (while keeping the zero soil N balance constraint) is twofold. First, there is a substantial increase in the area left unused, rising about fivefold, from 10,000 ha (scenario 2) to nearly 50,000 ha (representing nearly 20% of the total area available for agriculture). As a result, a situation of excess labor supply is created in which part of the labor pool in the NAZ is unable to find employment in agriculture. Both cattle keeping and (particularly) banana activities diminish, the latter decreasing by some 30,000 ha. Second, there occurs a dramatic technology shift in banana cultivation where pesticide-intensive technologies are substituted for production technologies that use less pesticide. Environmental indicators all improve, with the maximum allowable amount of pesticides used (50% of the amount in the base scenario) not even being realized (as evidenced by the 7 kg a.i./ha used which is only 25% of that in the base scenario). However, simultaneous improvements in both sustainability and environmental indicators are very costly indeed, as evidenced by a further decline in regional value added to a level which is only about 40% of that achieved in the base scenario.

During the late 1980s and 1990s, Costa Rican banana exports have fluctuated around a trend of about 80 x 10^6 cases of 18.14 kg each, or about 1.44 x 10^6 tons (Jansen and van Tilburg, 1996; CORBANA, 1994). Recently, there has been quite some political turmoil regarding EU policies that try to favor banana imports from the so-called ACP countries (a number of African and Caribbean countries to which the EU offers preferential market access through the so-called Lomé treaties) at the expense of banana imports from Latin American countries such as Costa Rica. In any case, in the short to medium term it seems highly unlikely that Costa Rica will be able to expand its banana exports much above current levels. This situation was translated in modelling terms by introducing into the base scenario model (which has no restrictions on soil mining) a restriction that limits banana exports to a maximum of 1.44 x 10^6 tons. The results of this fourth scenario dramatically show the economic dependence of the NAZ on banana cultivation. Compared to the base scenario, regional value added collapses by more than 60%, due to a decrease in banana area to about 49,000 ha, roughly its current level. Banana technologies selected by the model are extensive and relatively low-cost. About 75% of available agricultural land is now used for cattle raising which occurs for about 65% on natural pastures with low inherent productivity and low stocking rates. The remaining 35% of the pasture land is mixed grass-clover where stocking rates are somewhat higher. Compared to the base scenario, sustainability and environmental indicators all improve substantially, but at a high cost in terms of income foregone.

At 113 kg/ha/yr, soil mining of N is still substantial in the fourth scenario. This is mainly due to the substantial area devoted to traditional cattle raising on natural pastures with little or no fertilizer input. In order to assess the implications of an improvement in the sustainability of the current situation, a zero soil N balance restriction was imposed on the model used in the fourth scenario. Regional income decreases further to less than 30% of that obtained in the base scenario (and decreasing by 23% relative to scenario 4), mainly due to a nearly 50% decrease in banana area compared to scenario 4 (from 48,000 to 27,000 ha) as well as a much less dramatic decrease in pasture area. Technology shifts occur in both banana cultivation (which reverts back to more fertilizer-intensive technologies) and beef production (where all cattle is now raised on grass-clover mixtures). Again, the soil K balance improves as the result of the zero soil N balance restriction, even though this gain in sustainability comes at a cost of deteriorating environmental indicators (with the exception of pesticide use which on an a.i./ha basis decreases marginally).

Table 7.5. Results of scenario analyses in terms of total added value for the whole area, labor use in terms of percentage of internal availability, soil nitrogen balance NBAL in terms of kg/ha of used land, applied active pesticides PAI and broad land use types (in % of total land area of 447,000 ha). See text for explanation of Run 1 to 5. For comparison, actual land use data from Table 7.2 have been repeated here.

	Actual	Run 1	Run 2	Run 3	Run 4	Run 5
Added value (10^9 colon)	?	220	157	93	84	65
Labor use (% of available)	?	122	121	83	47	42
NBAL (kg N/ha)	?	-270	0	0	-113	0
PAI (kg/ha)	?	28	22	7	6	5
Land use:						
Unused (forest)	48	38	41	49	38	50
Pasture/cattle	39	22	34	32	49	43
Banana plantation	10	38	24	18	11	6
Crops	3	2	1	1	2	1

7.5.3 Concluding remarks

Environmental quality problems generally have both an economic and an ecological side, suggesting the possible existence of trade-offs between the two . Even though, at the farm level, such trade-offs do not necessarily have to be negative (as demonstrated earlier in the workshop by Stoorvogel and Bowen, leading to win-win type situations), at the regional level they are typically perceived as negative, at least in the short run. Given their set of objectives, the LP model for the NAZ of Costa Rica as described above allows policy makers the opportunity to explore various alternative strategies while making the trade-offs involved explicit. For example, the efficiency of alternative environmental policies can be compared by examining their costs (in terms of reductions in regional value added) as well as the improvements in sustainability and environmental indicators achieved. Obviously, it should always be kept in mind that, rather than the exact numerical results obtained, what really matters are relationships and trends.

References

Belder M 1994 Land use and land use dynamics in the Atlantic Zone of Costa Rica. Report 84 (Phase 2). Atlantic Zone Program, CATIE-UAW-MAG, Turrialba, Costa Rica

Bouma J, Brouwer J, Verhagen A, Booltink HWG 1995. Site specific management on field level: high and low tech approaches. Pages 453-73 in: Bouma J, Kuyvenhoven A, Bouman B, Luyten J, Zandstra H (eds) Eco-regional approaches for sustainable land use and food production. Proceedings of a symposium on eco-regional approaches in agricultural research, 12-16 December 1994, ISNAR, The Hague. Kluwer Academic Publishers, Dordrecht, The Netherlands

Castillo L, de la Cruz E, Ruepert C 1997 Ecotoxicology and pesticides in tropical aquatic ecosystems of Central America. Environmental Toxicology and Chemistry, 16(1): 41-51

CORBANA (Corporacion Bananera Nacional) 1994 Costa Rica: estadísticas de exportación bananera 1993. San José, Costa Rica

de Vries P 1992 Unruly clients. A study how bureaucrats try and fail to transform gatekeepers, communists and preachers into idels beneficiaries. Ph.D thesis, Wageningen Agricultural University, the Netherlands

FAO 1976 A framework for land evaluation. FAO Soils Bulletin 32. Rome

Geurts JAAM, Jansen HGP, van Tilburg A 1997 Domestic demand for food in Costa Rica: a double-hurdle analysis. CATIE Serie Técnica, Informe Técnico No. 286, Turrialba, Costa Rica

Hackett C 1991 PLANTGRO, A software package for coarse prediction of plant growth. CSIRO, Melbourne Australia

Hazell PBR, Norton RD 1986. Mathematical programming for economic analysis in agriculture. New York: Macmillan Publishing Company

Hengsdijk H, Quak W, Bakker EJ, Ketelaars JJMH 1996 A technical coefficient generator for land use activities in the Koutiala region of south Mali. DLV report no. 6, AB-DLO/Department of Development Economics, Wageningen, the Netherlands

Herrera W, Gómez LD 1993 Mapa de unidades bioticas de Costa Rica. Instituto Geografico de Costa Rica, San Jose, Costa Rica

Hijmans RJ, van Ittersum MK 1996. Aggregation of spatial units in linear programming models to explore land use options. Netherlands Journal of Agricultural Science (44): 145-62

Jansen DM, Schipper RA 1995 A static descriptive approach to quantify land use systems. Netherlands Journal of Agricultural Science (43): 31-46

Jansen DM, Stoorvogel JJ, Schipper RA 1995 Using sustainability indicators in agricultural land use analysis: an example from Costa Rica. Netherlands Journal of Agricultural Science 43: 61-82

Jansen HGP, Stoorvogel JJ, 1998. Quantification of aggregation bias in regional agricultural land use models. Forthcoming in Agricultural Systems

Jansen HGP, van Tilburg A (with J. Belt and S. Hoekstra) 1996 Agricultural marketing in the Atlantic Zone of Costa Rica: a production, consumption and trade study of agricultural commodities produced by small and medium scale farmers. CATIE Serie Tecnica, Informe Tecnico No. 271, Turrialba, Costa Rica

Jansen HGP, Wesseling C, Uytewaal E, Stoorvogel JJ, 1997. Health externalities and pesticide use in the Atlantic Zone of Costa Rica: an economic analysis. Paper submitted to Ecological Economics

Kaimowitz D, n.d. Livestock and deforestation in Central America in the 1980s and 1990s: a policy perspective. Unpublished report, Instituto Interamericano de Cooperacion en la Agricultural (IICA), Coronado, Costa Rica

Keller M, Veldkamp E, Weitz AM, Reiners WA 1993 Effect of pasture age on soil trace-gas emissions from a deforested area of Costa Rica. Nature (365): 244-246

Kruseman G, Ruben R, Hengsdijk H, van Ittersum MK 1995. Farm household modelling for estimating the effectiveness of price instruments in land use policy. Netherlands Journal of Agricultural Science (43): 111-23

Kuyvenhoven A, Ruben R, Kruseman G 1997. Technology, market policies and institutional reform for sustainable land use. Paper presented at the XXIII International Conference of Agricultural Economists, August 10-16, Sacramento, California, U.S.A.

Murillo R, Mora J 1996. Situacion y perspectivas de los granos basicos en Costa Rica. Unpublished report, Instituto Interamericano de Cooperacion en la Agricultural (IICA), Coronado, Costa Rica

Rabbinge R, van Ittersum MK 1994 Tensions between aggregation levels. Pages 31-40 in: Fresco LO, Stroosnijder L, Bouma J, van Keulen H. (eds) The future of the land: mobilising and integrating knowledge for land use options. John Wiley & Sons, West Sussex, England

Rabbinge R, van Latesteijn HC 1992 Long term options for land use in the European Community. Agricultural Systems (40): 195-210

Salazar MAG 1977 Efecto de la frequencia de corte y de cuatro niveles de fertilización nitrogenada sobre el rendimiento y valor nutritivo del pastor estrella (Crynodon nlymfuensis). San pedro de Montes de Oca, Costa Rica

Schipper RA 1996 Farming in a fragile future. Economics of land use with applications in the Atlantic Zone of Costa Rica. Ph.D thesis, Wageningen Agricultural University, the Netherlands

Schipper RA, Jansen DM, Stoorvogel JJ 1995 Sub-regional linear programming models in land use analysis: a case study of the *Neguev* settlement. Netherlands Journal of Agricultural Science (43): 83-109

Singh I, Squire L, Strauss J. (eds) 1986 Agricultural household models: extensions, applications and policy. Baltimore: Johns Hopkins University Press for the World Bank

Stewart R 1987 Food pricing policy and its effects in Costa Rica. The case of rice and beans. Food Policy 2: 264-272

Stoorvogel JJ 1995. Integration of computer-based models and tools to evaluate alternative land use scenarios as part of an agricultural systems analysis. Agricultural Systems (49): 353-67

Stoorvogel JJ, Schipper RA, Jansen DM 1995[a]. USTED: a methodology for quantitative analysis of land use scenarios. Netherlands Journal of Agricultural Science (43): 5-18

Van Keulen H 1990 A multiple goal programming basis for analysing agricultural research and development. Pages 265-276. in: Rabbinge R, Goudriaan J, van Keulen H, Penning de Vries FWT, van Laar HH (eds) Theoretical production ecology: reflections and prospects. Simulation Monograph 34. Pudoc, Wageningen, The Netherlands

Veeneklaas F 1990 Formal description of the optimization model MALI5. Serie: competing for limited resources: the case of the fifth region of Mali. Report no. 3, CABO, Wageningen, and ESPR, Mopti, Mali

Veldkamp A, Fresco L 1996 CLUE-CR: an integrated multi-scale model to simulate land use change scenarios in Costa Rica. Ecological Modelling (91): 231-248

Vicentle-Chandler J, Abruna F, Caro-Castros R, Figarell J, S Silva, Pearson RW 1974 Intensive grassland management in the humid tropics of Puerto Rico, Univ. P.R. Agr. Expt. Sta., Bull. 223

Von Düszeln J 1990 Pesticide quality control in Costa Rica, Central America. Food Laboratory News (21): 26-29

Wesseling C, Ahlbom A, Antich D, Rodriguez A, Castro R 1996 Cancer in banana plantation workers in Costa Rica. International Journal of Epidemiology, 25(6): 1125-1131

Wielemaker WG, Vogel AW (eds) 1993 Un sistema de información de suelos y tierras para la Zona Atlántica de Costa Rica. Atlantic Zone Program (CATIE/UAW/MAG), Guápiles, Costa Rica

WRR (Netherlands Scientific Council for Government Policy) 1992 Ground for choices. Four perspectives for the rural areas in the European Community. Reports to the government no. 42, Sdu publishers, The Hague, The Netherlands

8. CLUE: A tool for spatially explicit and scale sensitive exploration of land use changes

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8.1. Introduction

8.1.1. Land use and cover change

Human induced conversions of land cover and changes in land use have important consequences for natural resources through impacts on soil and water quality, biodiversity, and global climate systems (Turner *et al.*, 1995). Most land cover modification and conversion is now driven by human use, rather than natural change (Houghton *et al.*, 1991). In general, land use is viewed to be determined by the interaction in space and time of biophysical factors like soils, climate and topography, and human factors, like population, technology and economic conditions (Turner *et al.*, 1993; Skole and Tucker, 1993). Interpretations of how such multi-dimensional land use/cover driving forces act and interact is still controversial, especially with respect to the assessment of the relative importance of the different forces and factors underlying land use decisions in specific cases. Relatively few regional comparative studies have addressed the role of these combined driving forces in agro-ecosystems in a spatially and temporally explicit way.

This paper deals with CLUE (Conversion of Land Use and its Effects): a tool for quantitative multi-scale analysis of actual land use and the spatially explicit modelling of land use change scenarios.

8.1.2. Land use and scales

In agro-ecosystems analysis, the scale at which the analysis is conducted will affect the type of explanation given to the observed phenomena. While pests and diseases might cause variation within a rice field, climate systems determine broad agro-ecological zones. At coarse (aggregated) scales, the high level of aggregation of data obscures the local variability but can show patterns invisible at detailed scales, and vice versa. Furthermore, factors determining land use (change) can operate at great spatial distance from the area affected. Thus, for dealing with the complex issues of land use/cover change, it is necessary to use a multi-scale approach that identifies and quantifies land use drivers and their interrelationships at various spatial scales.

8.1.3. The CLUE modelling framework

The CLUE modelling framework aims at a spatially explicit analysis of multi-scale relations in land use/cover dynamics. It uses actual, georeferenced land use as a starting point. This is especially important in situations where agricultural production is clearly below its biophysical potentials, indicating the importance of socio-economic conditions in the actual land use decisions. The CLUE methodology broadly consists of two consecutive steps.

First, past and present land use are being analyzed at different spatial scales through multiple regression methods. With these methods the most important biogeophysical and socio-economic drivers of land use are being determined, as well as the quantitative relations between these drivers and the surface area of different land use types.

In a second step, these quantitative relations are being used in a model, with which possible future land use changes can be explored in a spatially explicit way. This is done using different development scenario's, considering national changes in demand for agricultural products and multi-scale changes in land use change drivers.

CLUE was first applied for Costa-Rica (Veldkamp and Fresco, 1996; 1997a; 1997b). Current research is carried out for Ecuador (de Koning *et al*, forthcoming), Honduras, China (Verburg and Veldkamp, 1997; Verburg *et al.*, 1997) and Indonesia.

8.2. Multi-scale statistical analysis of land use

8.2.1. Aggregation levels

In order to investigate scale effects, a series of nested scales is constructed. The spatial organization of biophysical and socio-economic units only rarely coincide, and therefore processes and drivers do not overlap in space. To avoid this discrepancy, artificial scales are constructed on basis of a series of aggregation steps, starting with a uniform geographical grid. The grid approach and the chosen resolution are related to the resolution of biophysical as well as socio-economic input data. For example, in the study for Ecuador (de Koning *et al.*, forthcoming) the highest resolution grid consisted of 5 by 5 minute cells (9.25 by 9.25 km^2). This base grid contained almost 3000 cells. Higher aggregation levels were made by aggregating the grid data into larger grid cells, composed of respectively 2x2 base cells, 3x3 base cells, 4x4 base cells, 5x5 base cells and 6x6 base cells. This way 6 nested scales were created.

A major disadvantage of this grid approach is that one may loose information because the minimum grid size becomes the most detailed level of analysis possible and because of the borders of units which normally do not fit into one grid cell. A third disadvantage is the artificial nature of the units of analysis. However, once data are converted into these basic grid cells, similar and equally sized units can be compared without any spatial aggregation problem. Another advantage is that artificially gridded data can be aggregated into many different scales while for example data grouped in administrative boundaries can only be aggregated into a few predetermined scales.

8.2.2. *Data collection*

The georeferenced data used are (proxies of) factors that are considered important for land use in the area of study. The resolution of these data (that are integrated in a geographical information system) should be in correspondence with the resolution of the base grid. In general biogeophysical data are derived from maps and/or satellite images. Data used are soil fertility indicators, soil physical properties, soil erosion susceptibility, precipitation, temperature, extreme weather events, altitude, relief, geology etc.. Infrastructure data are for example distances to cities, markets, rivers and roads. Socio-economic data used are (rural and urban) population density, (agricultural) labor force, income and illiteracy.

The land use and cover data are derived from agricultural censuses, sometimes complemented with satellite images. Data needed are the surface areas of land use types and separate crops, crops yields, number of animals and their production, and management data such as irrigation practices, fertilizer use and mechanization.

Grid cells are not treated as homogenous units. For example with respect to land use types, a cell can consist of 10% grassland, 35% arable crops and 55% forest.

8.2.3. *Statistical procedure*

The hypothetical biogeophysical and socio-economic drivers of past and actual land are investigated with multiple regression methods (Figure 8.1). In order to take scale dependencies into account, this analysis is performed independently at the different artificial aggregation levels (= spatial scales).

First, the most important land use drivers (independent variables) for different land use types (dependent variables) are for each aggregation level selected from the basic set of hypothetically important variables by means of stepwise regression. The selected significant variables are then used to construct multiple regression models.

An example of such a model for a specific land use type at a specific scale is:

$$\%\text{permanent crops} = \beta_0 + \beta_1 * \text{rurpop} + \beta_2 * \text{prec} + \beta_3 * \text{slopes} + \beta_4 * \text{rurpov}$$

In this example the percentage of permanent crops in a certain cell is determined by a constant (β_0) and a by the density of the rural population, the total annual precipitation, the percentage of the cell that has steep slopes and the percentage of the rural population living in poverty.

Of these models the adjusted coefficient of determination is a measure for the amount of variation in the percentage of the land use type that can be explained. The standardized betas of the individual variables indicate the relative importance of a variable in the explanation of the percentage of a land use type, relative to the other variables.

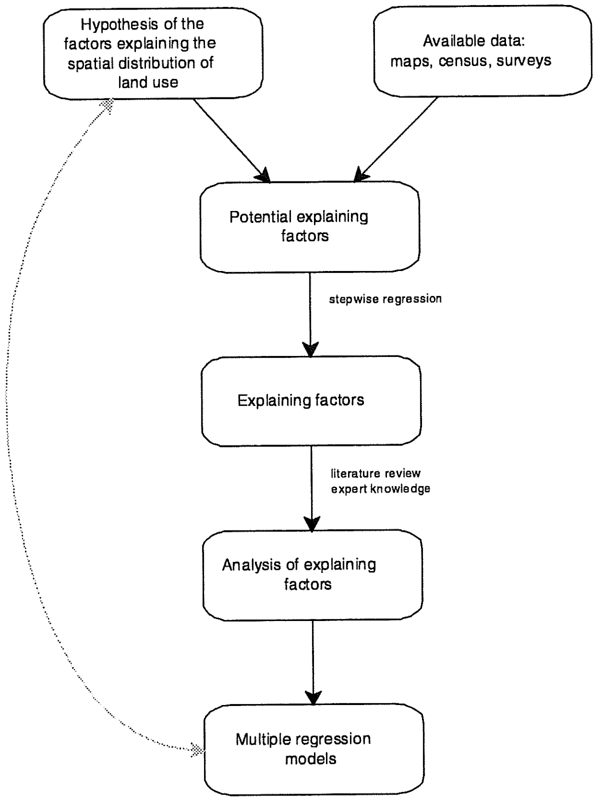

Figure 8.1. Overview of the statistical procedure.

8.2.4. Results

The studies for Costa Rica (Veldkamp and Fresco, 1997) and Ecuador (de Koning *et al.*, forthcoming) show that for most land use types the statistical regression models include biogeophysical as well as socio-economic variables. In general the coefficients of determination of the models increase with the aggregation level. Furthermore, the variables selected in the multiple regression models and their relative contribution change with the aggregation level. An example is given in Table 8.1, for the land use type grassland in the eco-region Pacific Coast in Ecuador. For three aggregation levels the significant variables in the regression models are given, ranked according to their relative contribution to the explanation of the variation in grassland area on basis of their standardized betas. The sign indicates the positive or negative relation of a variable with the area grassland. While at the lower aggregation levels the distance to the nearest main road is the most important variable, this variable is not included at the highest aggregation level while at this level the agricultural labor force as percentage of the total labor force is the most important variable. Another socio-economic variable, rural illiteracy, is only included in the model for the highest aggregation level. Also altitude is only included at this level.

Table 8.1. Regression models for grassland area in the eco-region Pacific Coast, Ecuador, at three aggregation levels. Variables (with their sign) are ranked according to their relative contribution in the regression equation on basis of their standardized betas.

2x2 grid		4x4 grid		6x6 grid	
Variable	**sign**	**Variable**	**sign**	**variable**	**sign**
Distance to road	-	Distance to road	-	% agricultural labor	+
% steep slopes	+	% light textured soils	-	% low fertility soils	-
% heavy textured soils	+	Annual precipitation	+	% steep slopes	+
Distance to rivers	-	% medium fertility soils	+	Altitude	-
% low fertility soils	-	% agricultural labor	+	% rural illiteracy	+

One should interpret these results with caution. No strong conclusions should be drawn for individual variables. Though the stepwise regression procedure corrects for multi-collinearity, remaining correlation between variables limits the interpretation of the regression coefficient of a single variable with respect to it's one to one correlation with the dependent variable.

The Costa Rica case showed that a contribution can even change from negative to positive depending on the level of aggregation. The changes with aggregation level can be attributed to changes in variability. At the detailed scales the relationships are strongly influenced by the variability in observations while at the coarser scales the general trends have a larger contribution because the variability is obscured by the high level of aggregation. The scale dependency is also caused by variables that act over a considerable distance such as urban population concentrations. Depending on the scale of analysis these variables will affect the relationships found.

As a consequence of the scale dependency in land use systems one should use relations derived at a certain aggregation level only for analysis and implementation at the same aggregation level. Errors will be induced when relations derived at detailed scales are used at highly aggregated scales or the other way around. By combining coarse scale analysis and detailed scale analysis a more complete description of the land use system is obtained including general patterns, local variations and variables that influence land use over some distance.

8.3. Modelling of future land use change scenarios

8.3.1. General structure of the model

The results of the statistical analyses give quantitative insight in the multi-scale structure of land use. The next step is the modelling of possible future land use change scenarios. This is the actual CLUE model, that can broadly be divided in a demand an allocation module (Figure 8.2) which interact with a population and yield module.

In the demand module the national demand for agricultural commodities is estimated for a series of future years on basis of different projections of the factors determining this demand. The allocation module calculates local changes of different land use type areas on basis of changing demands, using the results of the statistical analysis and applying the multi-scale approach by looking at regional and local driving forces for land use change. The model produces results with time steps of one year, and aims at future exploration of about 20 years. Below, the demand and allocation module will be explained in some more detail.

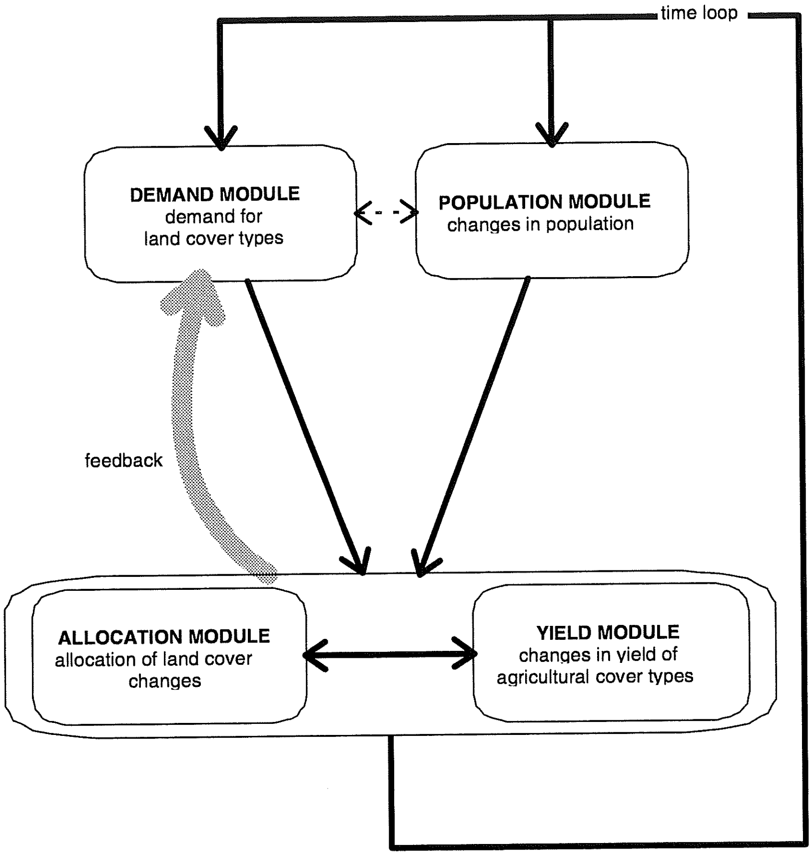

Figure 8.2. General structure of the CLUE model.

8.3.2. Demand module

In the CLUE demand module, the total area needed for different land use types is calculated on the basis of national demands for separate commodities. The demands for these commodities are the sum of domestic consumption volumes and export volumes. Export volumes can be related to international prices and national subsidies. Domestic intake is a function of population size, population composition and consumption patterns. Consumption patterns can be related to macro-economic indicators like gross domestic product, purchasing power and price levels. Historic data are used to calibrate the commodity volume demand functions. Future developments are hard to predict, and therefore different possible development scenarios are being formulated, taking into account varying projections of future population development and diet patterns.

Commodity demands calculated as production volumes are translated into areas through crop specific yields (for animal products production per animal and stocking densities are used). Different developments of yield for separate crops can be included through the yield module. On basis of the calculated areas for separate crops, the needed areas for broader land use types are calculated.

8.3.3. *Allocation Module*

In the CLUE allocation module, the area demand for separate land use types is allocated to the basic grid cells using a nested scale approach. The idea behind the allocation procedure is that local land use change is determined by local biophysical and socio-economic conditions, as well as by conditions at higher scales. This is related to the fact that decisions at the local level are the result of local processes, but also by processes that operate over large distances.

In the allocation module, the national demand for each land use area is allocated first to the cells at the higher aggregation levels in order to establish the comparative advantages between these larger cells, representing regions. Then, within these larger cells, local changes of all land use types in the smallest cells are calculated on basis of their locally specific biogeophysical and socio-economic conditions, but taking into account the conditions in the larger cells in which these cells are nested.

The actual calculation of the expected area changes at the different scales is done by using the scale-specific regression equations from the statistical analysis. The area of a certain land use type in a cell, is determined by the multi-dimensional space made up by the land use drivers. If a cell has less area of a certain land use type than expected on basis of the regression equation, area increase of that land use type is considered feasible (and vice versa). The actual fraction of change allowed is established through an iteration procedure in which a new equilibrium is calculated. This is done simultaneously for all land use types, accounting at the same time for competition between land use types within cells.

The changes of biophysical and socio-economic drivers are also taken into account, thereby changing the multi-dimensional space within which land use is situated and calculated. For Ecuador, for example, the changes in local population densities are included.

In the multi-scale allocation procedure top-down and bottom-up effects are being mimicked. The demand is allocated from national to intermediate and local levels, but local conditions can constrain increases in land use, thereby forcing other areas to grow or even prohibit the national demand to be allocated. In the model, local effects like the protection of areas through national parks, or areas becoming unsuitable through deterioration of biophysical resources can be included as different scenarios.

8.3.4. *Results*

Scenario studies have been executed for Costa Rica (Veldkamp and Fresco, 1997a; 1997b) and Ecuador. With the output of the model yearly dynamics in space and time of different land use types can be evaluated simultaneously. The lower boundary of spatial detail is determined by the size of the smallest grid cells. An example of results at that level are shown in Figure 8.3 for the changes in grassland area for a base scenario in Ecuador. This example shows a growing grassland area due to increased demand for animal products that is the result of a growing population. It should be realized that here only relative cell surface fractions of one land use type are given. For a complete interpretation of land use changes, the other land use types have to be taken into account as well. The actual data can be analyzed and specific areas of interest can be located. A selection of the results can be seen at the CLUE website: http://www.gis.wau.nl/~landuse1/clue.html.

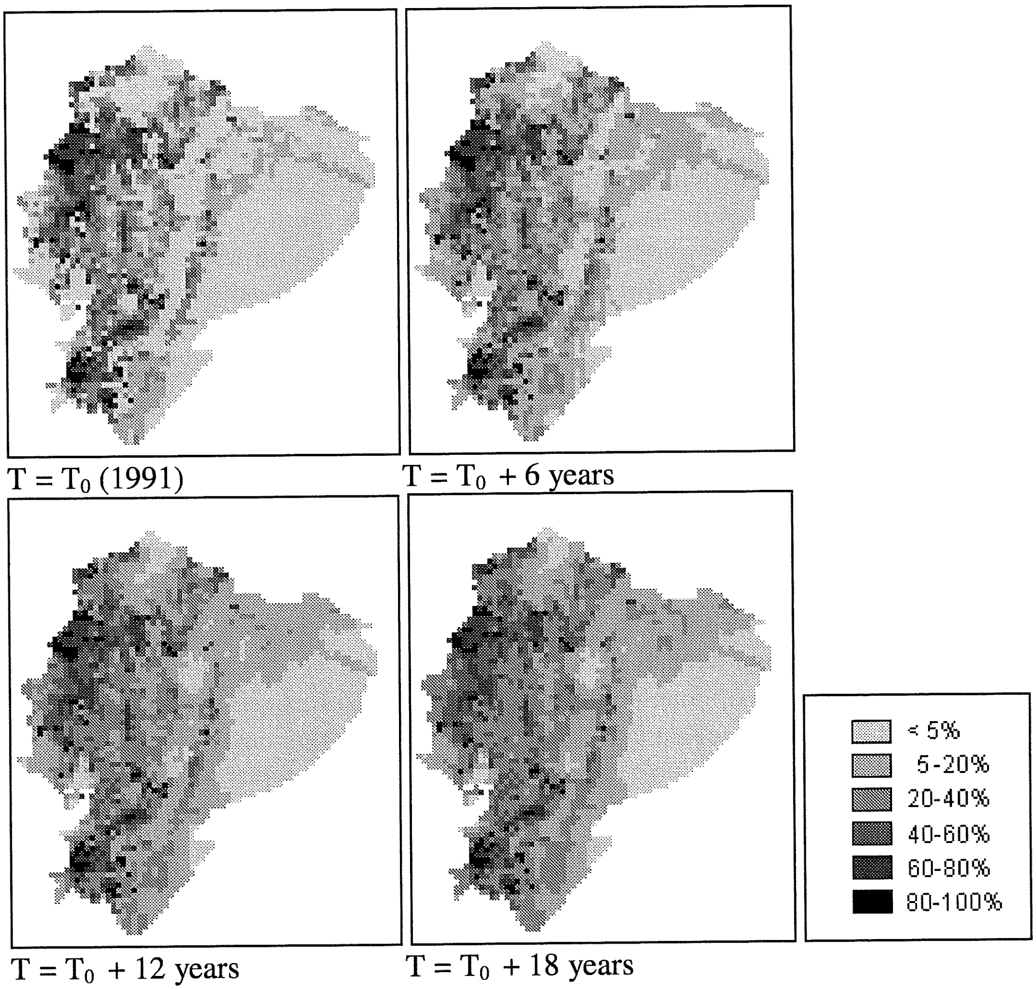

Figure 8.3. Changes in grassland area under a baseline scenario (growing population, equal diet). In the legend the percentage of the cell area under grassland is indicated. (preliminary results for Ecuador).

8.4. Conclusions

In this paper a spatially explicit and scale sensitive approach to land use change modelling has been demonstrated. A multiple regression procedure was presented that selects and quantifies drivers for different land use types from a set of potentially explaining socio-economic and biogeophysical factors. Results from studies for Costa-Rica and Ecuador demonstrate different (relative contributions of) drivers at different aggregation levels, indicating that the spatial structure of land use is scale dependent.

The CLUE modelling framework incorporates the multi-scale quantitative information on land use drivers in a dynamic model that explores future land use change scenarios taking into account scale dependencies of drivers and comparing different development scenario's. Results from Costa-Rica and Ecuador have shown the feasibility of such a modelling procedure.

The data demand for the application of CLUE is rather high. Most data are taken from biophysical maps with their related databases, and from socio-economic and agricultural censuses. Sufficient spatial detail is necessary and the data should cover the complete study area. Standardization of the collection and storage of data will greatly facilitate the approach. Currently the use of remote sensing images to support ground data is being investigated. Ongoing research on the CLUE model, is directed towards a more crop (management) specific approach.

Attention is furthermore being paid to the assessment of impacts of land use changes on natural resources, such as soils, water and biodiversity. An example of a sustainability indicator for land use is the soil nutrient balance, that was calculated for the basic grid cells for Ecuador (de Koning *et al*, 1997). This indicator gives information if and where depletion of soil fertility is taking place. Integration of land use change modelling and impact assessment models will give more insight in effects on natural resources.

Further scope is expected by combining the presented method of land use change modelling on basis of actual land use, with other approaches such as interactive linear-programming models and studies exploring yield potentials.

8.5. Summary of the tool

Tools Fact Sheet	
Name	**The CLUE modelling framework**
Version	**2.0**
Development	**The CLUE group of Wageningen Agricultural University, consisting of: A. Veldkamp, J. Bouma, L.O. Fresco G.H.J. de Koning, K. Kok, P.H. Verburg A.R. Bergsma**
System requirements	**MS Windows (3.1 or 95)**
Links with commercial software	**Statistical analyses are executed with SAS 6.11 (but other statistical packages can be used). The land use change model is programmed in C. Data are prepared by Arc/Info, ArcView or Idrisi, and visualization is possble with different grid-based GIS packages,**
Documentation	**Version 1.2 (written in Pascal) has been documented by Schoorl *et al.* (1997). Documentation of version 2.0 (written in C) is in progress.**
Objectives	**CLUE has been developed for the spatially explicit multi-scale modelling and analysis of land use change**
Data Requirements	**Georeferenced biogeophysical and socio-economic data that cover the whole study area and match the spatial resolution of the study.**
Boundary conditions	**Spatially, the lower boundary is that of the basic grid cells, of which the size is determined by the resolution of the input data (for Costa Rica 7 by 7 kilometers, for Ecuador 9 by 9 kilometers), while the upper boundary is the national level. The time horizon set for future scenarios is 20 years.**

Future developments	**The model version discussed here, lumps individual crops to bigger land use type groups. Future developments of the model include a crop (management)-specific approach and the application of spatially specific attainable yields. Other planned developments are the modelling of biophysical landscape processes, further implementation of socio-economic processes, and the use of remote sensing images.**
Homepage	**http://www.gis.wau.nl/~landuse1/clue.html**

References

Houghton RA, Lefkowitz DS, Skole DL 1991. Changes in the landscape of Latin-America between 1850 and 1985. I. Progressive loss of forests. Forest Ecology and Management, 38: 143-172

Koning GHJ de, Kop PJ van de, Fresco LO 1997. Estimates of sub-national nutrient balances as sustainability indicators for Ecuadorian agro-ecosystems. Agriculture, Ecosystems and Environment 65: 127-139.

Koning GHJ de, Veldkamp A, Fresco LO (forthcoming). Land use in Ecuador: a statistical analysis at different aggregation levels.

Schoorl JM, Veldkamp A, Fresco LO 1997 The conversion of land use and its effects (CLUE-CR). A regression model applied to Costa Rica (Pascal version 1.2). Quantitative Approaches in Systems Analysis 8, PE and AB-DLO, Wageningen

Skole D, Tucker C, 1993 Tropical deforestation and habitat fragmentation in the Amazon: satellite data from 1978 and 1988. Science 260: 1905-1910

Turner BL II, Ross RH, Skole D 1993 Relating land use and global land cover change. IGBP report no. 24, HDP Report no. 5.

Turner BL II, Skole D, Sanderson S, Fischer G, Fresco LO, Leemans R 1995 Land-use and land-cover change, Science/Reserach plan, IGBP report no. 35, HDP Report no. 7.

Verburg PH, Veldkamp A 1997 Modelling the spatial pattern of land use change in China. Proceedings Wageningen-China-workshop AB-DLO, May 97

Verburg PH, Koning GHJ de, Kok K, Veldkamp A. 1997 Quantifying the spatial structure of land use change: an integrated approach. ITC-journal, special edition: proceedings of the Conference on Geo-information for Sustainable Land Management

Veldkamp A, Fresco LO, 1996 CLUE-CR: an integrated multi-scale model to simulate land use change scenarios in Costa Rica. Ecological modelling, 91: 231-248

Veldkamp A, Fresco LO, 1997[a] Exploring land use scenarios, an alternative approach based on actual land use. Agricultural Systems 55: 1-17

Veldkamp A, Fresco LO, 1997[b] Reconstructing land use drivers and their spatial scale dependence for Costa Rica (1973 and 1984). Agricultural Systems 55: 19-43

9. Discussion

9.1. Introduction

The discussion and conclusions are a reflection of the discussion during the workshop. Input of all the participants has lead to this Chapter. Different tools have been presented during the workshop. At the last day of the workshop short presentations were given of other tools that have been developed:

- SISDA[1]: a software package developed in Brazil (Chapter 4). It is a database of soil, climate and farms throughout Brazil, tied to a simple water balance model. Designed primarily to help farmers increase water use efficiency under irrigation. SISDA has been well-received by farmers, researchers, and extensionists. SISDA, which has a well-designed user-friendly interface, provides a good example of the benefit derived from having professional programmers work alongside the scientists.
- ICIS: The International Crop Information System software includes a database recording all genetic components of a breeding program as well as field trial results. ICIS represents an ongoing effort by several CG centers to develop a flexible yet standard database.

Although the workshop did not aim to be complete, the tools are generally seen as a good reflection of tools that are available for the analysis of land use options. All the tools rely heavily on information technology. However, not all the tools will yield automatically alternative land use options. They have to be seen in a broader "research chain". Within the context of the "research chain" links to decision makers and stakeholders are crucial. These links are not always clear and in general there is very little to warm a politician's skeptical heart. Improved possibilities are required that:

- explain the models,
- indicate boundary conditions and data requirements,
- provide user interface (and the interfaces should be standardized à la Bill Gates), and
- indicate possible research chains for the user through clear flow charts.

Workshops like this one can be extremely useful for researchers to get an overview of the tools that are available. Different types of courses can be organized to present tools for land use options (Table 9.1). At the same time, the needs for future lines of research can be identified during the workshops. We have to deal with a wide array of users and uses of the agricultural land use/management tools (Figure 9.1) and need a clear map to find our way.

Table 9.1 types of courses for tools to assess land use option

Objective	Awareness	Technician	Users	Decision maker
Nr of tools/models	Many	1-2	1-2	1
Content	Examples, limitations, objectives	Hands-on, Full insight Including source code?	Application oriented, Examples, Limitations	Emphasis on research chains, possibilities, quality and costs
Duration	1 week	1 week	2 weeks	1 day

[1] A description of SISDA has been included in the proceedings (Chapter 8)

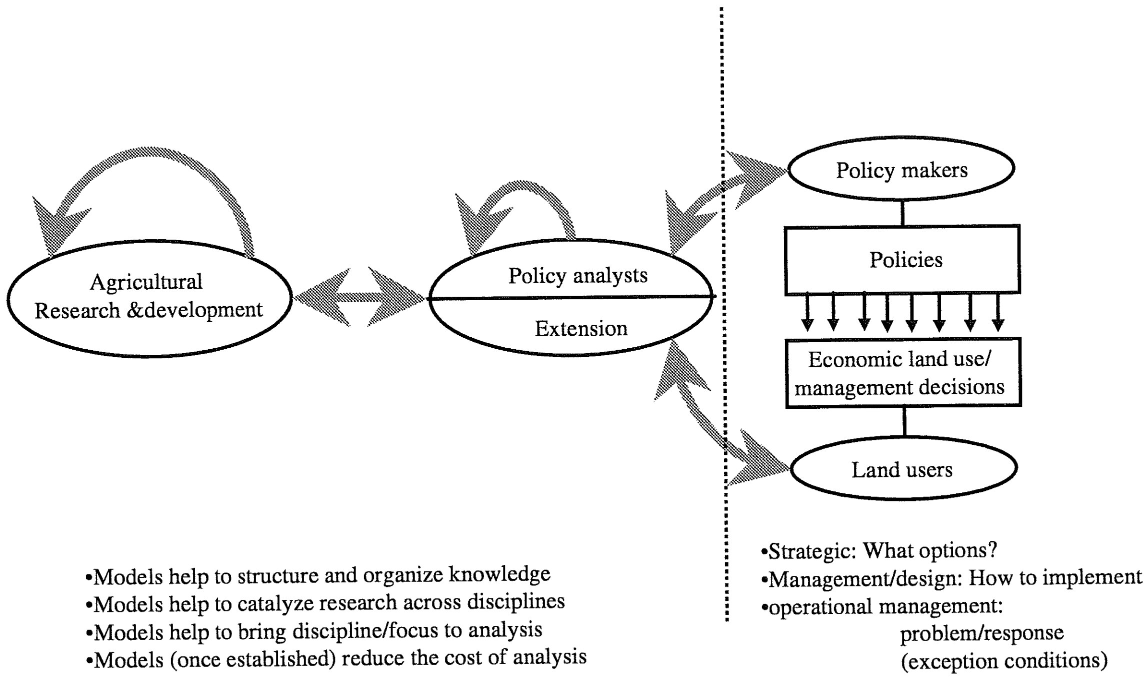

Figure 9.1 Agricultural land use/management models: users +uses

9.2 Discussions around the different presentations

9.2.1. Introduction

Although the introduction mentions four different categories of models, they are not all represented this week. The policy model (Category 4) is missing. It should be represented next time, as it is so closely related to the question whether certain land-use options can be realized.

The concept of the "research chains" and the associated spinoff in terms of "research negotiations" is judged positively by participants and is seen to have a high potential in designing and guiding research efforts. However, there is a need for clear definitions of "objective functions" to guide the selection process.

Temporal aspects are not represented explicitly in the "research chain" approach. The research chains represent temporal change implicitly by including multi-year simulations in K3-K5 approaches.

The seven steps to be taken when designing and executing research projects include now model consideration before data selection. However, the point is made that on farm level (limited) available data should guide the selection of models.

More empirical, qualitative approaches are used at higher scale hierarchies, while more deterministic and quantitative approaches are used at lower scale hierarchies. However, this is not necessarily always the case and a flexible approach needs to be taken when designing a research project.

9.2.1. BanMan

The BanMan case shows that simulation modelling at the K5 level can be an effective element of a practical decision support system, even though it is not yet possible to simulate the growth of banana.
Three crucial issues were identified by the manager of the Rebusca farm:
(i) Estimates of the yields, three months before harvest so that container capacity could be reserved,
(ii) adjustments to biocide and fertilizer applications to avoid excessive leaching, and
(iii) identification of areas within the farm that stayed behind in production
To address (i) the number of stress days during the first six months of crop development was calculated with the K5 simulation model LEACHM at the pedon level. This number could be related to yield. For (ii) LEACHP was used to identify periods with relatively low risk for leaching and areas with higher risk for leaching.For (iii) the information system was used to compare measured yields for different soil types at a given date and to define areas with deviations from the average, requiring on-site tests to identify causes.
The question was raised why soil types were used. Why not separate soil factors to yield, avoiding early stratification of the data yielding rigidity in the system, well known from soil survey. It was pointed out that approaches (i) and (ii) used calculations for point data based on augerings for the soil information system. Only (iii) used soil units, each one with identical functioning in terms of soil water and nutrient regimes, that were based on simulations for each of the borings. This was not a classical soil survey!

Relating basic soil data (texture, drainage etc.) rather than soil units to yield is difficult, because yields are not obtained for points but for areas of land. Interpolation techniques can be applied to extend the point data, but this is rather cumbersome. Besides, the functional soil units allow effective communication with the farmer!

This approach can be applied, in principle, to other cropping systems as well, requiring point observations on soil, yield data and close interaction with stakeholders to define key management issues. The latter are bound to be different all the time for different production systems in various socio-economic settings.

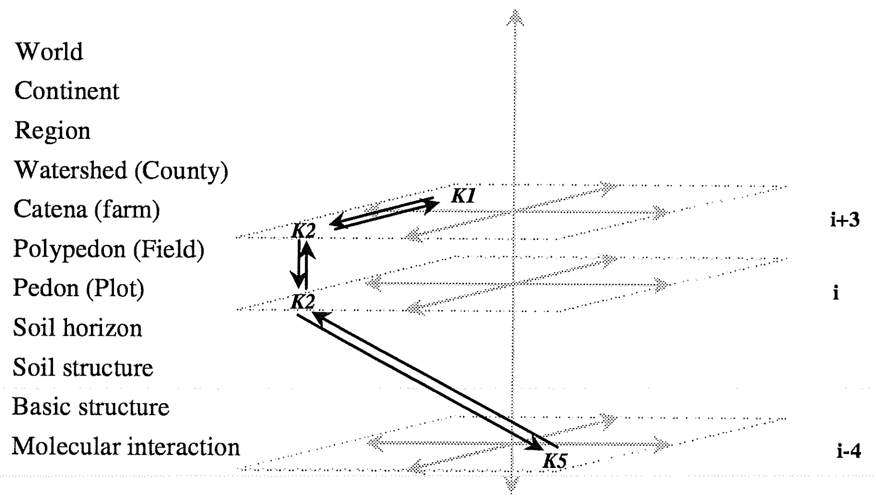

Figure 9.2. Research chain of BanMan

9.2.2. DSSAT

A case was made for using simulation modelling with the DSSAT package (K4level) in the context of agronomic field experiments. The design of the experiments can be affected by focussing on relations that turned out to be most important in simulation runs while results can be more easily extrapolated to other areas.

As presented, the model is seen as a research and education tool. It was pointed out that research was indeed focused on a practical problem in Brazil and that this link needs to be emphasized to avoid the incorrect impression that research is an objective in itself. Both decision support and exploration of options for future land use were addressed in the case study.

Questions were raised as to the relevance of using this rather complicated model in data-poor environments in marginal areas. Why not make use of simpler models without e.g. daily time steps. It was pointed out that this observation was in link with the "research chain" concept of Bouma (1997): compare very simple, "quick and dirty" techniques with ever more sophisticated techniques in terms of cost/benefits. Always consider the type of problem being studied and always keep communicating with the stakeholders. An example from Brazil showed how a government request on water use was handled rapidly by using a simple model (Chapter 8). They feel that after this initial success the door is open for more detailed work, which would not have been the case when this more detailed work would have been proposed right away.

Are K4-K5 models indeed "research tools" or do they simply recycle old knowledge" They are felt to be indispensable when studying production systems using data of different disciplines, as they make interdisciplinary communication possible. In this sense they are excellent "research tools". Increasingly, we not only look at production but also at environmental quality as we study sustainable land use. Leaching of biocides, for example, is difficult to "estimate" nor can tradeoffs between production and environment be made very well with "quick and dirty" methods. They do not stand in court! Of course, models can only reflect and schematize existing know-how. As demonstrated in this case study, they can help guide research into profitable directions.

Models are useful to make research assessments. Trends are often (but not always) as good as absolute levels.

Models are seen as effective tools to link agro-ecology with economics. Indeed studies at increasing level of detail (see above) would be good to establish the most effective level of communication.

Experts from Costa Rica reported a feeling that models are still being considered to be academic. Policy makers hesitate to accept them. Models tend to get bigger and bigger and thereby less and less realistic for applications in data-poor environments. A plea is made for simplicity and for continuous interaction with the stakeholders: "What is the question?". An example from a study in Talamanca (Costa Rica) indicated that the original hypothesis of research was changed dramatically after interaction with a group of stakeholders, in this case Indians.

Serious questions were raised as to real contributions of models to science and to a basic understanding of biophysical processes. Claims to this effect should be better documented.

This was a workshop on "information technology as a tool to assess land use options in space and time". This was not a workshop on modelling. Perhaps a stronger focus in this particular case on the problem to be studied would have been useful, rather than a technical demonstration of the indeed impressive possibilities of the DSSAT system. Sometimes, land use options can be derived well with expert knowledge and common sense with no (K3 to K5) model input. See examples in Bouma (1993)

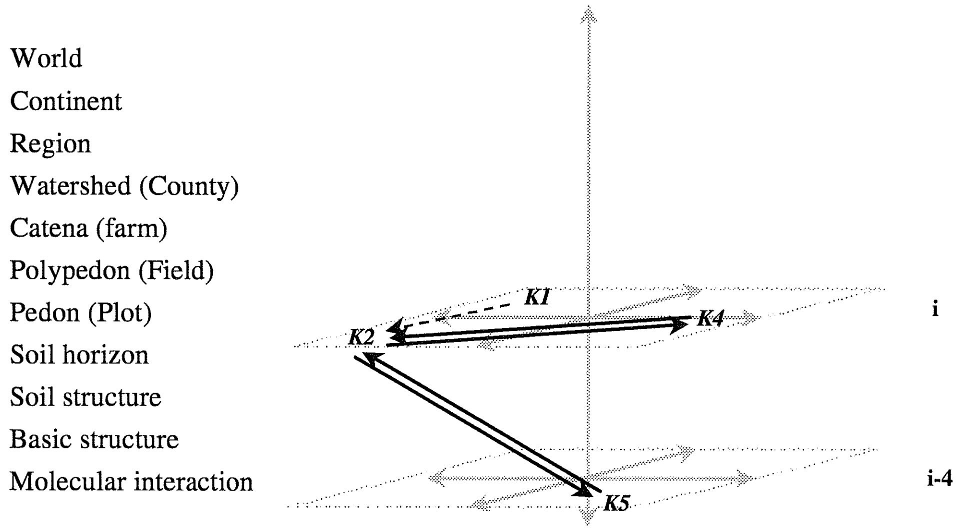

Figure 9.3. Research chain of DSSAT

9.2.3. LINTUL

Working at world level implies that many heterogenities within grid cells are not considered. Working smaller scales, such as watersheds is difficult, because lack of appropriate data. Rather than use "fixed" zones, it may be preferable to use "dynamic" zones with a focus on the effects of different technologies rather than on given commodities. Increasing the availability of meteorological data within the watershed is possible through, for instance, interpolation between weather stations and by correcting temperatures for altitude.

Comparing LINTUL modelling with DSSAT, we find that the former is more focused on modellers while the latter offers more facilities for end users. The reason why LINTUL is applied was initially explained using two examples: agro-ecological zoning on a global scale and ideotyping. Later it was pointed out that management decisions as to which variety to plant and whether to plant late or early, can be defined in decision support systems at the field and farm levels. Of particular interest is the quantitative expression of risks, focusing on frost and drought.

Farmers have developed many rules of thumb when growing potatoes in the challenging Andean environment. These are not considered in the model as presented. Would it not be advisable to take these expert rules into account and fit simulation in at points in the decision chain where this is most relevant? This would be so, but the application of the model goes beyond management decisions as it also addresses effects of alternative land-use scenarios. For instance: what happens when less water becomes available for irrigation due to urban demands which always prevail: do we plant fewer hectares of potatoes or do we use earlier cultivars.

Does the model deal with the effects of accumulated stress ("hardening")? No, it can only be done by introducing different genotype properties.

Who decides about future research on the model? Two lines are distinguished here: (i) basic research to calibrate the model for diverse environments, (ii) adding features required by users. The latter presents a potential problem: what was initially a simple model may grow out of control by adding many subroutines. A clear need is seen to focus on obtaining a robust model that catches the physiology of the plant.

The question was raised whether potential productions calculated by the SUBSTOR potato model in DSSAT and LINTUL are the same? The models differ in their basic structure. Whether model results are similar is not clear, but several workshops held in the early nineties suggest large variabilities among modelling results using the same datasets. Rather than comparing models using a single dataset, it is better to focus on specific applications and choose the proper model to obtain answers. Current work on land quality indicators by the World Bank considers real versus potential production as a quality indicator. As scientists we cannot afford to keep quarreling about different outcomes of different models and complain that we do not know enough, but we should decide on one suitable method considering the type of question being asked. This is being done.

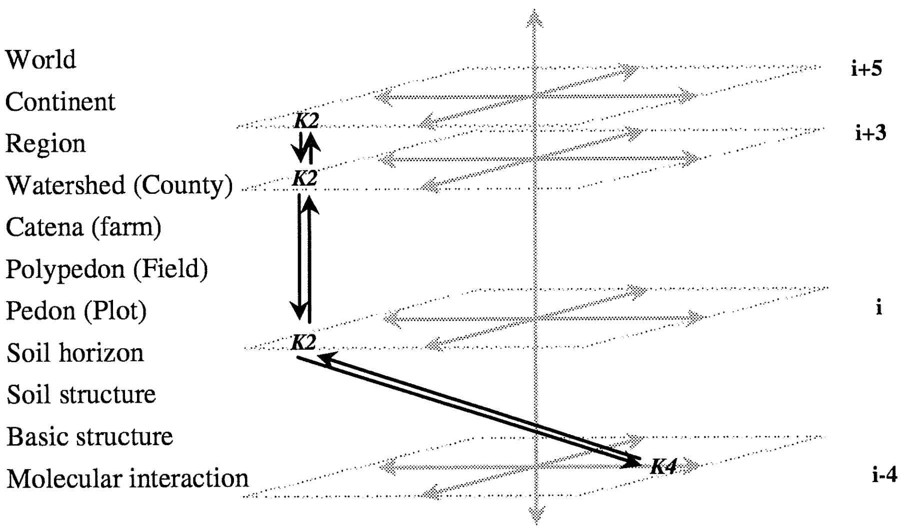

Figure 9.4. Research chain of LINTUL

9.2.4. *The Tradeoff model*

The Tradeoff model has a relatively short time horizon and data requirements (mainly in terms of survey data) are high. The applicability of the model relies strongly on the fact whether the derived distributions and relations can be extrapolated both in space and time. Although, this has not been studied so far, it is suspected that extrapolation can be done. A case study carried out in the Carchi area (for which the model has been developed originally) should evaluate this.

The core of the Tradeoff model is complex and difficult to understand. It is, therefore, likely that the model will be used as a black box This kind of problems is not unique for the Tradeoff model. Many simulation models, although the basic principles of crop growth are perhaps better known, have similarly complex source codes. It is essential that both error ranges and boundary conditions of the models are well documented.

The relations and distributions in the Tradeoff model are based on surveys, and thus, as a result on actual land use. It is questioned whether the model can consider the introduction of new cultivars and/or technologies. In principle a number of factors represent the development of agriculture and indirectly the input/output ratios or, in other terms, input use efficiencies. With these factors the sensitivity for new technologies can be evaluated.

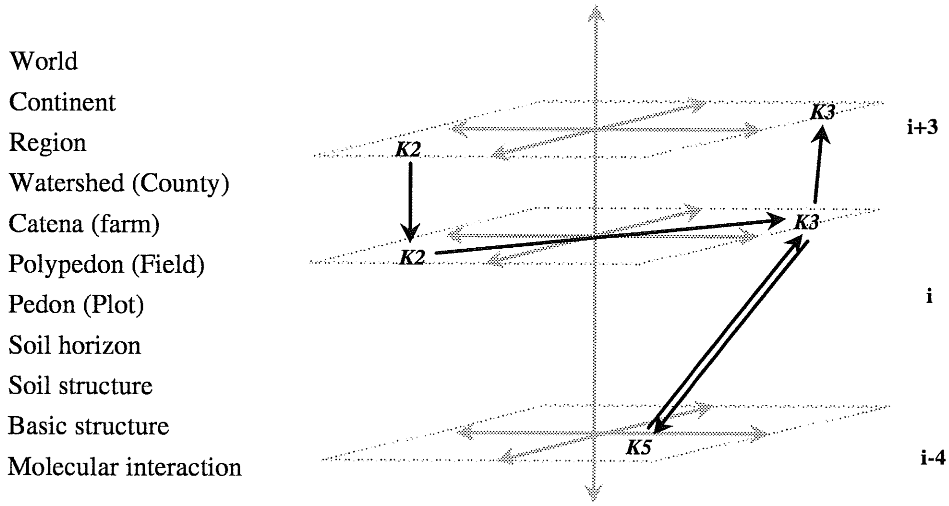

Figure 9.5. Research chain of the Tradeoff model

9.2.5. USTED

People from the region see the need for tools like USTED to *e.g.* evaluate alternative land use systems (for example systems of agroforestry and organic farming) in an *ex ante* manner. However, serious limitations of time are being experienced. Policy makers need to take the decisions <u>now</u>. In many cases there is no time for an extensive study of a particular region. Within Costa Rica groups exist that deal with *e.g.* organic farming and the evaluation of double purpose systems. The tools should be made available to these organizations. It is stressed that a multi-disciplinary team is required for the management of the USTED system. In Ecuador an interdisciplinary team is currently being trained since 1991 by the government for the application of agricultural models. This might a step that should be followed in other countries for the application of complex models. Only then models can be applied in a sound way that also allows for a proper analysis of the results and the transfer (making use of information technology) to the policy makers.

The use of linear programming model implied the description of a large, but limited, number of agricultural production systems. Currently these systems are described statically by a number of relevant technical coefficients. It is questioned whether one should not incorporate, which does not allow for distribution function. It is stressed that the techniques exist to do so, but this has not been elaborated so far in the USTED methodology.

Models like USTED do not consider the scale level where real decisions are being: the farm. This is seen as a weak point in the methodology and therefore linkage is also foreseen in the future with researchers developing policy models at the farm level. Serious constraints are the tow scale levels whereas a procedure for upscaling from the farm level to the regional level is still lacking. However, before a real linkage between the different tools can be made some procedures to scale the policy models up to the regional model.

USTED does not allow for the analysis of actual trends *e.g.* the degeneration of pastures in Latin America. It explores alternative possibilities in the future. Actual land use and from actual land use towards new forms of land use are not included.

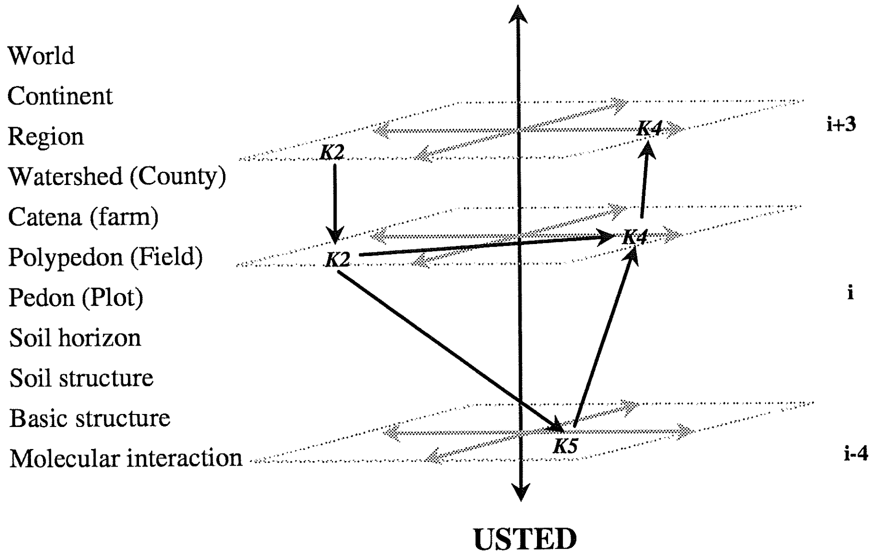

Figure 9.6. Research chain of USTED

9.2.6. CLUE

There is a question about the use of step-wise regression which assumes a certain degree of independence of a variable, which is certainly not always the case. The stepwise procedure in CLUE is a standard statistical selection procedure, testing for multicolinearity. The discussion elaborates on possible approaches for statistical analysis:

- constructing a theoretical model → statistical analysis
- constructing a base set of variables on basis of possible relations with land use and land use → stepwise regression analysis.

The latter is used in CLUE, because no *a priori* models are available for integrated assessment of biophysical as well as socio-economic factors driving land use at different scales. The same holds for economic variables, which can be incorporated. Further development of these methods can support theoretical frameworks that can subsequently be incorporated in CLUE.

The point is raised that the procedures in CLUE are empirical, *ad hoc* and do not present a clear hypothesis that is being tested. A large body of economic theory is available describing relations between land use and land value, effects of different demand, etc. When studying biophysical processes, laws of physics are respected. Dealing with land use, the same goes for economic laws. Still, after much discussion and hands-on exercises with the software, the conclusion is reached that interesting results are obtained at different scale levels. Bio-physical and socio-economic variables and bio-physical have to be taken into account in an integrated spatially explicit way taking into account multi-scale dynamics. This work demonstrates that different land use drivers – as defined by objective statistical procedures – operate at different scale levels. Further development will include incorporation of more economic considerations, and ongoing work in Costa Rica may provide a good venue.

CLUE work was initiated by science-driven IGBP activities and not by stakeholders. However, contacts are being established with policy makers.

The question was raised why expectations about the effect of certain land-use drivers were not tested. Now, the process is mechanistic and results can only be accepted. The suggested approach has been tested but was not more successful than the objective one that was ultimately followed.

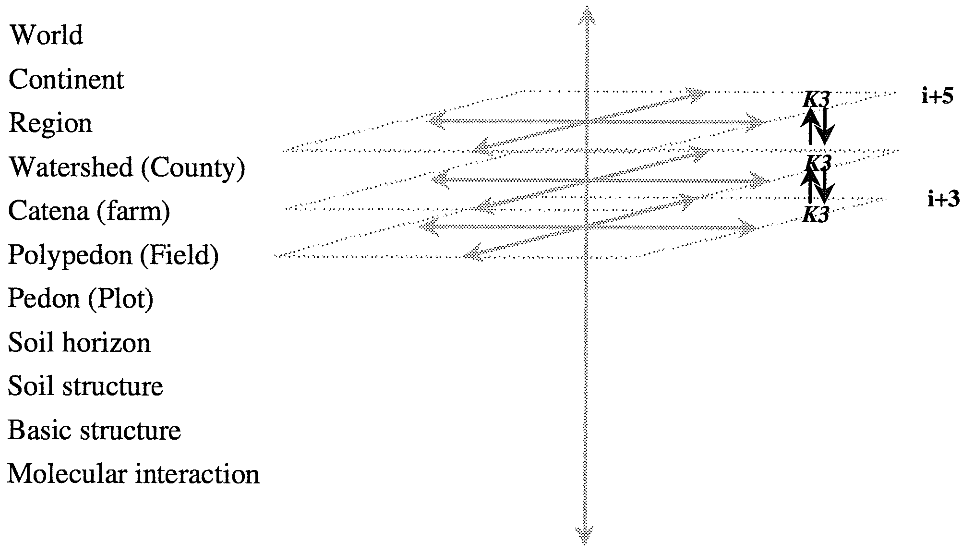

Figure 9.7. Research chain of CLUE

9.3 General discussion

In the general discussion several aspects related to information technology and the application of systems analysis were brought forward.

The systems should be user-friendly. Only then, the systems will be accepted and implemented for the analysis and evaluation of agricultural land use and management.

As a result of the complexity of the systems, data availability is in many cases a serious constraint. The generation of complex databases with reliable data of recent date and with sufficient spatial coverage requires a lot of resources. In many cases, policy makers do not want to spend many resources and they certainly do not have the time. They want answers now and not after a couple of years. Although of course data can be generated, the availability of a number of basic data at the national level (e.g. soil survey, census data, production data) is the responsibility of governments and can play an important role in the generation of additional more detailed data. In countries like Ecuador consortia are created (e.g. FUNDAGRO: *la Fundación para el desarrollo Agropecuario* and REPAAN: *Red de Pastizales Andinos*) to get a critical mass of scientists that is working on similar type of analysis. Cooperation of scientists is not only extremely useful to deal with the problems of data availability, it also improves the discussion during the development of models and tools.

For the application of systems analysis, the availability of simple, more general, K2-3 type of models is essential. Those models may provide results soon, and as a result may attract the attention of the stakeholders. The development of SISDA in Brazil and the application of ALES in Costa Rica are good examples.

Model development is an extremely useful process and it enables researchers to learn the basics about systems development. Experiences from e.g. *la Universidad Catolica de Chile* learn us that it is an essential training process. Just transferring ready-made finished models is certainly not a good procedure.

Priority setting is extremely important. Where are we going with our systems analysis and model development. During the workshop several observations were made from scientists of the Latin American countries with respect to important issues that need to be tackled. Some examples:

Bolivia:

- What are the options to rehabilitate degraded lands (as a result if erosion, water availability)
- What are the options for the diversification of the agricultural sector?
- How can we reduce the risks as a result of weather extremes?
- The definition of a set of minimum boundary conditions for sustainable land use?

Peru:

- There is a need for expert systems that support farmers in their decisions. Most of the knowledge is already available as the result of a long process of trial and error by the farmers themselves. A compilation of this knowledge and the incorporation of a number of new concepts (sustainable development) is required in the form of an expert system (like the case of SISDA).
- Current developments require the development of well structured databases at institutes to enable them to use simulation models.
- Problem definition and the subsequent analysis and search for solutions should be a parallel process of interaction with the stakeholders The simulation models are a tool that play a role in the analysis but are certainly not an objective.

Costa Rica

- Currently simulation models are only available for a limited number of crops or agricultural systems. Approaches need to be find to deal with more complex agroforestry systems and forest management systems.
- It is essential to validate the models under a wide range of agro-ecological conditions.

It was recognized that problems occur when one works on software development within an academic framework. It is not always easy to reconcile the development of a useful and practical application with the need to publish academic article. It is suggested to restructure academic priorities so that software tool development can emphasize practical applications.

9.4. The tools in summary

Model	Declared Land use/management scope	Implementation strategy	Objective function	Benchmark control	Primary units of analysis			Commodity	Technology
					Spatial/bio	Decision makers			
						#	Level		
BanMan	Improved land use management	Precision agriculture	Max. returns	Yields	Plot	1	Plot	1	1
DSSAT	Predict technology response	Process simulation	Best fit (techn + expert)	Controlled biophysical experiments	Unit area of plant production	n.r.	n.r.	≈ 10	$N_{(actual)}$
LINTUL	Predict technology Response	Process simulation	Best fit	Theoretical potential yield + modifiers	Unit area of plant production	n.r.	n.r.	1	-
USTED	Generating land use configurations under alternative scenarios	Regional optimization	Maximize value added	-	Units of enterprise outputs	1	Region	$N_{(actual\ and\ potential)}$	. $N_{(actual\ and\ potential)}$
TradeOff	Identify tradeoffs	Stochastic land use and management responses	max prod min health effects min leaching	Actual land uses and man practices	Plot	$N_{farmers}$	N_{plots}	$N_{(actual}$	$N_{(actual)}$
CLUE	Predict land use dynamics and driving factors	Regional development	Best fit (stat)	Past land use (dynamics)	Arbitrary nested scales	n.e.		$N_{major\ LU\ classes}$	n.r

Figure 9.7 Overview of the different tools (n.r.: not relevant; n.e.: not explicit)

10. Conclusions

1. Assessing land use options in space and time requires much information and data. Availability of information technology is essential to allow data manipulation and interpretation. Technology tools include database management systems, GIS, Remote sensing, expert systems and simulation models with different degrees of complexities. Selection of the proper tools is a key issue when studying land use options. Simulation models are excellent tools and they have a clear niche in the reasearch chains to study land use options. However, they should also be seen within such a context and not become the objective.

2. Definition of land use options should proceed in close consultation with stakeholders to allow relevant selections from the very high number of options that can theoretically be derived. Ideally, consultation should result in an integrated, joint effort.

3. Depending on the scope of the problem to be studied, a selection should be made of the type of research to be pursued:
   - effects of using current land use to assess future developments (*e.g.*CLUE);
   - exploration of "windows of opportunity" (*e.g.* DSSAT, LINTUL, USTED);
   - identification of policy options to realize particular attractive options (Tradeoff model), and
   - development of decision support systems for any given land use system (*e.g.* BanMan, DSSAT).

   The sequence of these four approaches is logical and can be pursued to arrive at land use options that are realized in practice.

4. Information needed to arrive at realistic land use options is derived from user expertise, expert knowledge and simulation models of varying complexity. This information can be classified along two scales, one ranging from qualitative to quantitative and the other from empirical to mechanistic. Research chains can be visualised when this information is plotted as a diagram using and connecting different scale levels. Thus the selected research procedure is visualized and alternative procedures can easily be derived. Scale diagrams have been derived for the various studies presented during the workshop.

5. A strong concern has been expressed that the presented models are too complicated and that inadequate attention has been paid to quick and simple procedures that may work well for a given problem. Indeed, it may be advisable to start any study with the most simple procedure showing its potential and, particularly, its limitations. The latter can be overcome by applying more sophisticated methods. The stakeholder is bound to be willing to pay for such methods when he sees the limitations of the simple methods ("Research negotiation").

6. The red thread through all presentations has been the implicit objective of improving land use practices to the extent that sustainability criteria are met (FAO considering the following elements: stability of production; high product quality; acceptable risks; acceptable soil and water quality and socio-economic implications). Land use systems are sustainable when they operate within defined indicators and threshold values for each element.

7. The following seven steps are recommended when studying land use options in space and time:
   - Problem definition in interaction with stakeholders including definition of the unit of analysis.
   - Selection of research methodology (*e.g.* exploratory; predictive; policy oriented and decision support) and identification of participating disciplines.
   - Model development, considering scale hierarchies.
   - Establish data requirements to be satisfied with existing data and new data collection.
   - Model application.
   - Quality assessment: accuracy and reliability; risk.
   - Presentation of results: due attention to role information technology.

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Annex 2. Workshop programme

Monday, September 29

9:00-9:30	Words of welcome by the organizing committee
9:30-10:00	Official opening of the workshop by Dr. H. Zandstra, Director General of CIP
10:00-10:30	Coffee break
10:30-11:30	Workshop introduction by Dr. J. Bouma, Scientific Director of the C.T. de Wit Graduate School for Production Ecology
11:30-12:00	Organizational aspects of the workshop

BanMan: A decision Support System at farm level.

J.J. Stoorvogel (C.T. de Wit Graduate School of Production Ecology)

13:00-13:30	Introduction and application
13:30-14:00	Introduction to the exercises
14:00-16:00	Hands-on exercises
16:00-17:00	Concluding remarks and discussion

Tuesday-September 30

DSSAT: a decision Support System at field level.

W. Bowen , P.Wilkens (CIP/IFDC)

8:00-8:45	Introduction and application
8:45-9:30	Introduction to the exercises
9:30-12:00	Hands-on exercises DSSAT-shell
13:00-16:00	Hands-on exercises application of DSSAT
16:00-17:00	Concluding remarks and discussion

Wednesday- October 1

Lintul - Potato: a potato simulation models for agro-ecological zonation,, ideotyping and risk assessment

R. van Haren and A. Haverkort (AB-DLO)

8:00-8:30	Introduction and application
8:30-9:00	Introduction to the exercises
9:00-11:00	Hands-on exercises
11:00-12:00	Concluding remarks and discussion

CLUE for modeling land use dynamics.

F de Koning (Wageningen Agricultural University)

13:00-13:30	Introduction and application
13:30-14:00	Introduction to the exercises
14:00-16:00	Hands-on exercises
16:00-17:00	Concluding remarks and discussion

Thursday- October 2

USTED: exploratory modeling of land use scenario's, an example for the livestock sector

B. Bouman and H. Jansen (REPOSA)

8:00-8:45	Introduction and application
8:45-9:30	Introduction to the exercises
9:30-12:00	Hands-on exercises PASTOR
13:00-16:00	Hands-on exercises scenarios
16:00-17:00	Concluding remarks and discussion

Friday-October 3

The tradeoff model: agricultural production versus environmental quality.

J Antle (Montana State University) and

J. Stoorvogel (C.T. de Wit Graduate School for Production Ecology)

8:00-8:45	Introduction and application
8:45-9:30	Introduction to the exercises
9:30-12:00	Hands-on exercises modules
13:00-16:00	Hands-on exercises tradeoffs
16:00-17:00	Concluding remarks and discussion

Saturday-October 4

AM Evaluation of results by course participants: relations between the various procedures and discussion of future research needs.