Formalizing agro-ecological knowledge for future-oriented land use studies

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Stellingen

1. Ingenieursbenaderingen zijn onmisbaar bij het systematisch en doelgericht identificeren van productie-opties op perceelsniveau ten behoeve van een gefundeerde afweging van verschillende vormen van landgebruik.

   Dit proefschrift

2. Kennishiaten die het ontwerpen van toekomstgerichte systemen bemoeilijken dienen de disciplinaire onderzoeksagenda te sturen.

   Dit proefschrift

3. De geringe beschikbaarheid van gegevens in ontwikkelingslanden is een grote belemmering voor algemene toepassing van ingenieursbenaderingen.

4. Zwaardere maatschappelijke randvoorwaarden zullen het belang van ingenieursbenaderingen in het onderzoek groter maken.

5. Het onvermoeid vasthouden aan de term ‘low and high-input agriculture’ in discussies rond landbouw, milieu en economie degradeert iedere poging tot een heldere probleemanalyse tot een discussie over middelen in plaats van doelen.

6. Niet-grondgebonden landbouw hoort thuis op het industrieterrein en niet in het landelijk gebied.

7. Het afronden van een inburgeringscursus is moeilijker dan het voltooien van een proefschrift.

8. Voetbal op kunstgras is als landbouw zonder grond.

Stellingen behorende bij het proefschrift van Huib Hengsdijk:
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Abstract

Identification and ex-ante assessment of alternative land use systems is increasingly important to develop systems that are able to fulfill multiple and possibly conflicting needs of mankind.

This study contributes to the development of a formalized approach to identify and engineer future-oriented land use systems at the field level enabling the systematic exploration of land use options at farm and regional level. Case study data from the Atlantic zone of Costa Rica and West Africa are used to develop, test and elaborate the required approach, and to implement the approach in two operational tools.

A generic procedure is presented consisting of three steps: (i) goal-oriented identification and design of land use systems, (ii) quantification of biophysical production possibilities and (iii) identification of the optimal mix of inputs required to realize production possibilities. Typically, this approach addresses the future and explores *possible* alternatives and not *plausible* or *probable* developments. The approach is based on the integration and synthesis of process-based knowledge of physical, chemical, physiological and ecological processes involved, and empirical data and expert knowledge regarding agronomic and livestock relationships using a variety of numerical tools. The procedure allows to efficiently engineer future-oriented land use systems that are consistent with the objectives at stake while no options are excluded in an early phase of development.

Consequences of various sources of uncertainty, i.e. in process knowledge and data, and in temporal variation, are made explicit for inputs and outputs of engineered land use systems. These analyses enable a better management or reduction of uncertainty through the identification of alternative systems with smaller uncertainty margins, and identification of research aimed at a more complete understanding of involved processes.

The existing conceptual engineering framework is expanded with an approach that allows taking into account non-equilibrium soil N-conditions. The development of N-dynamics of various crop rotations is made explicit, so that their long-term effects on the productive capacity of land use systems can be accounted for in making decisions.

Implementation of the approach in two operational tools shows that formalization of agro-ecological knowledge is a means to improve communication among research disciplines, empirical and theoretical research, and stakeholders and researchers. The tools can be used stand-alone and enable the exploration of land use options at farm and regional level.

Keywords: agro-ecological engineering, land use system, modeling, uncertainty, temporal variability, Costa Rica, West Africa.

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Since my first job, I have been working in different settings on land use analysis and, specifically, on the design and exploration of land use systems. Many colleagues have contributed to the development of my scientific career, eventually resulting in this thesis. Particularly, I want to acknowledge (in alphabetical order): Evert-Jan Bakker, Bas Bouman, Wim van Dijk, Gert-Jan van Dongen, Jan Ketelaars, Gideon Kruseman, Henk van Latesteijn, Hans Jansen, André Nieuwenhuyse, Peter Roebeling, Wim Quak (†), Dirk Scheele and Rob Schipper. I am very grateful to them! Special thanks go to Cor Langeveld and Jim van Laar for valuable discussions during the last stages, to Gon van Laar for sharing tips and tricks on the layout of this thesis, and to Olga Tromp for designing the cover.

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Chapter 1

General introduction

1 General introduction

1.1 Introduction

Agriculture faces important challenges in the 21st century. In the developed world, consumer attitude to food and its production process changes drastically. Consumers demand food production that takes into account environmental and nature interests, and the way animals are reared and kept. Food safety, which is closely related to product quality and the production process, is high on the public agenda. These developments require agriculture that uses external inputs judiciously and pays more attention to environment, nature and animal welfare. Moreover, farmers produce in a global economy market with declining price supports. Therefore, farm incomes are under pressure and are a poor basis for investments required for adjusting farming practices to these new demands. At the same time agriculture, especially in developing countries, is challenged to feed a rapidly growing population that increasingly demands a more luxurious diet. Both, the number of people to be fed and the changes in consumption pattern, require that the low agricultural production in many of these countries must be increased considerably in a sustainable way. However, any growth in production must be attained in a situation of an increasing scarcity of land and water resources, which are also claimed by rapid urbanization. Their exploitation requires, therefore, a well-balanced consideration of multiple interests.

Both in developed and developing countries, agriculture faces an array of interrelated objectives and constraints, which call for development of new systems. Such revision of existing agricultural systems must explicitly take into account the multiple and possibly conflicting needs of mankind in the 21st century. This means that the wide range of objectives related to land use must be at the center of the quest for finding widely acceptable systems. The variety and nature of problems are complex and can neither be solved by a single discipline nor by changes at only one particular scale, for example, field, farm or region. They require research efforts in which knowledge and information from different viewpoints (e.g. production, environmental and socio-economic) and scales are integrated and synthesized to explore alternatives. At the start of a new era, with complex questions and high demands, generic concepts and methods are needed to synthesize existing and compiled agronomic knowledge for the benefit of the design and exploration of systems that can fulfill future requirements of mankind.

1.2 Agro-ecological engineering

Traditionally, agricultural research has a firm rooting in empirical and statistically valid dose-effect experimentation. A classic example are the numerous field experiments in which the effect of different fertilizer levels on crop production are analyzed to recommend optimum fertilizer strategies to farmers. Due to variability in weather and soil conditions, several years of experimentation at various locations are often required to identify suitable fertilizer strategies. Since human memory, agricultural research has centered on expensive and time-consuming field experiments to improve parts of the system. In the 1960's, the nature of agricultural research changed drastically with increasing understanding of the processes involved and the possibilities to integrate these insights using computers. They allowed synthesis of detailed process-based knowledge in simulation models in order to explain the functioning of crops. Since then, simulation models of all kinds of agro-ecosystems have been developed and used for explanatory purposes and practical applications. Only until recently, such models are sufficiently accurate to be used for predictive and explorative purposes.

The problems agriculture is facing in the 21st century are interrelated and highly complex, involving agronomic, economic, social and environmental objectives. Disentangling such relationships using experiments only is almost impossible, as many factors have to be varied simultaneously. In addition, many of the problems exceed the experimental field level and have a regional or even global dimension. Experimentation at such aggregate levels is impossible due to a combination of the number of alternatives, the scale and involved costs and risks. Whether it is the scale or complexity, associated cost or risk, or uncertainty in environmental conditions, empirical experimentation is not the most efficient and only way to explore acceptable alternatives. Simulation models are helpful to gain insight in complex relationships and answering 'what if' questions. However, they are little goal-oriented, which is essential for a targeted design of alternative systems that contribute to required objectives. Hence, new tools are needed to efficiently design and explore alternative agricultural systems at farm and regional scale.

Agro-ecological engineering approaches aimed at design and exploration of alternative land use systems at various scales may be helpful to analyze the complex problems that agriculture faces and to identify appropriate options. Engineering approaches are based on mathematical representations of well-founded agro-ecological principles while taking into account available resources and prevailing land-related objectives. These approaches integrate and synthesize process-based knowledge of physical, chemical, physiological and ecological processes, and empirical data regarding agronomic and livestock relationships using a variety of numerical tools. Typically, engineering approaches are highly voluntaristic, i.e. they address the future and explore *possible* alternatives and not *probable* or *plausible* developments. Therefore, such approaches are fundamentally different from methods that build on extrapolation of knowledge from historical and existing land use. Extrapolation methods are unable to adequately capture technical opportunities and the synergy of agronomic production factors at the basis of the biophysical production process, since they basically rely on past and present performance that eventually do not determine *future options*. Projections of past and present developments with associated inefficiencies in resource use, inappropriate knowledge and skills, and institutional and structural barriers do not allow identification of innovations that may result in discontinuities with the past.

In this study, engineering methods are central that enable the design of new and technically feasible land use systems at the land unit level and quantify such systems in outputs and the inputs required for realizing such outputs. Using other engineering methods, many of such alternatives engineered for the land unit level can be allocated to farming or regional land use systems. They are then concurrently and rapidly screened with respect to their contribution to objectives at farm or regional level, and trade-offs among objectives can be made explicit. The last decade, for example, various regional studies have been performed (e.g. Van Latesteijn, 1999; Bouman et al., 1999) to explore options on the basis of land use alternatives at land unit level that were defined using engineering methods (De Koning et al., 1995; Hengsdijk et al., 1999). These studies contributed to a transparent discussion on policy objectives related to regional land use by showing the technical possibilities and consequences of imposing different priorities to, for example, environmental and food security objectives. Other studies have used land use alternatives engineered for the land unit level to guide empirical farming systems research (Bos and Van de Ven, 1999; Ten Berge et al., 2000). Such farming systems studies enable a quantitative consideration of a broad spectrum of alternative farming systems, including very innovative and risky ones, before such systems are developed in an empirical setting. These modeling approaches, both at regional and farm level, allow exploring options that are difficult to determine otherwise and contribute to the methodological portfolio of systems analysis. In addition, these approaches allow interactive identification of options with stakeholders, which may help to reach a consensus on apparently conflicting interests and may provide a learning platform on how systems function and how to deal with them in the future (Van Ittersum et al., 1998).

Hence, over the last decade, engineered land use systems at the land unit level have been frequently used to explore options at farm and regional level. Remarkably, guidelines for identification of relevant and manageable sets of land use alternatives for the land unit level and formalization of procedures required to characterize alternatives are hardly available. This is unsatisfactory, since the results of any exploration of land use options for farm or region depends on the type of alternatives that are designed and the way they are quantified. Ad hoc methods may result in incomplete and/or inadequately characterized sets of alternatives. Consequently, future options may be misrepresented while such methods impede further development of a systematic approach to the identification of future options. Concurrently, used (unsystematic) approaches often involve major time and resource commitment, which is cost-ineffective (Nibbering and Van Rheenen, 1998). More transparent and generic engineering procedures are needed to coordinate the large body of work that is required to support and improve decision-making with respect to future land use.

1.3 Aim and scope

This study explicitly addresses agro-ecological approaches to engineer land use systems at the field level. The goal of this study is to contribute to the development of a formalized approach to identify and engineer future-oriented land use systems enabling the systematic exploration of land use options at farm or regional level. Formalization of concepts and procedures is required to efficiently engineer alternatives that are consistent with the objectives at stake while at the same time no options are excluded in an early phase of development. A generic step by step procedure is presented in general guidelines, of which implementation depends on location and time frame specific conditions. In addition, lack of knowledge and lack of data required to quantify land use systems may result in deviations from the proposed procedure. A formalized approach should enable the development of operational tools to engineer relevant and manageable sets of future-oriented land use systems in terms of outputs and the inputs required for realizing these outputs.

Like every design based on theoretical insights and secondary information sources, engineered land use systems must be examined with respect to their robustness before they are tested empirically or used to support decision processes.

Since agriculture, by definition, is practiced in an unpredictable environment, consequences of temporal variability for the performance of future-oriented land use systems is an important aspect in the engineering process and, therefore, requires specific attention including as to how to reduce and manage such uncertainty.

The future productive capacity of land use systems is an important characteristic of sustainable land use. Therefore, alternative systems developed behind the drawing board should be tested with respect to their performance over time and their consequences for the resource base.

Case study data and information from two areas, the northern Atlantic zone of Costa

Rica and semi-arid West Africa have been used to formalize an engineering approach, to test and elaborate this approach and to illustrate the implementation of different underlying concepts in operational tools. The choice for both regions is based on experience of the author in both regions, within the project *Duurzaam Landgebruik en Voedselvoorziening - DLV* (Van Keulen et al., 1998) and the Research Program on Sustainability in Agriculture – REPOSA (Bouman et al., 2000), rather than that these regions are typical for the approach described.

The emphasis in this study is on systems including crops, while systems including animals are only occasionally discussed, although the approach is applicable to such systems as well. In this study, *field* and *land unit* level are used interchangeable, while *land use systems* and *production systems* are used synonymously to indicate cropping systems at the field level.

1.4 Outline of thesis

Since the chapters of this study are based on published or submitted journal articles some repetition among chapters is apparent but it assures that chapters can be read independently. In combination, they describe a formalized method to engineer land use systems, its testing and further development, and application in operational tools.

In Chapter 2, a goal-oriented approach is presented to identify and engineer future-oriented land use systems. This formalized approach allows ex-ante assessment of engineered land use systems at the field level to be further screened or developed in experimental settings. Different steps in the approach are illustrated using case study data from both Costa Rica and West Africa. In this chapter, explanation of the underlying theory and principles is central. In the following chapters, the approach is implemented to test, elaborate and apply various concepts using various numerical tools.

In Chapter 3, effects of uncertainty in knowledge and data related to three important N-relationships in engineered land use systems are discussed for their inputs and outputs. Consequences of this type of uncertainty are made explicit to better manage, or reduce it.

A special case of uncertainty is dealt with in Chapter 4, i.e. the unpredictability of the physical environment that is inherent in most agricultural production systems. Here, the effect of temporal variation on inputs and outputs of land use systems in West Africa is examined. The consequences of uncertain input-output relationships for both strategic decision-makers and designers of future-oriented systems are discussed. This chapter also illustrates how numerical tools are applied to design systems with less variable performance.

In Chapter 5, the existing conceptual engineering framework is expanded with an approach that allows taking into account non-equilibrium conditions of the natural resource base. In this chapter, the development of N-dynamics of different rotations is made explicit, so that their long-term effects on the productive capacity of future-oriented land use systems can be accounted for in making decisions. In addition, an outline of an alternative method is proposed allowing identification of management strategies aimed at realizing multiple goals simultaneously.

Integration of concepts, data and knowledge into operational tools is described in Chapter 6. Two tools are presented that enable quantification of livestock systems and cropping systems in terms of inputs and outputs. Both tools have been developed for land use systems in the northern Atlantic zone of Costa Rica but they have a generic structure that allows easy transfer to other regions. Their use as stand-alone tool in the ex-ante analysis of land use systems is illustrated.

Chapter 7 gives an overall discussion of the approach and numerical tools applied, while future prospects of the approach within the field of agro-ecological engineering and possible improvements of the approach are indicated.

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Chapter 2

A goal-oriented approach to identify and engineer land use systems

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2 A goal-oriented approach to identify and engineer land use systems

Abstract

This chapter describes a formalized approach to identify and engineer future-oriented land use systems. Such land use systems can be used to explore options for strategic decision-making with respect to land use policy and to do ex-ante assessment of land use alternatives to be further tested or developed in experimental settings. The so-called goal-oriented approach consists of three steps: (1) *goal-oriented identification and design of land use systems*; (2) *quantification of biophysical* production possibilities; and (3) defining the optimal mix of inputs, i.e. the production technique, required to realize production possibilities. The goal-oriented identification and design depends on the land-related objectives of a system under study, whereas plant, animal and environmental characteristics determine biophysical production possibilities. Characteristics of the production technique determine the realization of production possibilities. General guidelines are given to structure the specification and number of alternatives to be explored and to apply agro-ecological principles required for quantification of future-oriented land use systems. Concepts of the approach are illustrated with data from the northern Atlantic zone of Costa Rica and the Sudano-Sahelian zone of Mali. Finally, suggestions are given for the application of the approach at spatial and temporal scales exceeding the field level and time horizon of 1 year.

2.1 Introduction

Rural land use faces unprecedented challenges: a rapidly growing population has to be fed, putting pressure on agricultural production, while at the same time public concern about ecosystems, natural resources and multifunctional purposes of land call for appropriate management and attention. Only quantitative methods can disentangle the complex relationships between agricultural production, environment and economy, and thus improve the transparency of choices at stake. In the late 1970s land evaluation was coined to assess land performance quantitatively (Beek, 1978) but it lacked value-driven criteria to identify and show consequences of explicit choices, limiting its use for policy making. Over the last decade, future-oriented studies have been executed at farm or higher spatial levels using optimization approaches, i.e. linear programming. Agricultural, socio-economic and environmental options for rural land use have been explored in an integrated and quantitative way based on explicit land-related objectives, providing relevant information for policy-making (e.g. De Wit et al., 1988; El Shishiny, 1988; Alocilja and Ritchie, 1993). An important condition for such future-oriented studies is an adequate description of agricultural production alternatives. Many land use studies, however, hardly discuss the underlying data and concepts used for the description of land use alternatives (e.g. Fernandez-Riviera et al., 1995), and choices concerning the type of alternatives that are considered are not made explicit. They often lack a conceptual framework that helps the structuring of the specification and number of alternatives to be analyzed and the application of agro-ecological principles to quantify future-oriented alternatives. This is unsatisfactory, since ad-hoc methods are time and cost-ineffective (Nibbering and Van Rheenen, 1998), and may result in blurred explorations of future options. Alternatively, studies at process level (e.g. Kropff et al., 1995), which are scientifically still most rewarding, usually do not consider how the gained knowledge can be exploited in studies that aim at identification of options for a farm or region.

This chapter presents a formalized goal-oriented approach that converts information on specific aims for new agricultural systems into a targeted identification and quantification of such systems using a variety of numerical tools and well-founded agro-ecological principles. The aim of this engineering approach is to obtain a manageable set and appropriate description of land use alternatives in terms of quantified outputs and their required inputs. Our goal-oriented approach starts with the targeted identification of alternatives, i.e. the underlying choices are made transparent and open to discussion so that the likelihood to ignore options in an early phase of development is reduced. The approach results in a coherent and operational framework that is illustrated with examples from two case study areas, the northern Atlantic zone of Costa Rica and the Sudano-Sahelian zone of Mali. Consequences of the approach for scale phenomena are discussed. Before presenting and illustrating the approach, the primary application domain of the engineering approach is discussed, i.e. exploring land use options for strategic decision-making, since it determines the requirements that the approach must meet. Subsequently, the concept of land use systems is explained to stress that we build on existing terminology and theory.

2.2 Aim and requirements of future-oriented land use studies

Future-oriented land use studies aim at identification of strategic options taking into account available resources and objectives of various stakeholders in a given area. Available natural resources determine biophysical production possibilities, while both available natural and technical resources determine the feasibility of such production possibilities. Land-related objectives determine how resources are applied and refer to, for example, attainment of food security, safeguarding of agricultural employment or reduction of the environmental impact caused by agricultural production. The combination of biophysical possibilities, their technical feasibility and objectives results in the so-called 'window of opportunities', indicating the scope for choices from a biophysical and technical point of view within which land use policy can operate. The time horizon in which such choices may be realized is often less important than showing opportunities to realize objectives and the possible trade-off among objectives, thus improving the basis for policy formulation.

For future-oriented studies, a fundamentally different approach is required than in methods that build upon extrapolation of knowledge on historical and existing land use. Extrapolation methods are unable to adequately capture technical opportunities and the synergy of agronomic production factors at the basis of the biophysical production process, since they basically rely on past and present performance that eventually do not determine *future options*. Projections of past and present developments with associated inefficiencies in resource use, inappropriate knowledge and skills, and institutional and structural barriers obscures the window of opportunities and does not allow identifying discontinuities.

In future-oriented studies, land use options must meet two important conditions. First, they must be possible from a biophysical point of view and feasible from a technical point of view, although such options may not be currently available or feasible for farmers in a given situation. Secondly, they must comprise a variety of contrasting alternatives allowing to realize different (and often conflicting) objectives so that no a priori options are excluded and the window of opportunities remains open and transparent.

In this chapter, a goal-oriented approach is introduced as a formalized and operational approach to design land use alternatives and to quantify their inputs and outputs based on knowledge of the underlying biophysical processes of plant and animal production, technical insights and required objectives. Engineered land use options are future-oriented or alternative in the sense that they are based on available resources and explicit aims that guide their design, while taking into account the latest developments in plant and animal production sciences and well-founded agro-ecological principles warranting technically optimal resource use. In the goal-oriented approach the whole set of physical inputs is considered jointly so that demonstrated interactions and synergistic relationships of inputs in the agricultural production process can be taken into account (De Wit, 1992). Consequently, land use must be described as discrete phenomena, each uniquely characterized by inputs and outputs.

2.3 Unit of analysis: land use systems

This chapter uses the *land use system* as the unit of analysis, a concept that was introduced as early as 1978 in Beek's landmark work on land evaluation (Beek, 1978). This is the smallest spatial level at which agronomic, environmental and economic factors unite and interact, and the level is an important building block of many future-oriented land use studies. Here, a land use system is defined as a combination of a land use type and a well-defined physical environment that is uniquely characterized by its inputs and outputs, and possibly land improvements such as irrigation and drainage (after Driessen and Konijn, 1992). A *land use type* is a combination of a crop type (e.g. crop species, specified by cultivar) and production technique (e.g. use of inputs). The *physical environment* is defined as a physical area of land that is uniform in its climate and soil characteristics and qualities.

Though inputs and outputs of land use systems are usually expressed per hectare per year, the concept of land use system is also suitable to characterize perennial and livestock systems. The lifespan of both systems exceeds 1 year and consequently input-output relationships of such systems change over time.

Since land use systems often have to serve multiple objectives, their inputs and outputs have to be defined in both physical and monetary terms. For example, input requirements such as the amount and type of fertilizers and labor must be expressed in their own units and in their associated monetary costs. Output of land use systems must be divided into harvested products, for example, crop yields or residues, meat or milk, and other outputs, which are called environmental impact indicators, specifying emissions to the environment (e.g. nutrients, greenhouse gases) or the use of natural resources (e.g. soil nutrients, soil organic matter) as a consequence of the agricultural production process. To analyze the efficiency of resource use in land use systems, inputs and environmental impact indicators are usually expressed per unit of area and/or per unit of harvested output, while environmental impact indicators and economic efficiency may also be expressed per unit of input (Van Ittersum and Rabbinge, 1997).

2.4 Goal-oriented approach

The goal-oriented approach consists of three steps required to arrive at a relevant and manageable set of alternative land use systems: (1) goal-oriented identification and design of land use systems, (2) quantification of biophysical production possibilities and (3) defining the optimal mix of inputs required to realize production possibilities (technical feasibility). The first step involves the identification and qualitative design of relevant land use systems, while the following two steps involve quantification of their inputs and outputs.

2.4.1 Goal-oriented identification and design of land use systems

Goal-oriented identification and design of land use systems hinges on the so-called *target-oriented approach.* Unlike traditional agronomic research that usually consists of analyzing dose (input) - effect (output) relationships, in the target-oriented approach first a target output level is determined, based on required objectives, and subsequently the optimal combination of inputs to realize this target. The target-oriented approach is based on the observation that numerous combinations of inputs are possible to realize a given output, but that an efficient set of inputs only can be identified if the required objectives are explicit. Given crop, animal and environmental characteristics, technical knowledge of the processes involved, and the required goals of the land use system, it is possible to identify the minimum input requirements to attain a well-defined output. When, for example, in a given situation water is a scarce production factor that should not be sacrificed for agricultural purposes (i.e. for irrigation), water-limited production levels may be aimed at and consequently used as a target for the set of inputs required for their realization. The target output is often not only the yield, but may also refer to, for example, the emission of nutrients or the environmental impact of biocides. Since the scope of problems facing rural land use is so wide and diverse, engineered land use systems for explorative purposes often aim at such goals simultaneously. In production ecology, such a value-driven approach in the design of land use systems is often referred to as *production orientation* (Van Ittersum and Rabbinge, 1997).

To apply the target-oriented approach properly, land-related objectives must be identified adequately. In each study area, objectives may be different and the core of the goal-oriented approach is that land use systems are designed while taking into account such location-specific objectives. Usually, multiple objectives are important that are not explicitly formulated. Therefore, a thorough discussion about the system goals forms the basis of every engineering study. The way to identify these objectives is beyond the scope of the present chapter, but requires close interaction with stakeholders (FAO, 1993).

In a next step, land use systems are described qualitatively according to so-called *design criteria,* each including a number of variants that explicitly characterize land use systems (Table 2.1). Beside characteristics of the physical environment, criteria must relate to the type of plant or animal and to the characteristics of the production technique while taking into account the earlier identified goals. The selection of design criteria and their variants is of prime importance, since it determines the range of land use systems to be explored. Any relevant land use system not included at the start of a future-oriented study limits its potential usefulness at the end.

Table 2.1

Design criteria and their variants as implemented for rainfed cropping systems in two regional land use studies.

Attribute	Design criteria	Number of variants
For case study in Sudano-Sahelian zone (Bakker et al., 1998):		
Physical environment:	Climate zone	Three zones with different rainfall regimes: North Sahelian, South Sahelian, Sudanian zone
	Type of rainfall year	Two rainfall seasons (dry and normal): north Sahelian zone: 239 and 385 mm, south Sahelian zone: 423 and 605 mm, Sudanian zone: 642 and 840 mm
	Soil type	Seven soil types: clay depressions, clayey loam, loam, sandy loam, loamy sand, sand, gravel
Plant type:	Crop type	Eight crops with different products: millet, sorghum, maize, groundnut, cowpea (human consumption), cowpea (fodder), cotton, eucalyptus
Production technique:	Production/mechanization level	Four yield levels combined with different levels of mechanization: higher yield levels with increased use of implements
	Crop residue management	Four strategies for use of crop residues: stubble grazing with burning, harvesting, burning, ploughing
	Soil and water conservation measures	Three soil and water conservation measures: none, simple ridges, tied ridges
For case study in the northern Atlantic zone (Bouman et al., 1998):		
Physical environment:	Climate zone	One zone: northern Atlantic zone
	Soil type	Three soil types: fertile well drained, infertile well drained, fertile poorly drained
Plant type:	Crop type	Ten crops with different products: black bean, cassava, maize (fresh cobs), maize (grain), pineapple (local), pineapple (export), banana, plantain, palm heart, melina
Production technique:	Production level	Ten yield levels: highest target yield is stepwise reduced with 10%
	Mechanization level	Two levels of mechanization: low and high use of implements
	Crop residue management	One strategy for use of crop residues: ploughing
	Weed management	Two strategies for weed control: low and high level of herbicides
	Pest and disease management	Two strategies for pest and disease control: low and high level of fungicides and insecticides

The *physical environment* must be classified according to diagnostic criteria such as soil, climate and topographic characteristics that determine production possibilities of plants and animals. For example, soil texture and rainfall distribution may be appropriate diagnostic criteria to characterize the physical environment for rainfed cropping systems, since they determine water-limited plant growth and thus production possibilities through various processes. In mountainous areas, for example, altitude may be a suitable criterion to distinguish different temperature zones that affect crop choice and plant production.

The *type of plant* (or type of animal) to be considered should include a representative sample of suitable crops in a given area. Since it is not possible to take into account all crops that are suitable, not to mention all the varieties of a certain crop, a selection has to be made based on the way inputs and outputs of these crops affect identified objectives. Since future-oriented studies aim at exploring unexpected choices, while taking into account multiple objectives, crops or crop groups with contrasting input-output relationships are required that may contribute to different objectives. Such contrasts can be found, for example, in differences among annuals and perennials; cash crops and crops for (local) food self-sufficiency; crops in the current diet and crops that may be part of future diets; grain, root and tuber and legume crops; and crops varying in environmental impact. These crop groups should be adapted according to the goal(s) and area of study. By using representative and contrasting crop types, unexpected perspectives may be identified, including perceived or true land-related conflicts without excluding any option too early in the analysis. Representative crop types can include species that are currently not grown in an area of study, for example for economic reasons, but which are suitable from a biophysical point of view.

The feasibility of production possibilities is determined by the *production techniques*. Since numerous management operations are required to grow a crop (or to rear animals), most of which can be carried out in different ways, key criteria in the production process must be identified that can be influenced by production techniques and that are crucial to realize objectives of the required systems. If objectives relate to reduction of the environmental impact as a result of biocide use, key criteria refer to weed and disease management of land use systems, i.e. different and contrasting management alternatives should be considered each with different biocide requirements. Objectives related to the reduction of nutrient emission require criteria referring to such emissions, for example, management variants that differ in the amount, timing, frequency and means of fertilizer application. When objectives have a socio-economic character, criteria are relevant that refer to the ratio between labor and capital inputs of land use systems.

2.4.2 Biophysical production possibilities

For each combination of physical environment and type of crop, plant production possibilities can be estimated based on knowledge about the underlying processes of plant production. The concept of hierarchical production levels (Rabbinge, 1993), is a useful guideline to classify yield levels as function of different production factors, i.e. growth-defining (e.g. temperature), growth-limiting (water or nutrients) and growth-reducing (e.g. pests) factors that each differentially affect the plant production process (Van Ittersum and Rabbinge, 1997). Crop growth simulation models exist that take these production factors into account and allow quantification of production possibilities in different physical environments (e.g. Tsuji et al., 1998).

For plant production of pasture sub-systems, the concept of hierarchical production levels is also applicable. Pasture production is usually expressed in terms of its quantity (dry matter) and quality (metabolizable energy and nutrient content) since they both, together with animal characteristics and environmental conditions, determine meat and milk production of livestock systems. For animal sub-systems, climate (particularly temperature and day length) and genetic animal characteristics determine potential production levels (Spedding, 1988). Growth-limiting factors include water, nutrients and (metabolizable) energy that in sub-optimal supply limit animal production. Growth reducing factors in livestock production include all kinds of animal health constraints (diseases, injuries, etc.) that may constrain production if no adequate protection measures are taken. Also for animal production, simulation models have been developed that translate these concepts into practical production estimates (e.g. Sanders and Cartwright, 1978).

2.4.3 Technical feasibility of production possibilities

In the goal-oriented approach it is the art of finding the technically optimal combination of inputs to realize particular target outputs which is often called the best technical means (Van Ittersum and Rabbinge, 1997). Primary inputs (e.g. water and nutrients) fulfill essential roles in growth and development of plants and animals, and they can not be substituted. Secondary inputs (e.g. implements, labor) have different roles in the production process and, to a certain extent, can be mutually substituted based on the required objectives. For example, manual weeding (labor) can be replaced with chemical weeding (biocides), which affects the amount of biocides that is important if land use systems (also) aim at environmental goals.

In addition, other agro-ecological principles and technical knowledge are available that support the process of defining technically efficient combinations of both primary and secondary inputs to realize target outputs, taking into account the goals of the land use system aimed at: (1) the amount of primary inputs required for a particular target yield can be derived from the yield level aimed at and input recovery factors. Fine-tuning of inputs at appropriate levels, usually results in high input use efficiencies (in a technical sense) in plant production. This principle also applies to animals, since animals with a good health status and balanced feed supply have higher energy utilization efficiencies (Spedding, 1988). (2) To sustain production (in biophysical sense) natural resource stocks must be maintained (e.g. soil nutrient stock, and soil organic matter stock). This implies that inputs withdrawn from the natural resource base must be replenished to guarantee constant input-output relationships over time. (3) Technological developments such as breeding of species with improved morphological and physiological plant design, genetic improvements and advances in nutrition in animal production, and improvements in field management (e.g. fertilizer application, crop protection and higher plant densities) have contributed to increased resource use efficiency (Ruttan, 1998). These developments still have not come to complete fruition in many parts of the world. While engineering alternative land use systems, such technological developments should be carefully considered within the current technological context of the area under study. (4) The technical feasibility of biophysical production possibilities is closely related to the properties of the physical environment. For example, production techniques using mechanization are difficult to apply in mountainous areas. Production techniques must be geared to such conditions. Engineering inputs to attain target outputs requires careful consideration of the limitations that available natural resources impose on the use of particular inputs.

2.5 Operationalization of the goal-oriented approach

Concepts of the goal-oriented approach are applied and illustrated using two future-oriented land use studies in different regions, one in the northern Atlantic zone of Costa Rica (Bouman et al., 1998) and one in the Sudano-Sahelian zone of Mali (Bakker et al., 1998), for both of which a variety of alternative land use systems were engineered. The first case study area (0.45 million ha) is in the permanent humid lowlands of the northern Atlantic zone of Costa Rica, with an annual rainfall of about 4000 mm well distributed over the year, and the second case study area is in the (semi-) arid Sudano-Sahelian zone of Mali (46 million ha), with an annual rainfall ranging between 300 and 1000 mm with a prolonged dry period of 4 - 8 months.

2.5.1 Goal-oriented design

In Table 2.1 design criteria for rainfed cropping systems are shown as applied in both case studies. Theoretically, all variants of each criterion can be combined, each combination characterizing a set of unique cropping systems that have been explored in both studies.

A low level of food security of which high spatial and temporal variability in rainfall are two of the major causes (Cocheme and Franquin, 1967) characterizes the Sudano-Sahelian zone. Therefore, three climate zones have been distinguished to account for the variation in climate within the Sudano-Sahelian zone and its effect on plant production. In addition, two seasons with contrasting rainfall regimes are distinguished, one representing a dry year and one representing a year with average rainfall, based on long term rainfall data, to account for the great variability in rainfall among years and its impact on yields. In the case study area of the northern Atlantic zone variation in weather over the years was so small (Bessembinder, 1997), that no different rainfall regimes were identified. The 74 soil units originally identified in a soil survey for the Atlantic zone (Wielemaker and Vogel, 1993) were classified into three physical environments suitable for agriculture, based on diagnostic land qualities (soil fertility and drainage conditions), and on diagnostic land characteristics (slope and stoniness): physical environments with fertile well drained soils, infertile well drained soils and fertile poorly drained soils (Hengsdijk et al., 1999). Each of these physical environments was subdivided into mechanizable and non-mechanizable sub-units, the latter having slopes of more than 25% and/or soils with more than 1.5% of stones, indicating the link between characteristics of the physical environment and the feasibility of production techniques. The 68 soil/vegetation units originally identified in a land inventory study for the Sudano-Sahelian zone (PIRT, 1983) were classified into 7 soil types, based on diagnostic soil qualities, i.e. soil texture, profile depth and the presence of gravel since they determine water availability and as such are key variables for plant production.

Eight crops were considered relevant for the northern Atlantic zone: black bean, cassava, maize, pineapple, banana, plantain, palm heart and melina. For both maize and pineapple two crop types were identified each with different market purposes (export and local) and different input-output relationships because of different means of production. The selection of crops was based on the broad mixture of annuals, perennials and tree crops currently present in the northern Atlantic zone, on the presence of crops in the local diet, on the economic importance of crops and on expert opinions about the biophysical suitability of crops currently (almost) nonexistent in the Atlantic zone. For the Sudano-Sahelian zone seven annual rainfed crops and one tree crop were chosen: millet, sorghum, groundnut, maize, cowpea for human consumption, cowpea for fodder purposes, cotton, and eucalyptus (Quak et al., 1996). The former five are a major part of the local diet and therefore crucial for food self-sufficiency; cotton is the major cash crop whereas cowpea fodder is an important source of cash income during the dry period, and its residual-N may improve the soil nutrient status (Bationo and Ntare, 2000). Except for eucalyptus trees, which are important for supply of fire and construction wood, no other perennials are taken into account, as their biophysical potential is limited due to the extended dry period.

Criteria characterizing the production techniques are based on local conditions and problems of the area under study. In the Sudano-Sahelian case study different levels of mechanization are linked to different target production levels, i.e. higher production levels are realized with the use of more implements than lower production levels which are realized with the use of more manual labor. The intertwining of production and mechanization levels is based on purely pragmatic considerations, i.e. to limit the number of options to be explored in the land use model. In the case study of the northern Atlantic zone, mechanized field operations are limited in view of the high rainfall intensities, the high risk of soil compaction, and the narrow passage in perennials. Two levels of mechanization are identified. Management of crop residues and soil-and water conservation measures are important means to increase production and to prevent further deterioration of land resources in the Sudano-Sahelian region (e.g. Sanders, 1989; Day et al., 1992). In the northern Atlantic zone the environmental impact as a result of biocide use is of great concern (Wesseling, 1997). Therefore, different variants for the control of weeds, and pests and diseases have been distinguished, each with a different environmental load.

2.5.2 Estimation of biophysical production possibilities

Estimation of production possibilities can be done in various ways, ranging from estimates by field experts to detailed simulation models that calculate crop development and growth on daily basis. In the case of the Sudano-Sahelian zone water limited yield levels were estimated based on relationships among crop transpiration, vapor pressure deficit and yields (Tanner and Sinclair, 1983). Water availability for crop transpiration was based on a thorough analysis of hydrological processes in land use systems including run-off, percolation and evaporation (Quak et al., 1996). Run-off was estimated using the intensity and duration of rainfall showers and the soil surface storage capacity. Effects of soil and water conservation measures were taken into account, i.e. different types of tillage ridges improving the surface storage capacity. Percolation, i.e. the amount of water lost to soil layers below the rooting zone of crops, was determined according to an empirical equation of Breman and De Ridder (1991). Evaporation, finally, was based on the potential evapotranspiration calculated and the development of canopy cover during the growing season. The vapor pressure deficit, i.e. the difference between saturated and actual vapor pressure was calculated according to Goudriaan (1977). Subsequently, the estimated water-limited yields were reduced to account for unavoidable losses to diseases and pests and sub-optimal water supply due to local variability. These correction factors were crop dependent and based on expert estimates.

In the case of the Atlantic zone yield estimates were based on expert knowledge since for most crops considered (section 2.5.1) no other methods existed. These yield estimates for crops served as targets for quantification of other outputs and inputs of cropping systems aiming at high soil productivity. Environmental concern about biocides used in Costa Rican agriculture also called for exploring production orientations aimed at reducing the environmental impact of biocides. Therefore, two other types of systems were considered with reduced use of biocides. In the first type, herbicides were substituted for manual weeding methods so that labor requirements increased but the input of herbicides was reduced and the estimated target yields still were maintained. In the second type, an integrated pest and disease management was considered in which the amount of pesticides (i.e. fungicides and insecticides) was reduced because of better crop monitoring and hygienic measures, both of which require additional labor. The use of biocides in these systems is lower compared to that in systems aiming at high soil productivity; however, field experts argued that yield losses were inevitable in the humid northern Atlantic zone despite extra monitoring and hygienic measures. So, the aim to reduce the environmental load as a result of pesticide use also causes a reduction in the initially estimated target yields. Table 2.2 shows an example of four alternative cassava systems in which different weed and pest and disease management alternatives are compared and differences in selected inputs and outputs are illustrated.

Table 2.2

Comparison of selected inputs and outputs of cassava systems with different options for weed and pest and disease management.

Pest and disease management	Pesticides	Integrated	Pesticides	Integrated
Weed management	Herbicides	Herbicides	Manual	Manual
Outputs				
Prime quality product (kg ha^{-1})	15000	11250	15000	11250
Second quality product (kg ha^{-1})	7500	5625	7500	5625
Third quality product (kg ha^{-1})	2500	1875	2500	1875
Inputs				
Biocides (kg a.i. ha^{-1})	2.2	1.8	1.4	1.0
Total labor requirements (d ha^{-1})	67	60	73	66
Labor requirements for non-harvest operations (d ha^{-1})	17	22	23	29
Total costs ($ ha^{-1})	1872	1866	1870	1865
Biocide costs ($ ha^{-1})	81	70	29	18

2.5.3 Determination of technical feasibility

The starting point for determining the required amount of nutrients for alternative land use systems is a situation in which soil nutrient stocks at the end of the growing period equal the stocks at the start of a growing period. These situations can be denoted as 'sustainable' with respect to nutrient stocks, and they are a basis to determine the minimum nutrient requirements that have to be applied during the growing period. In the case study of the northern Atlantic zone, nutrient requirements of perennial systems have been based on this principle. In Table 2.3 an example of a banana system is shown with a cropping cycle of 15 years and annual harvests. Because the growth of perennials – by definition – lasts longer than 1 year, nutrient balances in consecutive years have been modeled taking into account nutrients that turn over in the crop to the following year and crop residue-N (accounted for unavoidable losses) that remains in the system after harvest. In the first 3 years production is increasing, the following years a constant yield level is attained and in the last year all crop residues are left in the field decomposing. Nutrients released from crop residues left in the field in year *n* become available in year *n+1*. Nutrients released with decomposing crop residues in the last year of the crop cycle (year 15) become available in year 1. Supplies from natural resources (deposition and symbiotic N-fixing bacteria) are taken into account while all supply items are subject to losses. The N-loss percentage (52% of applied Nitrogen in the example) is a summation of estimated losses due to volatilization, denitrification, leaching and erosion. Estimations of individual loss processes are based on empirical data, drainage characteristics of soils and expert knowledge.

In the case study of the Sudano-Sahelian zone, biophysical production possibilities of pasture and animal sub-systems were determined separately (Quak et al., 1996; Bakker et al., 1996). Production of pasture sub-systems was matched with livestock sub-systems at the level of the case study area by means of feed rations, comprising both pasture fodder and crop residues. Pasture fodder (and crop residues) was classified into ten quality categories according to its availability in the dry and wet season and its nitrogen content that is highly correlated with the digestible organic matter content of fodder. Based on these ten feed categories different feed rations were calculated that were geared towards maintenance of specific animal production levels, i.e. the quantity and quality of feed in the feed rations was fine-tuned to the digestible organic matter requirements of well-defined animal production targets. The starting point in the calculation procedure of feed rations was that each feed ration consisted of one feed available in the wet season and at the most two different feeds available in the dry season, so that over the entire year animal production targets could be attained. Calculated feed rations account for possible deficits in feed requirements in the dry period due to the availability of fodder with a low digestible organic matter content and compensate these deficits with high quality fodder in the wet period. Feasible combinations of feeds formed a great number of alternative feed rations for each animal production target so that a number of variants were available to link pasture and animal production at aggregate level.

Table 2.3

Example of procedure used to calculate the nitrogen requirements of a banana system. Total N-loss fraction is 0.52. All data in kg N ha^{-1} y^{-1}.

	Year 1 up to 15				
	Year 1	Year 2	Year 3	Year 4 up to 14	Year 15
Crop N-uptake					
Fruit	121	137	161	161	161
Fruit stem	16	19	22	22	22
Leaves	257	291	342	342	342
Stems	86	97	114	114	114
Roots	101	115	135	135	135
Total	581	659	775	775	775
Gross supply of nitrogen					
Crop residues left at field from previous year	591	236	267	314	314
Wet deposition	2	2	2	2	2
Symbiotic bacteria	5	5	5	5	5
Net supply of nitrogen					
Crop residues left at field from previous year	285	114	129	152	152
Wet deposition	1	1	1	1	1
Symbiotic bacteria	2	2	2	2	2
Total	288	117	132	155	155
N-turned over in crop to next year	–	208	236	277	277
N-shortage = total crop uptake – total net supply – turnover in crop	294	335	409	344	344
N-requirements = N-shortage / (1 – N-loss fraction)	609	695	847	714	714
N-balance	0	0	0	0	0

2.6 Interactions between spatial and temporal scales

Analyzing interactions between spatial and temporal scales is of crucial importance for understanding agro-ecological processes (e.g. Dumanski et al., 1998). Land use systems quantified according to the goal-oriented approach are engineered with specific spatial scales in mind, i.e. the field level. Land use systems are often used to explore land use options for an aggregated level (farm, region, etc.) using models that are static and cannot deal with interactions between spatial units. For example, climate and soil characteristics and qualities are used to calculate effects of soil and hydrological processes for specific land use systems at field level. Summation of runoff/erosion at field level is, however, not equal to the total runoff/erosion at a regional scale since water and soil losses of a single land use system may be an enrichment for adjacent land use systems, situated in lower parts of a toposequence. Interactions among adjacent land use systems are not taken into account in calculations at field scale. Ideally, input-output relationships of land use systems should be defined as function of the outputs of soil and hydrological processes of adjacent land use systems. Though most future-oriented land use studies at aggregate levels comprise geo-referenced databases, the dynamic adjustment of input-output relationships as function of allocated land use is usually impossible, since it requires a predefined allocation scheme of land use systems. A way to deal with such spatial phenomena is to describe land use systems at higher aggregated scales instead of the field scale. For hydrology-related processes, the watershed level may be a suitable scale level, while for additional spatial phenomena (e.g. airborne diseases and pests that easily disperse through large areas of the same type of crop) other aggregate levels may be required. Land use systems are then combinations of different physical environments, with a mixture of land use types of which the outputs may consist of multiple harvested products. The allocation of land use types within these 'aggregated' land use systems determines the input-output relationships of such land use systems. It implies that, for aggregated land use systems special methods have to be developed, for example based on simulation techniques which allow to take into account the spatial interactions among agro-ecological processes (Styczen and Storm, 1993).

Concurrently, engineered land use systems are often designed with a specific temporal scale in mind, i.e. 1 year. However, the order and frequency of cultivation of annual crops determine many input-output relationships, for example, those with regard to nutrients and soil born diseases and pests. Nutrients left in crop residues or residual mineral store after harvest of one crop may contribute to the soil nutrient stock and thus affect input-output relationships of the following crop. The effects of such processes exceed the time horizon of 1 year, while their magnitude depends on the specific cropping sequence. Most temporal scale phenomena can be captured by engineering entire crop rotations so that interactions among successive crops with respect to soil nutrients, plague organisms, etc. can be explicitly accounted for (e.g. De Koning et al., 1995). Rotations of annual crops can be considered a type of perennial system with a mixture of land use types of which the outputs may consist of multiple harvested products. The frequency and order in which crop types are grown determine inputs and outputs of such land use systems. Though describing land use systems as entire crop rotations enables to account for temporal interaction of agro-ecological processes, the number of options that can be formulated increases enormously since crops can be arranged in so many combinations. Intelligent selection procedures must be developed to reduce the number of potential crop rotations.

2.7 Discussion and conclusions

The goal-oriented approach offers guidelines to systematically identify and engineer a manageable set of alternative land use systems for future-oriented purposes without excluding alternatives in an early phase of development. Engineered land use systems are no blueprints for crop cultivation or animal rearing since their description lacks the day-to-day decision-making that governs agricultural production. Such systems merely describe technically feasible and efficient combinations of inputs required to realize well-defined target outputs and unavoidable secondary outputs. The goal-oriented approach starts with defining target outputs of land use systems, since they determine the performances aimed at, while inputs are considered the means to realize them.

The approach has demonstrated its usefulness in various future-oriented studies to support strategic decision making with respect to land use, since it allows to identify opportunities and limitations of a system that for reasons of scale and time with empirical experimentation are difficult to capture (section 2.1). The approach may also serve to explore alternative land use systems as building blocks of farming systems, providing a sound basis for selecting systems to be tested in practice. A priori unfeasible or undesired alternatives can be excluded from further empirical experimentation at field or farm level, while more attention can be focused on promising options, thus exploiting limited research resources more efficiently.

In both case studies, various agro-ecological principles and different methods have been applied to quantify biophysical possibilities and technically feasible production techniques of future-oriented land use systems. Usually, the method depends on the type of input or output quantified, required level of detail, availability of data and mechanistic models to describe various agro-ecological processes. In addition to available time and financial resources, such aspects are closely related to the aim and scale of study (Fresco et al., 1994). The scale at which land use systems are designed is important for the way in which some agro-ecological processes can be taken into account. The relative importance of a process in a given situation, purpose of study, availability of data all may be decisive factors in the choice to describe and explore land use systems not at the field level, but at higher aggregate levels, both in space and time. Generally, in future-oriented studies at aggregate level (e.g. region) methods suffice that describe underlying processes with less detail than studies at lower aggregate level (e.g. farm), since the type of questions differ. This implies, for example, that design criteria used to characterize land use systems for studies at farm level should include more but less contrasting variants compared to regional studies. Pragmatic reasons, such as data availability or the manageability of the number of options to be explored in land use studies, may lead to deviations from the anticipated path. Unavoidable choices impeding the implementation of underlying theoretical concepts should always be made as explicit as possible since they may unintentionally obscure the window of opportunities. Therefore, this chapter attempted not to give a blueprint of a procedure but a framework, including concepts and guidelines to support the identification and engineering of future-oriented land use systems.

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Chapter 3

Uncertainty in technical coefficients for future-oriented land use studies: a study for N-relationships in cropping systems

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3 Uncertainty in technical coefficients for future-oriented land use studies: a case study for N-relationships in cropping systems

Abstract

Engineering of land use systems for policy-oriented future studies and the development of new farming systems requires various information sources. Often, both process knowledge and data are subject to uncertainty that affects quantification of land use systems in their inputs and outputs. This chapter analyzes the effects of uncertainty in three important N-relationships relevant for quantification of future-oriented cropping systems: (i) N-leaching as function of crop characteristics, (ii) N-concentration as function of yield level, and (iii) the recovery of crop residue-N. Based on verifiable assumptions, uncertainty in these three N-relationships is specified in terms of N-loss and production costs of cropping systems. Data and process knowledge as applied in LUCTOR, a summary model to design and quantify inputs and outputs of cropping systems for the northern Atlantic zone of Costa Rica, are used as a case study. All three relationships and their uncertainty have a major impact on N-loss of cropping systems while effects on costs are limited and depend on the share of costs for fertilizer management in total production costs. Analyses as presented explicitly specify uncertainty of process knowledge and data used in future-oriented studies. Therefore, such analyses enable a better management or reduction of uncertainty through the identification of cropping systems with smaller uncertainty margins, and identification of research aimed at a more complete understanding of involved processes.

3.1 Introduction

Computer-aided design of future-oriented land use systems is an important engineering method to explore options that are not easily identified using experimental or traditional analytical methods. Engineering methods are based on mathematical representations of well-founded agro-ecological principles while taking into account available resources and land-related objectives. Hence, strategic options can be identified improving decision-making at the field, farm or regional level (e.g. Thornton et al., 1995; Rossing et al., 1997; Bouman et al., 1998). Engineered land use systems are characterized by their outputs and inputs required to realize such outputs, which jointly are often called technical coefficients and expressed in both physical (e.g. yield, labor requirement and emission) and economic terms (e.g. costs and gross return) per hectare per year.

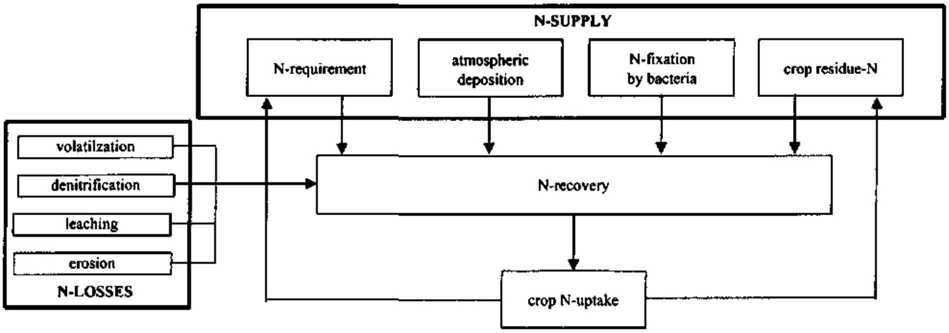
Engineering of land use systems requires sound agro-ecological concepts and appropriate databases. Underlying information required to quantify technical coefficients consists of a mixture of process based knowledge of physical, chemical, physiological and ecological processes involved, empirical data and standard data with respect to agronomic and livestock relationships. Often, both knowledge and data required to quantify relevant processes are incomplete as the consequence of, for example, inaccuracy in measured data, the stochastic nature of processes, or the lack of process knowledge and data. Expert estimates are commonly needed to complete knowledge and fill data gaps. Hence, applied knowledge and data are subject to uncertainty that affects the reliability of generated information, and hence decision processes (be it policy-oriented or studies aimed at developing new farming systems) based on this information (e.g. Bouman et al., 1998; Ten Berge et al., 2000).

The goal of this chapter is to analyze the effects of uncertainty caused by a lack of knowledge and limited data availability concerning three important N-relationships relevant for quantification of future-oriented land use systems. Data and process knowledge as applied in LUCTOR (Land Use Crop Technical coefficient generatOR) are used as a case study (Hengsdijk et al., 1999). LUCTOR is developed for design and quantification of cropping systems in the humid lowlands of the northern Atlantic zone of Costa Rica. Nitrogen relationships applied in LUCTOR are essentially the same as those used for quantification of cropping systems in future-oriented studies performed in other regions (e.g. Van Duivenbooden and Veeneklaas, 1993; De Koning et al., 1995; Quak et al., 1996). Identification of uncertainty at the designer's desk allows taking uncertainty into account before applying engineered land use systems in model studies or testing such systems in practice. Uncertainty is made explicit with the goal of better managing or reducing it.

First, N-relationships as modeled in LUCTOR are described and their major characteristics discussed. Subsequently, three N-relationships in LUCTOR are identified that are subject to different sources of uncertainty. Consequences of uncertainty are analyzed for selected technical coefficients of cropping systems, i.e. N-loss and production costs. Finally, specific conclusions are drawn with respect to the consequences of uncertainty in the discussed N-relationships and general conclusions are drawn as to how this type of analyses can support systems design.

3.2 Modeled N-relationships in LUCTOR

Based on land-related objectives, LUCTOR integrates biophysical and technical information and enables quantification of technical coefficients of a large number of cropping systems, for example, with banana, black bean, cassava, grain maize, fresh maize cobs, palm heart, plantain and pineapple (both for export and the local market) for the northern Atlantic zone of Costa Rica (Hengsdijk et al., 1998; 1999). LUCTOR is a summary model in which processes and interactions are incorporated in a descriptive, rather than a explanatory fashion, with time steps of one year and focussing on strategic, rather than tactical or operational decision-making (Penning de Vries, 1982). Cropping systems generated with LUCTOR are future-oriented in the sense that explicit aims guide their outputs and inputs, while taking into account the available natural resources and various well-accepted agro-ecological principles. Nitrogen input and output of cropping systems are calculated with the so-called 'target-oriented approach' (Van Ittersum and Rabbinge, 1997): first a crop output (e.g. in terms of N-uptake or N-emission) is determined and subsequently, the required N-input to realize this output. An important presumption in the calculation procedure is that N-balances of cropping systems are in equilibrium. Annual N-uptake and N-losses are replenished with N from natural sources and an amount of N externally supplied that is calculated by LUCTOR and called *N-requirement.* This is a generic term for all human-supplied N and may include fertilizers, manure, compost or any combination. In this chapter, we assume that N-requirements are applied as N-fertilizer only. In Fig. 3.1 the calculation procedure for N-requirements of annuals is schematically illustrated.



Available N = (atmospheric deposition + N-fixation + crop residue-N) * N-recovery

N-requirement = (crop N-uptake - available N) / N-recovery

Fig. 3.1
A schematic presentation of the procedure applied to calculate N-requirements of annual systems in LUCTOR.

First, total crop N-uptake is calculated. For all crop types, yield levels, dry matter distribution over crop parts and their minimum and maximum N-concentrations are determined based on various information sources as described below. It is assumed that the highest N-concentrations in crop parts match with the highest yields and the lowest N-concentrations with the lowest yields (Van Keulen and Wolf, 1986). Linear regression between minimum and maximum N-concentrations results for each given yield in associated N-concentrations of crop parts. Multiplication of dry matter of the various crop parts with their associated N-concentration gives total crop uptake. For black bean it is assumed that 75% of the total N-uptake originates from the crops' specific N-fixing capacity. Based on empirical data, Giller and Wilson (1991) estimated maximum N fixation by grain legumes to vary between 72 and 98% of their total N-uptake.

Second, the N-loss fraction is determined comprising losses due to volatilization, (de)nitrification, leaching and erosion. Volatilization losses via ammonia were estimated at 5% of N supplied to the system since soils in the northern Atlantic zone have predominantly low pH and it is assumed that the type of supplied N is little sensitive to ammonia emission. The (de)nitrification losses via nitric oxide (NO) and nitrous oxide (N_2O) were estimated to vary between 6 and 10% of supplied N, depending on the type of soil (Eichner, 1990; Veldkamp and Keller, 1997). Leaching losses were estimated as a function of the amount of rainfall percolated below the rooting zone, since N-losses are closely related to the downward water flow. The percentage of supplied N leached with the percolated water, is arbitrarily set at 60% of the ratio between percolated and infiltrated water, of which the latter is derived from Sevenhuysen and Maebe (1995). This implies that if all infiltrated water percolates below the rooting zone; at most, 60% of the supplied N disappears from the system. Possible effects of drainage on the infiltration-percolation characteristics of soils are accounted for. Erosion is of minor importance in the relatively flat northern Atlantic zone with volcanic soils that have high hydraulic conductivity (Dercksen, 1991). Nitrogen lost via erosion varies between 1.7 and 2.4 kg N ha^{-1} y^{-1} depending on soil type. Summation of the various loss fractions results in the total loss fraction, which is complementary to the N-recovery.

Using the calculated N-recovery, the available N is determined based on the N-supply from natural sources (fixation by symbiotic bacteria and atmospheric deposition), totaling 7 kg ha^{-1} y^{-1} (Stoorvogel, 1993), and N taken up by crop parts that remain in the field after harvest. Actually, it is assumed that N taken up by roots and residual crop parts is continuously recycled within the cropping system, while taking into account the calculated N-recovery. For annual crops, the recovery of recycled residue-N is 60% of the calculated N-recovery, since they only take up N during a part of the year, in contrast to perennials that take up N throughout the year. It is further assumed that mineralization and immobilization of soil N is a continuous process that has reached a steady state and does not affect the soil N-stock of cropping systems.

Finally, N-requirements of cropping systems are determined based on the calculated N-recoveries, total crop N-uptake and available N (Fig. 3.1).

3.3 Analysis of nitrogen input and output

Often, N-crop relationships are analyzed using three associated relationships (De Wit, 1953): (a) the relation between yield and N-uptake of which the ratio is called the N-utilization efficiency, (b) the relation between N-application rate and N-uptake of which the ratio is called the N-uptake efficiency or N-recovery, while the third one can be derived from the previous two, namely, (c) the relation between N-application rate and yield of which the ratio is called the N-use efficiency. These relationships are graphically shown in Fig. 3.2.

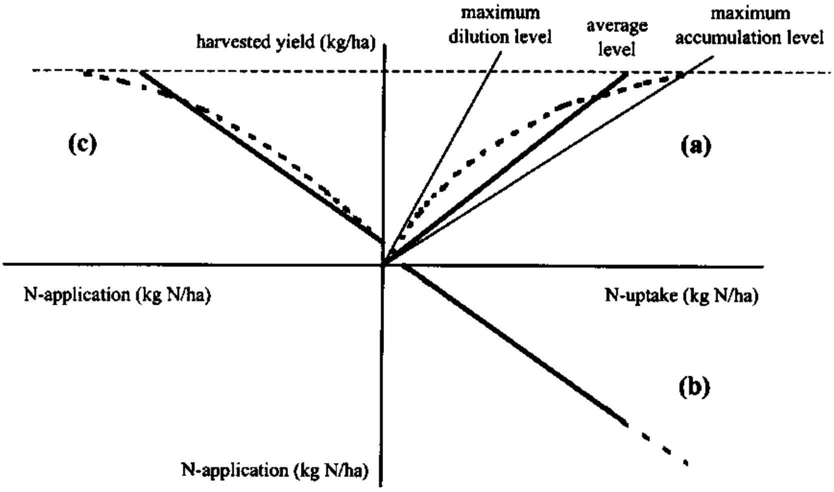


Fig. 3.2

A standard graphical analysis of crop response to N applications showing the relation between (a) harvested yield and uptake (N-utilization efficiency), (b) N-uptake and N-application (N-uptake efficiency), and (c) N-application and harvested yield (N-use efficiency). Solid lines indicate relationships using constant N-concentrations in plant tissue (constant N-efficiency), while dashed lines are based on increasing N-concentrations (decreasing N-efficiency) with increasing yields (also see text).

Analysis of N-relationships of cropping systems engineered with LUCTOR can be performed largely along these relationships, but due to particular design characteristics, LUCTOR differs in one aspect. The term *N-requirement* is used instead of *N-application* since no N-response reaction is analyzed, but an external amount of N required to maintain a well-defined production level is calculated. Though N-application and N-requirement have much in common, they are not the same. Since we aim at balancing N-input and -output of cropping systems (zero change in soil N-stock) the relationship between N-requirement and yield has no intercept with the yield axis, as does the relation between N-application and yield shown in quadrant (c) of Fig. 3.2. In general, zero N-applications result in low yields and depletion of soil N-stocks and these situations are not considered in LUCTOR.

Although N-application and N-requirement are not completely exchangeable, in the following, the terms N-use efficiency, N-uptake efficiency and N-utilization efficiency are maintained, implicitly referring to the ratio between harvested yield and N-requirement, N-uptake and N-requirement, and yield and N-uptake, respectively.

3.4 Uncertainty in N-relationships

Uncertainty is caused by variability in random processes and a lack of understanding of how the real world works. In agro-ecological models, both result in uncertainty with respect to input data and process knowledge, and consequently, in model output. In this chapter, uncertainty caused by lack of knowledge and limited data availability concerning three N-relationships is elaborated and effects on technical coefficients analyzed.

3.4.1 N-leaching as function of crop characteristics

Uncertainty exists as to how N-losses are exactly determined by factors, such as climate, soil, crop, management and their interaction. In LUCTOR, N-losses depend on a combination of rainfall and soil characteristics, for example, ample rainfall favors losses via leaching. Similarly, leaching losses will be high if crop characteristics are unfavorable for efficient N-uptake, for example, due to a poorly developed rooting system. Crop characteristics related to leaching are of particular importance in the humid Atlantic zone with an annual rainfall between 3000 and 6000 mm and year-round water surplus. The relationship between plant characteristics and N-leaching is, however, poorly understood and still difficult to quantify (Stockdale et al., 1997) but affects both N-utilization efficiency and N-use efficiency of cropping systems. Consequences of this uncertain relationship are made explicit by expanding the used knowledge base with a qualitative rating system for crop characteristics affecting N-leaching.

3.4.2 N-concentration as function of yield level

In LUCTOR, it is assumed that high N-concentrations are associated with high yields, and lower N-concentrations with low yields, resulting in decreasing N-utilization efficiencies and N-use efficiencies with increasing yields as shown in many experiments under *ceteris paribus* conditions (Van Keulen and Wolf, 1986). A fundamental question in this respect is whether N-concentrations necessarily increase with higher yields. De Wit (1992) hypothesized that most production resources (including N) are used more efficiently, and no production resources are used less efficiently with increasing yields, due to further optimization of growing conditions. This hypothesis implies that N-use efficiencies can be maintained at high values up to the highest production levels. In LUCTOR, other inputs than nitrogen (e.g. P, K and biocides) are tuned to the yield level aimed at, thus optimizing growing conditions and allowing to use N-inputs in the most efficient way. Under such conditions, constant N-use efficiencies may be feasible up to fairly high yield levels. Implicitly, this means that N-concentrations remain constant (and thus N-utilization and N-use efficiency) over the entire yield range. The area over which N-utilization efficiencies remain constant, is bounded by N-concentrations at a maximum dilution level, above which no plant growth is possible and by N-concentrations at a maximum accumulation level indicating that other growth factors are limiting (Janssen et al., 1990). Both bounds are shown in Fig. 3.2 together with the lines representing the hypotheses of decreasing and constant N-utilization efficiency and N-use efficiency. In this chapter, consequences of the alternative hypothesis are quantified, i.e. N-concentrations remain constant over the entire yield range.

3.4.3 Recovery of crop residue-N

Crop residue-N may become available for uptake by a subsequent crop after residue decomposition, a process that is governed by soil conditions (temperature, soil moisture content, etc.) and composition of the residual material (C/N ratio). This process is still poorly understood, i.e., whether crop residual-N contributes to the N-supply of a subsequent crop continues to be subject of discussion (e.g. Struik and Bonciarelli, 1997). In LUCTOR, residual N is recycled within the system after taking into account unavoidable losses, thus affecting N-use efficiency of cropping systems. In perennials, the recovery of residue-N is assumed identical to that for other N-sources (e.g. N-fertilizer). In annuals, however, recovery of residue-N is assumed to be lower due to poor synchronization between decomposition of crop residues and crop demand. Consequences of this uncertain relationship are quantified using a range of extreme values of residue-N recovery.

3.4.4 Type of uncertainty considered

Summarizing, the modeled N-relationships in LUCTOR include a number of uncertainties, caused by a combination of limited data availability and imperfect knowledge of involved processes. For example, quantitative information about root characteristics of many tropical crops is scarce while such traits may affect N-uptake of crops and, thus, N-losses due to leaching (O'Toole and Bland, 1987). Alternatively, methodological and empirical bottlenecks complicate a better understanding of the relationship between N-concentration and yield level. Underlying stochastic processes (e.g. weather) complicate quantification of the N-relationships, but they are not the topic of this chapter. In this chapter, relevant input parameters of LUCTOR are adjusted within well-defined ranges based on verifiable assumptions concerning the relationships involved. Hence, consequences of uncertainty in these relationships are made explicit, so that effects on N-losses and production costs of cropping systems can be assessed. Since future-oriented systems are subject to unknown future price regimes, relative input prices are used as prevailing in 1996 in the northern Atlantic zone.

3.5 Consequences of uncertain N-relationships

3.5.1 N-leaching as function of crop characteristics

Three key characteristics are identified that affect N-leaching and thus N-recovery of cropping systems in the humid Atlantic zone (De Willigen and Van Noordwijk, 1987): (i) root distribution and depth, (ii) fertilizer management, and (iii) length of the growing period.

Root distribution and depth are determining factors, since they dictate the soil volume that can be exploited. The deeper and denser roots are spread in the soil compartment, the more opportunity plants have to take up N before it percolates below the rooting zone. Fertilizer management refers to the frequency and location of N application. In banana and plantain, for example, fertilizer is applied once a fortnight at the base of each plant. In this situation, N-leaching is supposedly lower than in crops in which N is applied less frequently and broadcast as top-dressing. The length of the growing period relates to the available time plants have for N-uptake. In annuals, N-supply and demand must be synchronized in a limited part of the year, thus increasing the risk for N-losses, particularly in the stages shortly after sowing/planting. This in contrast to perennials that are able (and require) to take up N throughout the year, thus supposedly attaining higher N-recoveries.

Since quantitative information on effects of these key characteristics on N-leaching is lacking, crop types have been rated qualitatively for each characteristic. Ratings varied between 1 and 11, indicating that crop characteristics are favorable and unfavorable for leaching losses, respectively. Subsequently, the average rating has been converted into a quantitative value to modify the originally determined leaching loss fraction of each crop type. It is assumed that an average rating of 6 is equivalent to the originally calculated leaching loss, an average rating of 1 increases leaching by 50%, and an average rating of 11 decreases it 50%. In Table 3.1, the ratings for the three characteristics are given, including the average rating and the resulting N-recovery of cropping systems on a fertile well-drained soil. Ratings are based on a mixture of general expert knowledge and crop-specific information (Table 3.1). The average ratings indicate that, for example, leaching in palm heart is 30% less and in cassava 13% higher than without taking into account these key characteristics.

The relative change in N-recovery is less than that in leaching loss, since the total loss fraction also includes losses due to volatilization and (de)nitrification that are assumed not to be affected by these key characteristics. The originally estimated N-recoveries ranged from 0.48 (for banana and plantain) to 0.52 (for other crop types), while the crop-specific recoveries vary between 0.38 and 0.63. Consequences of the adjusted N-recoveries for the total amount of N lost in different cropping systems are shown in Fig. 3.3a.

Table 3.1

Qualitative ratings for three key crop characteristics affecting N-leaching, and the adjusted N-recovery for cropping systems on a fertile well-drained soil.

	Root distribution	Growing period	Fertilizer management	Average rating	N-recovery
Banana	1	11	11	7.7	0.55
Black bean	3	1	3	2.3	0.38
Cassava	5	6	3	4.7	0.47
Maize cobs	4	1	3	2.7	0.39
Maize grain	4	1	3	2.7	0.39
Palm heart	9	11	7	9.0	0.63
Pineapple for export market	3	9	8	6.7	0.54
Pineapple for local market	2	9	7	6.0	0.52
Plantain	1	11	11	7.7	0.55

Sources: Van Noordwijk, 1987; De Willigen & Van Noordwijk, 1986; Gowen, 1995

Annuals all show an increase in N-loss per hectare as the consequence of lower N-recoveries, up to 70% for black bean, while perennials show a decrease in N-losses, up to almost 40% for palm heart, due to higher N-recoveries. In Fig. 3.3a and following figures only percentage changes compared to the base values are shown, for comparison among cropping systems. This implies that systems with a *relatively* large increase in N-loss still may have a low absolute N-loss per hectare compared to systems with smaller relative changes. For example, the black bean systems in Fig. 3.3a have the highest relative increase in N-loss, but at the highest yield levels, N-loss of black bean is less than 50 kg ha^{-1} while N-losses of other cropping systems at the highest yield levels are at least twice as high.

In Fig. 3.3b consequences of crop-specific N-recoveries in terms of production costs per hectare are shown as function of different yield levels. Higher N-requirements of annuals, as a consequence of lower N-recoveries, result in increased production costs, while in perennial systems costs decrease as a consequence of higher N-recoveries. Effects are stronger at higher yields since the share of costs associated with N-requirements (fertilizer and labor costs for application) in total costs increases. Changes in costs compared to the non-crop specific recoveries never exceed 8%. The change in production costs of both crops with the greatest positive and negative change in N-loss in Fig. 3.3a, black bean and palm heart, respectively, is distinct. While production costs of black bean increase less than 2%, the costs of palm heart decrease with almost 8% due to differences in the share of N-fertilizer costs in total costs which is much smaller for black bean.

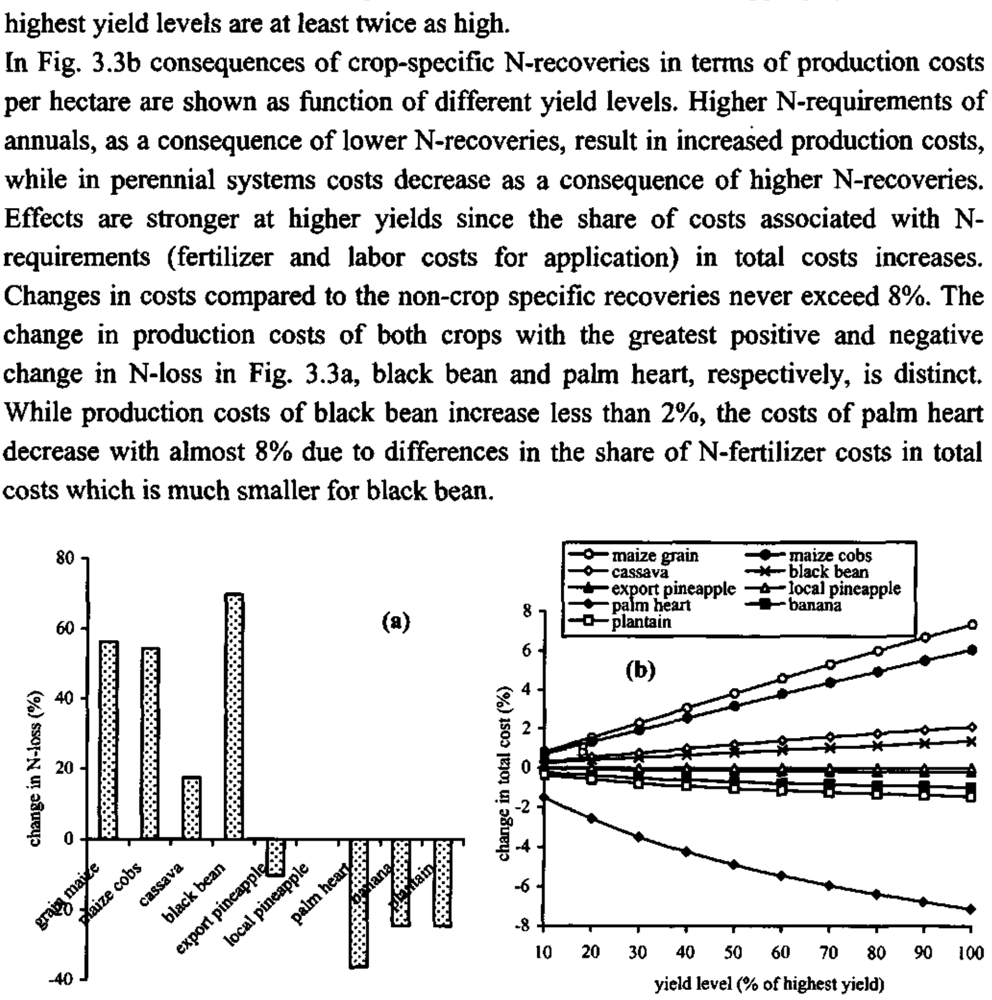


Fig. 3.3

Percentage change in N-loss (a) and total production costs (b) of cropping systems as a consequence of using crop specific N-recoveries.

3.5.2 N-concentration as a function of yield level

In the original setting of LUCTOR, N-concentrations in crop parts increase with higher yields, thus simulating lower N-use efficiencies at higher yields. To analyze the effect of N-use efficiencies that remain constant up to the highest yield level on technical coefficients, N-concentrations of crop parts have been kept constant over the entire yield range. Average N-concentrations of crop parts were used based on the minimum and maximum values as defined in LUCTOR. In Fig. 3.2, this average N-concentration is indicated as the 'average level'. As the result of constant recoveries and N-concentrations, N-use efficiencies of cropping systems remain high up to the highest yield level. In Fig. 3.4, this effect is illustrated for N-relationships in a system with maize cobs and compared to the assumption that N-concentrations increase with yield level. With constant N-concentrations, N-use efficiencies are lower in the lower yield ranges and higher in the higher yield ranges compared to increasing N-concentrations at higher yield levels (Quadrants (a) and (c) of Fig. 3.4). With a diminishing use-efficiency at higher yields, N-requirement is almost 60 kg N ha^{-1} higher at the highest maize yield level compared to using a constant use-efficiency. At the lowest yield level, N-requirement using a constant N-use efficiency is only 5 kg N ha^{-1} higher.

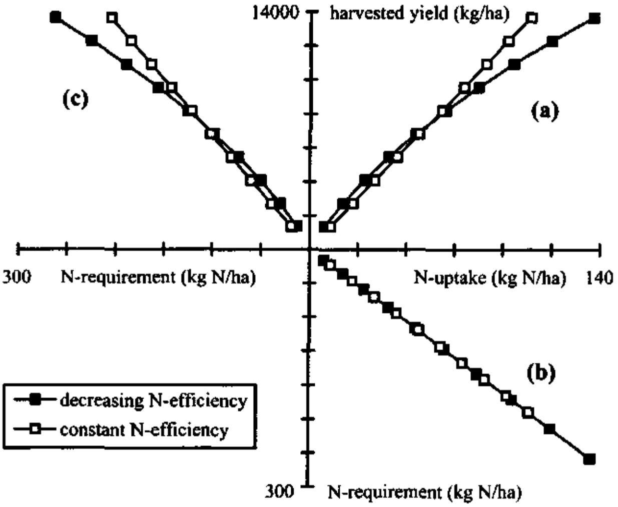


Fig. 3.4

Nitrogen relationships generated for maize (fresh cobs) systems with constant and diminishing N-utilization efficiency and N-use efficiency.

In Fig. 3.5a, change in N-loss per hectare of cropping systems as function of the yield level is shown using constant efficiencies. In the lower yield ranges, N-loss using constant efficiencies is up to 40% higher (for maize systems). In the higher yield ranges, N-loss is up to 25% lower using constant efficiencies. For banana and plantain, deviations are smallest and for maize largest, since the minimum and maximum N-concentrations of maize differed more than those of other crops.

In Fig. 3.5b, the economic consequences of using a constant N-use efficiency in terms of production costs per hectare of cropping systems are shown as function of yield level. The higher N-requirements at lower yield levels, as the consequence of using constant N-use efficiencies result for all cropping systems in only slightly higher production costs. There is a difference between on the one hand cassava, palm heart and both maize systems and on the other hand banana, plantain, black bean and both pineapple systems. In the former group, N-fertilizer costs make a much higher contribution to total costs than in the latter. The difference between both groups is even more obvious at higher yield levels, where the share of N-fertilizer costs in total costs is higher.

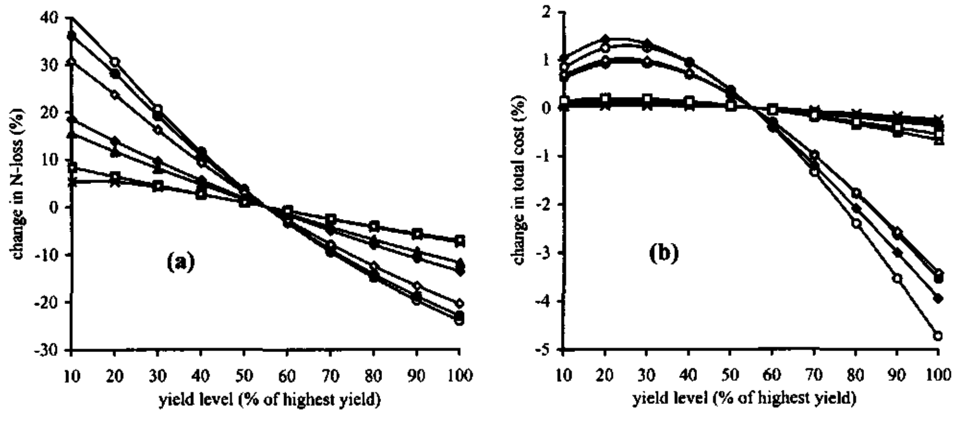


Fig. 3.5

Percentage change in N-loss (a) and total production costs (b) of cropping systems at different yield levels as a consequence of constant N-use efficiency compared to decreasing N-use efficiency at higher yield levels. See legend for Fig.3.3 for symbols.

3.5.3 Recovery of crop residue-N

Nitrogen from organic sources has to be transformed into inorganic form before it is available for crop uptake. Synchronization between release of inorganic-N (e.g. N from manure, catch crops, crop residues, etc.) and crop demand is a much studied phenomenon in agronomy (e.g. Van Faassen and Lebbink, 1990; Whitmore and Groot, 1997). Decomposition of organic matter depends on many factors, such as soil characteristics, temperature, soil moisture, composition of organic matter, etc., but is in general difficult to quantify both in amount and timing.

With respect to N-release from crop residues, two extreme positions are conceivable, i.e. one claiming that none of the crop residue-N becomes available for crop uptake (0% N-recovery) and one claiming that crop residue-N can be taken up without losses (100% N-recovery). The former position represents a situation in which crop residues decompose rapidly and the interval between harvest and replanting is so long that released N is lost before a subsequent crop can take it up. This situation is especially relevant for annuals that are grown once a year in a relatively short time-span. The situation of 100% N-recovery assumes that the release of crop residue-N is completely synchronized with crop uptake of the subsequent crop. This situation is relevant for perennials that take up N during the entire year. Since both theoretical points of view are unlikely to occur in practice, in LUCTOR an intermediate approach has been chosen. To account for non-synchronized release of crop residue-N in *annual* systems its N-recovery is set to 60% of the recovery used for other N sources (0.52, see earlier) resulting in 0.31. For crop residue-N in *perennial* systems the same N-recovery as for other N sources is applied, ranging between 0.48 (banana and plantain) and 0.52 (palm heart and pineapple).

In this section, both extreme viewpoints, 0 and 100% recovery of crop residue-N, are compared to the intermediate approach used in LUCTOR. In Fig. 6a, consequences for the calculated N-loss are shown. When none of the crop residue-N is recovered, N-losses increase up to almost 70% in palm heart while losses decrease when all crop residue-N is recovered. When no residue-N is recovered, N-losses of perennials increase relatively more than those of annuals, since the change in N-loss is compared with the base situation, in which N-recovery of crop residue-N is 0.31 for annuals and that for perennials between is 0.48 (banana and plantain) and 0.52 (palm heart and pineapple).

In Fig. 3.6b,c, the change in production costs of cropping systems is shown for 0 and 100% recovery of crop residue-N, respectively. In systems with a high share of N-fertilizer costs in total production costs (palm heart, cassava, and both maize systems), the costs increase (for 0% recovery) or decrease most (for 100% recovery).

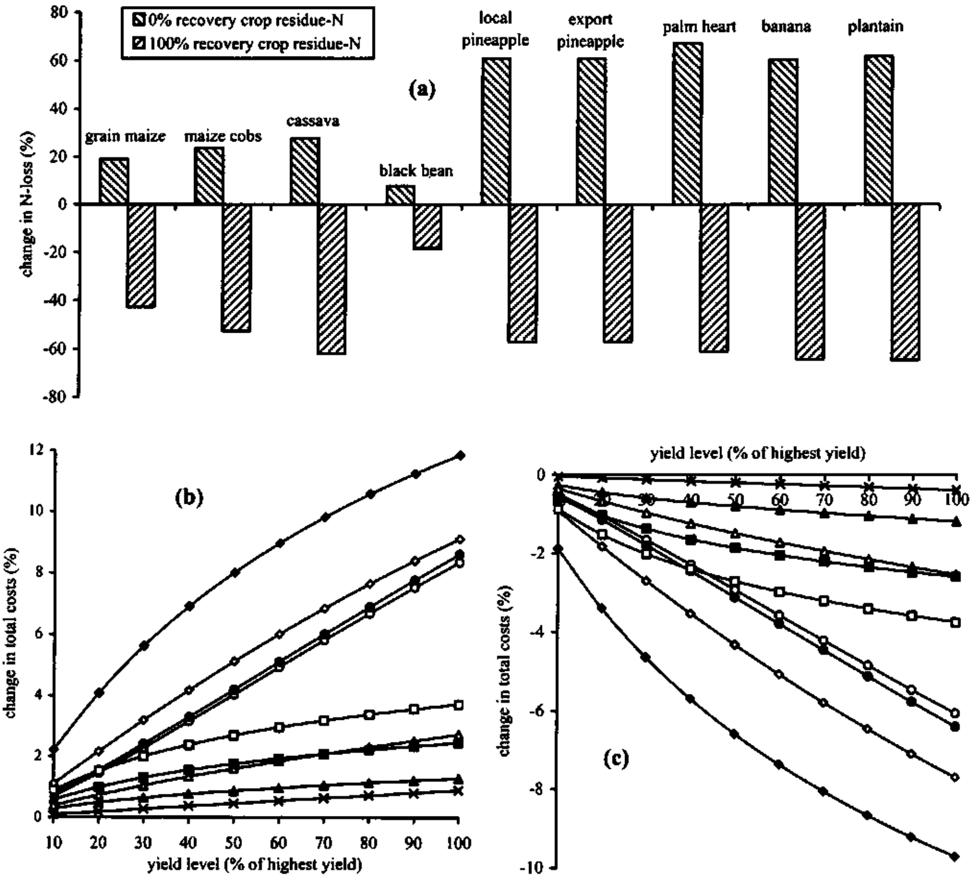


Fig. 3.6
Percentage change in N-loss of cropping systems as a consequence of different recovery fractions of crop residue-N (a); Percentage change in total production costs of cropping systems at different yield levels with 0 (b) and 100% (c) recovery of crop residue-N. See legend for Fig. 3.3 for symbols.

Production costs increase (Fig. 3.6b) or decrease (Fig. 3.6c) with increasing yield levels, since the share of costs associated with N-fertilizer application increases. As for both other N-relationships, the relative change in production cost as a consequence of modified N-recovery is much smaller than the effect on N-losses, which varies roughly between 10 and 70%, while the change in production costs only varies between 0 and 12%.

3.6 Discussion and conclusion

Effects of uncertainties in three important N-relationships in future-oriented cropping systems have been illustrated and quantified based on verifiable assumptions. The conclusions hold for the relationships in LUCTOR, but may be generalized to similar models, since the uncertainties studied relate to relationships with well-accepted relevance in agronomy. Since we focussed our analysis on uncertainty caused by a combination of data availability and imperfect knowledge of involved relationships rather than on uncertainty due to stochasticity, sophisticated methods like Monte-Carlo techniques are less suitable. Successful application of these methods relies on the assumption that uncertainty in the information source can be described by specifying probability distributions and mutual correlations (Janssen et al., 1994). Though underlying stochastic processes complicate understanding and quantification of many N-relationships, such processes are not the topic of this chapter. The type of uncertainty discussed in this chapter is also present in (agro-)ecological simulation models that describe processes in a more detailed fashion (e.g. Reckhow, 1994; Diekkrüger et al., 1995). The size and complexity of such models, coupled with limited empirical data available to calibrate and validate them, calls for summary models with less data requirements and less detailed description of processes. Summary models may have less explanatory power but they often perform better or equivalent to complex models, while the uncertainty caused by both data availability and imperfect knowledge can be better managed (Van Grinsven et al., 1995; Wegehenkel, 2000). Straightforward partial analyses as presented in this chapter, describe as to how uncertainty in information of a summary model, i.e. LUCTOR, affects technical coefficients of land use systems.

Table 3.2

Summary of the consequences of different assumptions for the three relationships, for N-loss and production costs of cropping systems. Numbers indicate the minimum and maximum percentage change (for all crop types and yield levels) compared to the base calculations with LUCTOR.

Relationship:	N-loss[1]	Production costs[1]
Crop specific N-leaching and N-recovery	–36% and +70%	–7% and +7%
N-concentration as function of yield level	–23% and +40%	–5% and +1%
Recovery of crop residue-N	–64% and +67%	–10 and +12%

[1] Low relative values may imply high absolute changes while for high relative values the reverse may be true.

The relationships analyzed affect biophysical characteristics (i.e. N-loss) relatively more than economic characteristics of land use systems (i.e. production costs). In Table 3.2, a summary is given of the effects of the three relationships on N-loss and production costs. Under the humid conditions of the northern Atlantic zone of Costa Rica, N-recoveries of cropping systems are almost one-to-one related to their N-leaching losses, while the change in total production costs as a consequence of variations in N-requirements is related to the share of N-fertilizer costs in total costs. At higher levels of N-fertilizer (and thus yield levels, following the target-oriented approach), the share of N-fertilizer costs in total costs increases and thus the effect of the variable N-relationship on production costs increases. The hypothesis that N-concentrations remain constant up to the highest yield levels showed the smallest effects for most cropping systems. Still, for maize systems, N-loss is about 40% higher and 23% lower in the lower and higher yield ranges, respectively, assuming constant average N-concentrations instead of higher N-concentrations at higher yields. Production costs are less than 5% lower or higher compared to the situation assuming decreasing N-use efficiencies. Recovery of crop residue-N has major effects on N-loss: a change of up to 67% compared to the base situation in which recovery of residue-N in annuals was assumed to be a little lower and in perennials equal to the recovery of other N sources. But also here, the economic consequences are relatively small, i.e. total costs change less than 12% as consequence of adjusted N-requirements.

When the focus is on accurate characterization of physical N-inputs and outputs of future-oriented systems, all three relationships should be carefully considered. When interests in other characteristics of land use systems prevail, e.g. production costs, accurate description of the processes underlying these N-relationships is less important. The share of costs associated with N-fertilizer management in total production costs is an important indicator as to how relevant it is to reduce uncertainty of these relationships. It must be kept in mind that in the current analysis costs are based on relative input prices as prevailing in 1996. Changes in future price relationships, however, can easily be incorporated in LUCTOR and their effects analyzed (Hengsdijk et al., 1999).

Partial uncertainty analyses as presented, support further development and application of systems design at farm or regional scale in three ways. First, uncertainty in technical coefficients characterizing future-oriented land use systems is made explicit. Ranges are identified within which values of technical coefficients may vary, depending on the knowledge and data used. Consequences of uncertainty can be considered more carefully before testing new land use systems in practice or applying them in land use models. Second, these analyses may support design of systems with smaller uncertainty margins. For example, crop choice, operations aimed at optimizing growing conditions or recovery of crop residue-N all affect the analyzed relationships differentially. When uncertainty of technical coefficients of a particular land use system is large and cannot be reduced or is difficult to manage due to, for example, interactions with driving variables that have a stochastic nature (e.g. weather), alternative land use systems (other crops, other treatment of crop residues, etc.) may be considered which have smaller uncertainty margins. Such alternatives may have more robust technical coefficients, and form therefore a more reliable basis for decision-making. Finally, the existence of uncertainty does not imply that engineered systems are inaccurate *per se* and generated technical coefficients unreliable, but merely indicates that our understanding of agro-ecological processes is still limited and that we have to take future decisions while taking into account such uncertainty. Analyses as presented are helpful to pinpoint data and knowledge gaps and to identify, often disciplinary, research topics aimed at more complete data sets and better understanding of involved processes thus allowing to reduce uncertainty of generated information in future-oriented studies.

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Chapter 4

The effect of temporal variation on inputs and outputs of future-oriented land use systems in West Africa

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4 The effect of temporal variation on inputs and outputs of future-oriented land use systems in West Africa

Abstract

The (semi-) arid area of West Africa is characterized by erratic rainfall that causes highly variable performances of cropping systems. This creates difficulties in strategic decision-making based on future-oriented production systems. In this chapter the degree of variation in inputs and outputs of future-oriented millet (*Pennisetum glaucum* L.) systems is quantified using a dynamic crop growth simulation model and a static technical coefficient generator. To determine inputs and outputs of future-oriented millet systems under (semi-) arid conditions, the target-oriented approach is operationalized for low-yielding conditions. Economic yield, N-loss and labor requirement are used as benchmarks for outputs and inputs of future-oriented land use systems. Weather data for 31 year characterize two sites in the (semi-) arid zone of Mali, while for each site two soil types with distinct properties were considered. In all four physical environments, inputs and outputs of millet systems have coefficients of variation (CV) exceeding 50%.

Consequences of the variable performances of these systems are discussed for both policy makers and designers of future-oriented systems. Engineering tools exist which help policy makers to quantify consequences of variability at different scale levels so that variability can be reduced or better managed. Examples are given of future-oriented cropping systems aimed at less variable yield. At one site, fine tuning of the sowing date to seasonal water availability reduced CVs of yield to 20-30% while long-term average yields increased with 40 to more than 130%. Water conservation measures increased yields with 40 to 230% and reduced their CVs with 28-50% in all four physical environments. Effects of various cultivation methods on the variability in inputs and outputs of future-oriented cropping systems can be rapidly explored using these tools. In addition, systematic analysis using such tools allows explicit analysis of gains and costs of various alternatives simultaneously.

4.1 Introduction

One of the main problems decision-makers on land use and food security have to cope with is an unpredictable and uncertain environment, both from an economic (e.g. prices or labor availability) and biophysical (e.g. weather or the incidence of diseases) point of view. Nowhere is the variable environment more manifest than in the (semi-) arid regions of West Africa where crop failure due to, for example, extremely low rainfall can be a matter of life and death. The challenge for agricultural research is to identify the sources of variability and to examine its consequences so that variability can be reduced or properly managed.

Options for agricultural development can be explored using computer-aided designs of future-oriented cropping systems (De Wit et al., 1988; Rossing et al., 1997). Such quantified designs are based on mathematical representations of established agro-ecological relationships, while taking into account the available resources and land related objectives in a given area. Exploring systems at the designers' desk is a flexible and economically efficient method to rapidly screen a wide range of alternative systems.

Crop growth simulation models, taking into account soil-crop-atmosphere interactions are often used to analyze temporal variation in yields (Muchow and Bellamy, 1991; Van Keulen and Seligman, 1992). Such variation, however, is likely to affect other outputs and inputs of future-oriented land use systems, such as fertilizer N-loss and labor requirements that in this chapter are used as benchmark for other outputs and inputs, respectively.

The objective of this chapter is first to quantify the degree of temporal variation in inputs and outputs of future-oriented cropping systems. Data from the (semi-) arid Sudano-Sahelian zone in Mali are used in a case study. Interactions among environmental factors and the crop are illustrated for four millet systems with distinct soil and weather properties. Secondly, based on these results, consequences of the variable performance of cropping systems for policy makers and system designers are discussed. Examples are given of the use of engineering tools to design future-oriented land use systems with less variable performance.

To enable quantification of temporal variation of inputs and outputs of future-oriented systems in (semi-) arid areas, the so-called target-oriented approach must be operationalized for such variable and uncertain conditions (Van Ittersum and Rabbinge, 1997). Hence, before analyzing the effects of temporal variation on inputs and outputs, this concept is discussed and operationalized in the context of such extreme conditions. Subsequently, the tools and underlying data are described that are used to quantify the temporal variation in millet systems in the case study area. A dynamic crop growth simulation model is used to determine water-limited yields for 31 years of weather data. Water-limited yields can be realized with natural moisture supply while the crop is optimally supplied with nutrients and protected against pests, weeds and diseases. These yields are used as target output to quantify fertilizer N-loss and labor requirements using a static technical coefficient generator that has been developed to quantify various types of inputs and outputs of land use systems in the Sudano-Sahelian zone. Finally, some general conclusions are drawn with respect to the applicability of this type of analysis for related research aimed at managing variability.

4.2 Methodology

4.2.1 Application of the target-oriented approach under temporal variation

The target-oriented approach is applied to tailor inputs to outputs of future-oriented systems (Van Ittersum and Rabbinge, 1997). The concept of the target-oriented approach is based on the assumption that for each agricultural output, not necessarily only yield, a minimum set of inputs can be defined with knowledge of the spatial and temporal variation in the physical environment. Based on empirical insights and theoretical knowledge of the underlying processes of plant production, the minimum primary inputs (seed, water, nutrients) required for a given yield level can be calculated. This combination of primary inputs defines under given circumstances the agronomic optimum, i.e. the most efficient mix of inputs from a production ecological point of view. The required combination of secondary inputs, such as labor, machinery and biocides to realize the specified yield level is ambiguous, since many substitution possibilities exists. For these inputs no optimum combination exist, but empirical knowledge, and site-specific constraints and objectives may guide the identification of their optimum mix.

Future-oriented studies aim at exploring possibilities for agricultural development. In arid and semi-arid areas, variable water availability causes temporal variation in water-limited yields that ultimately define (im)possibilities for rainfed agriculture. Often, interests are beyond exploring biophysical frontiers, and options also need to be expressed in economic (e.g. net return), social (e.g. labor requirements) or environmental (e.g. N-losses) terms. Such relevant characteristics of future-oriented land use systems can be calculated using the target-oriented approach.

Analysis of the effects of temporal variation on outputs and inputs in years with extremely low yields or even crop failure, introduces both conceptual and agronomic difficulties. The target-oriented approach assumes perfect tailoring of inputs to outputs, and consequently inputs in years with crop failure should be zero. However, that presents a serious conceptual simplification when interests are also in exploring the effects of variation on, for example, labor requirements and N-losses of land use systems. Even in years with crop failure, inputs will be required to establish a crop (e.g. field preparation, seed, sowing, starter N-gift). Agronomic problems relate to lack of knowledge and/or uncertainty on agronomic relations under low yield conditions. Fine-tuning of inputs to realize specific outputs is based on a combination of theoretical and empirical knowledge, usually gained by explanatory modeling and experimental research, respectively. Such models are developed for well-defined conditions with a limited number of (interacting) variables and experiments are performed under well-controlled conditions. These situations differ sharply from low yielding conditions in which various growth defining and reducing factors may interact simultaneously in a complex fashion that is (still) difficult to quantify in general operational formulations. For example, labor requirements for weeding, one of the most labor-demanding operations in growing millet, are difficult to estimate under dry conditions: Weed growth may be reduced similarly to crop growth which reduces labor requirements for weeding, but weed species more adapted to drought may require more weeding in low yield conditions.

To operationalize the target-oriented approach under low yield conditions, the following assumptions have been made: In a year with crop failure, inputs required up to the moment of first weeding are accounted for, including a basal dressing of 20 kg N ha^{-1} at sowing. This practice may imply that more N enters the system than is removed via harvested crop parts and losses, i.e. the externally applied fertilizer N may contribute to the soil N-stock. Moreover, it is assumed that labor requirements for weeding linearly increase with crop yield.

4.2.2 Study site

Water-limited yields of millet are simulated for two regions in Mali with distinctly different rainfall, Koutiala (12° 24′ N, 05° 28′ W) in the Sudanian zone and Mopti (14° 41′ N, 04° 06′ W) in the South Sahelian zone. Based on long-term daily weather data during 31 years (1950-1980), average annual rainfall in Koutiala is 1000 mm (std = 189 mm), in Mopti it is 549 mm (std = 130 mm). In Fig. 4.1A annual rainfall for the years 1950-1980 is shown, while Fig. 4.1B shows the average accumulated annual rainfall in both regions.

Average annual rainfall decreases with time, as has been described before (Sivakumar, 1989), which may affect the magnitude of variability of inputs and outputs of future-oriented land use systems. Rainfall probability distributions are shown in Fig. 4.1C. Probability that rainfall varies between –20 and +20% of the long-term average is higher in Koutiala than in Mopti, 74 and 55%, respectively.

For both regions, two soil types are considered, typical for the Sudano-Sahelian zone (PIRT, 1983). Their major characteristics are given in Table 4.1. While soil type A is a shallow soil with high runoff, soil type B has more favorable characteristics for retaining precipitation.

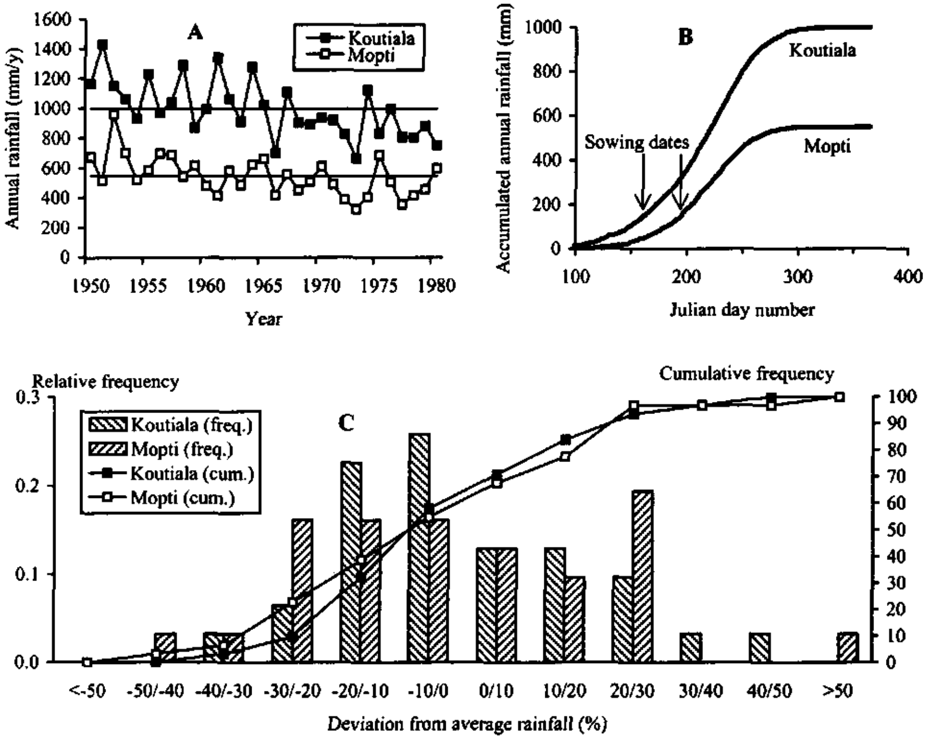

Fig. 4.1

Annual rainfall in Koutiala and Mopti during 1950-1981 (A), average accumulated annual rainfall in both regions with the sowing dates indicated (B), and probability of rainfall distribution (C).

Table 4.1

Major characteristics of the two soil types used in the simulations for Koutiala and Mopti, between brackets the approximated FAO soil classification.

	Soil type A (Leptosols)	Soil type B (Lixisols)
Texture	Gravelly	Loamy clay
Rooting depth (cm)	50	150
Non-infiltrating fraction of annual rainfall	0.50	0.25
Soil moisture content at field capacity (cm^3 cm^{-3})	0.098	0.348
Soil moisture content at wilting point (cm^3 cm^{-3})	0.058	0.167
Water holding capacity (cm^3 cm^{-3})	0.040	0.181

4.2.3 Calculation of water-limited yields

To calculate water-limited yields of millet, a calibrated generic dynamic crop growth simulation model WOFOST (version 7.1) is used (Boogaard et al., 1998). WOFOST simulates daily crop growth rate, based on climatic conditions (i.e. prevailing solar radiation, temperature and amount and distribution of rainfall), soil properties (i.e. soil depth, water holding capacity and infiltration capacity) and crop characteristics (i.e. length of growing cycle, photosynthetic characteristics and distribution of dry matter). A daily water balance keeps track of water entering and leaving the rooting zone. Water enters the rooting zone through rainfall while taking into account soil type specific non-infiltrating fractions (Table 4.1). Water leaves the rooting zone by soil evaporation, percolation and crop uptake used for transpiration. Under optimal water supply, crop uptake equals potential transpiration, under sub-optimal supply the transpiration rate is reduced. This reduces photosynthesis rate proportionally, resulting in reduced growth and yields. Severe drought may result in complete crop failure. The water-limited production level, calculated in this way, assumes that nutrient availability, weed, pest and disease control, and crop management are optimal for the calculated yield level. Sowing dates of millet were set to June 15 in Koutiala and July 16 in Mopti according to regional crop calendars (Fig. 4.1b). For both regions, a millet variety with a short growing cycle (< 80 days) was used. Although WOFOST has not been validated for either region, it has been applied in other parts of West Africa (Van Keulen and Van Diepen, 1990). As simulated yields are in the range that may be expected and interactions between calculated yields and rainfall patterns are apparent, the model can be used to illustrate general effects of temporal weather variation on inputs and outputs of millet systems.

Subsequently, the simulated yields have been used as target output in a static technical coefficient generator to calculate labor requirements and fertilizer N-loss (Hengsdijk et al., 1996). Labor requirements are based on all cultivation operations that are required from the time of field preparation to harvesting of the main produce, or in the case of crop failure, up to first weeding (see previous section). Labor requirements for some of the operations depend on yield level, e.g. harvesting and weeding, while other operations, such as field preparation and sowing always have to be carried out and require a fixed amount of labor per hectare. Operations are performed differently on both soil types: operations on soil type B are mainly carried out with animal traction, while due to the stoniness of soil type A operations rely predominantly on manual labor. Consequently, labor requirements on soil A are higher for a given yield level. It is assumed that N-requirements are met using N-fertilizers only.

N-requirements are defined as the amount of external N-fertilizer, calculated by the technical coefficient generator, that is required for a zero change in soil N-stocks of future-oriented cropping systems. Hence, N removed from the system (via harvested product and losses) is replenished with a calculated amount of N-fertilizer, taking into account unavoidable losses. The N-loss fraction, i.e. the complement of the N-recovery, is estimated using four simplified relationships representing four processes underlying N-losses, i.e. leaching, runoff, volatilization and low crop uptake. Based on the pooled data for the simulated period, relative N-losses as consequence of each of these processes were estimated assuming linear relationships. The relationship between percolated rainfall and partial N-loss fraction due to leaching (Fig. 4.2A) indicates that N-leaching is highest at high percolation and no leaching happens at zero percolation. The relationship between runoff and partial N-loss fraction as consequence of the N-load in runoff water (Fig. 4.2B) shows that N-losses increase starting from a base runoff (39 mm) up to a maximum at the highest runoff simulated in Koutiala (543 mm). The relationship between the partial N-loss fraction due to volatilization and rainfall (Fig. 4.2C) shows that from a base rainfall (251 mm) N-losses linearly increase up to a maximum at the highest rainfall in a simulated period (1195 mm). Partial N-loss fractions decrease with higher crop yields (Fig. 4.2D). It is assumed that at higher crop productivity N-losses are relatively lower as consequence of better developed rooting system (e.g. less N-leaching) and soil cover (e.g. less N-runoff). The total N-loss fraction has been calculated as the average of the four partial N-loss processes. In Fig. 4.2E and F, the integrated effect of the four relationships is shown as function of the simulated yields and rainfall in the simulated period, respectively. Average N-loss fractions vary between ± 0.2 and 0.7, resulting in fertilizer N-recoveries between 0.8 and 0.3, respectively.

4.3 Results and discussion

4.3.1 Effects of temporal variation

On the basis of 31 years of weather data, economic yield, fertilizer N-loss and labor requirements were calculated for millet systems in both regions and for both soil types, i.e. four different physical environments. Based on frequency distributions of the inputs and outputs, their temporal variation was assessed and expressed as the standard deviation relative to the mean, i.e. the coefficient of variation (CV).

Yields

The relationship between total annual rainfall and simulated millet yields (Fig. 4.3A) showed that below 500 mm rainfall, rainfed crop production was extremely low and in

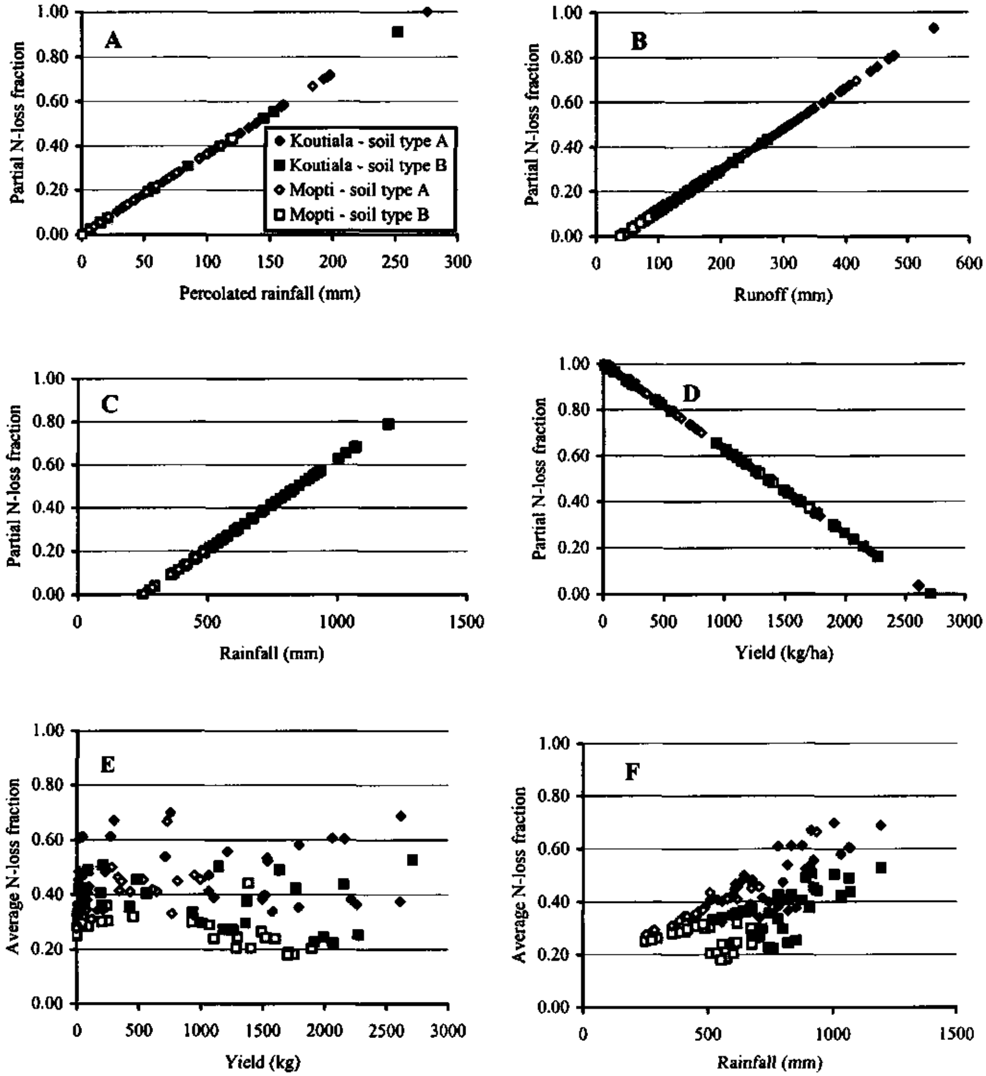

Fig. 4.2

Assumed partial N-loss fractions of millet systems as function of percolated rainfall (A), runoff (B), annual rainfall (C) and yields (D) using pooled data. In (E) and (F) the average N-loss fraction of these four relationships as function of yield and rainfall in the simulated period, respectively.

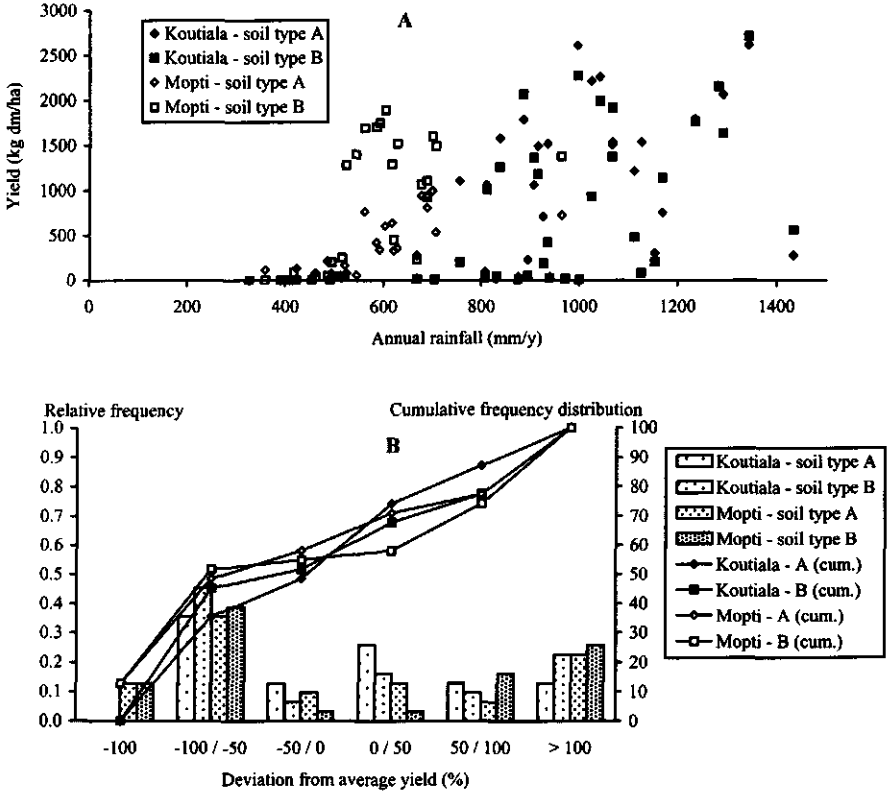

Fig. 4.3

Relationship between annual rainfall and simulated yield of millet systems (A) and distribution of simulated millet yields for each physical environment (B): Columns indicate the relative frequency in each deviation bin and lines the cumulative frequency distributions.

many years complete crop failure occurred. Above 500 mm rainfall, yields tended to increase with increasing rainfall although this relationship was not very robust for both regions and soil types. Even above 800 mm rainfall, production was often severely limited by water shortage, due to unfavorable distribution patterns.

Average yields in Koutiala for soil type A were about 20% higher than for soil type B since on soil type B a higher infiltration was required to reach wilting point and the higher soil moisture content resulted in higher soil surface evaporation losses. In Mopti average yields for soil type B were more than 100% higher than for soil type A as a consequence of the higher water holding capacity of soil type B. In Mopti, dry spells were more frequent than in Koutiala and the higher water holding capacity of soil type B acted under such conditions as a buffer that crops growing on soil type A were lacking.

Effects of highly erratic growing seasons are illustrated in Fig. 4.3B and Table 4.2, both showing large deviations from average simulated yields. In Mopti (on both soil types), crop failure occurred in more than 10% of the years, while for all four physical environments yields in at least 35% of the years were 50% or less than the calculated long-term average. In Mopti at soil type B, there was only 6% probability to achieve yields within ± 50% of the average yield, i.e. the probability of higher or lower yields than the average simulated yield was much higher. For the other three physical environments probabilities for yields within ± 50% of the long-term average were higher, but never exceeded 40%. The CVs (Table 4.2) also indicate the large variability in yields, which tended to be somewhat larger for Mopti than for Koutiala.

N-loss

N-losses from fertilizer were relatively low over a wide range of rainfall for all four physical environments, i.e. less than 30 kg ha^{-1} (Fig. 4.4A). Above 1200 mm rainfall, N-losses tended to increase more rapidly due to a combination of greater N-loss fractions (Fig. 4.2F) and more years with higher yields (requiring more fertilizer N) at higher rainfall.

Table 4.2

Effect of temporal variation on yields, N-loss and labor requirements for two regions in Mali (Koutiala and Mopti) and two soil types (A and B).

	Koutiala		Mopti	
	A	B	A	B
Yields (kg dm ha^{-1})				
Average	1085	876	316	696
Minimum	8	8	0	0
Maximum	2614	2710	995	1897
Standard deviation (CV%)	870 (80)	853 (97)	332 (105)	716 (103)
N-loss (kg ha^{-1})				
Average	30	14	8	7
Minimum	1	>0	>0	1
Maximum	177	90	29	24
Standard deviation (CV%)	35 (114)	17 (119)	6 (79)	4 (60)
Labor requirements (man-day ha^{-1})				
Average	51	43	22	37
Minimum	11	15	10	14
Maximum	107	103	47	76
Standard deviation (CV%)	32 (63)	28 (64)	12 (54)	23 (62)

Deviations from the long-term average N-losses for each of the four physical environments are shown in Fig. 4.4B. Though N-loss deviations were less than those for yields, they were still significant: Probabilities that N-losses in Koutiala were within ± 50% of the long-term average were 45 and 51% for soil types A and B, respectively. In Mopti these probabilities were 58 and 71%, respectively. Though N-losses in some cases may approach values that were 100% lower than the average N-loss, they never became zero (Table 4.2). Hence, some losses always occurred, though they were extremely low. Such low N-losses occurred at low yields where N-uptake almost entirely was provided by N from natural supply (rainfall and fixation by bacteria) while the starter fertilizer N-gift (20 kg N ha^{-1}) added to the soil N-stock. The lower CVs in Mopti were a consequence of the lower yields, associated with lower N-requirements and, thus lower fertilizer N-losses.

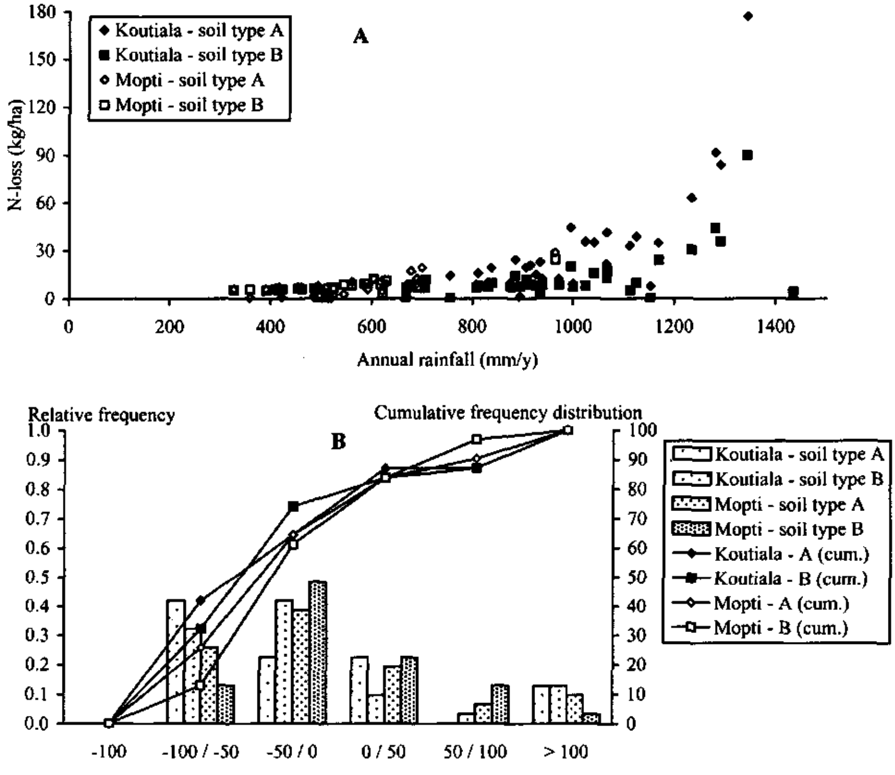

Fig. 4.4

Relationship between annual rainfall and N-loss of millet systems (A) and distribution of N-loss for each physical environment (B): Columns indicate the relative frequency in each deviation bin and lines the cumulative frequency distributions.

Labor requirement

The relationship between labor requirements and annual rainfall showed similarities with the yield-rainfall relationship (Fig. 4.3A). There was no strong relationship between labor requirements and rainfall. Labor requirements were related to yield levels, since for a number of operations they were yield-dependent. From the low rainfall ranges (below 500 mm), with regularly crop failures (Fig. 4.3A), the minimum labor requirements for crop establishment can be derived, namely 10-15 man-day ha^{-1}, depending on soil type.

Consequences of minimum labor requirements are also shown in Fig. 4.5, where the –100% bin is empty since labor requirements were never zero. Probabilities that labor requirements deviated more than 50% from their average for each physical environment were large. Only for Mopti (soil type A) the probability that labor requirements deviated less than 50% of the average exceeded 60%, for the other physical environments these probabilities were less than 40%. CVs were still high (Table 4.2) but in general lower than for N-losses and yields.

4.3.2 Future-oriented cropping systems

The results indicated that long-term average outputs and inputs of future-oriented cropping systems as determined for four different physical environments in the Sudano-Sahelian zone of Mali were not very precise unless temporal variation was explicitly taken into account. The magnitude of the error varied somewhat among the type of input or output, but was very high in all analyzed physical environments. Erratic rainfall patterns in relatively unfavorable physical environments caused large variations in characteristics of rainfed cropping systems.

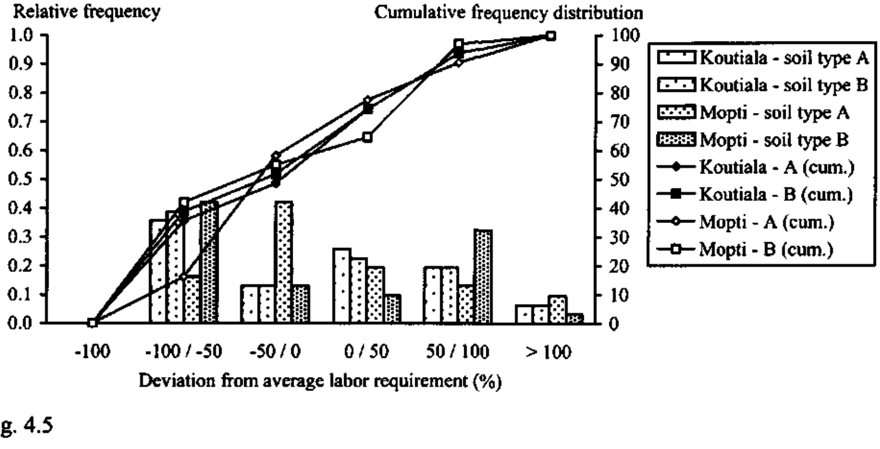

Fig. 4.5

Distribution of labor requirement for each physical environment: Columns indicate the relative frequency in each deviation bin and lines the cumulative frequency distributions.

What can we learn from this information and how should we deal with it in future-oriented policy studies or in the development of new farming systems? To answer this question it is necessary to distinguish between the consequences of temporal variation for policy-makers and designers of future-oriented systems since their points of view differ. Information on the probability of systems' performance helps policy-makers to manage variability and possibly related risk, more effectively. For designers, such information serves as basis for the design of systems with different degrees of variability. Hence, for both policy-makers and designers, information on temporal variability has a specific connotation and they, therefore, deal with it differently.

Policy-makers

Physical performances of cropping systems at the field level, as presented in the previous section, are often only of partial interest to decision-makers responsible for strategic policy formulation. Their main interests are the consequences of temporal variability at aggregate levels, i.e. farm households, regions or national levels. At these levels, poor physical performance of one type of cropping system can be compensated by favorable performance of others. The agricultural sector in the Sudano-Sahelian zone is organized at different spatial scale levels to reduce the risk of crop failure. At the field level, mixtures of varieties are often sown that respond differentially to water shortages (Vierich and Stoop, 1990), while at the farm household level, for example, crop diversification (Prudencio, 1993) and sowing along toposequences (Van Staveren and Stoop, 1985) aim at spreading such risks. At the regional or national scale, food shortages in one area may be compensated by food surpluses in other areas. In addition, yield variability is just one factor in income variability that is often of major interest to policy-makers. Variation in prices of inputs and outputs also contribute to income variability. In years with low yields, reduced aggregate supply may result in increased product prices that may stabilize incomes.

To gain insight in the consequences of temporal variability for such complex and interrelated processes at household or regional level, different approaches are required. Such approaches may be based on linear programming (LP) techniques that allow analysis of socio-economic, production and environmental aspects of land use in an integrated way. Decision support models based on LP contain a wide variety of land use systems (quantified in their inputs and outputs) that each may contribute to the objective(s) optimized. Inputs and outputs of land use systems can be defined for different probabilities, i.e. situations each representing distinct (expected) input and output levels. For example, land use systems can be characterized for both, years with above- and below-average yields. Subsequently, such land use systems can be used in several ways to illustrate the effects of temporal variability in inputs and outputs at aggregate levels. One method is to optimize an LP-model in separate runs with different sets of land use systems, each set representing a different probability, so that the consequences of temporal variability for the objective functions can be evaluated. Another method is to combine land use systems with different probabilities and optimize these together in an LP-model. Subsequently, various scenarios can be defined that represent different risk attitudes, expressed in different restrictions for (the) objective variable(s). For example, the degree of restriction on the permitted regional or farm household grain deficit in dry years may affect possible livestock production, which can be quantified in such an approach. It is beyond the scope of this chapter to discuss both methods here in detail but see e.g. Van Keulen and Veeneklaas (1993) and Bakker et al. (1998) for operationalization of the latter approach. Results of these types of models may draw attention of policy makers to the necessity of possible intervention measures or of development of alternative cropping systems with more stable performance under variable conditions. Aggregate systems (farms, regions, etc.) with many compensating factors may show only small differences among various likelihoods, while more vulnerable systems, with few alternatives may show similar fluctuations as the inputs and outputs of cropping systems presented in the previous section. Hence, different policy measures in relation to temporal variation will be required for vulnerable systems that may require active policy intervention to guarantee, for example, food security or a reasonable income. At the same time, development of alternative land use systems aimed at 'all-weather' performance may be stimulated, i.e. systems that show less variation in inputs and outputs under erratic weather conditions.

Designers of cropping systems

The millet systems as presented showed large variations in performance due to temporal variability. As discussed earlier, it is difficult to value variability of cropping system performance per se negatively or positively, since compensating effects may exist at aggregate levels. Variability also offers opportunities, certainly when variations in product prices are taken into account. Depending on the risk attitude of a producer, 'risky' systems may be preferred above less 'risky' ones and they, therefore, can not be excluded in an exploration of alternatives. Alternatively, to extend the choice portfolio, designers of future-oriented systems may aim at systems that show less variable performance.

Two examples are given of application of tools with the aim to develop systems of which the expected yield is less variable than shown in the previous systems. The first example refers to optimization of the sowing date, so that variability of expected yield of future-oriented cropping systems is lowest. Water-limited yields have been calculated with WOFOST using weekly sowing intervals starting 6 weeks before and ending 9 weeks after the originally set sowing date for Koutiala and Mopti, June 15 and July 16, respectively. Other data and settings of WOFOST are as described. In Fig. 4.6 results in terms of 95% confidence intervals are shown for each physical environment.

Graphs on the left hand side in Fig. 4.6 show the 95% confidence interval relative to the average yield for each sowing date, and graphs on the right hand side average yields and their 95% confidence interval at each sowing date. In all physical environments, confidence intervals of relative yields gradually decreased with delayed sowing date to a minimum, followed by an increase again. The minimum confidence intervals in Koutiala were considerably narrower than in Mopti indicating smaller CVs in yields. Moreover, in Koutiala, sowing dates with the lowest CVs (20-30%) were at soil type A 3 weeks and at soil type B even 5 weeks after the original sowing date. In Mopti, sowing dates with the lowest CVs (89-105%) were at soil type B only 2 weeks after and at soil type A at the original sowing date. Results for Koutiala indicate that the variability in expected yields could be reduced while at the same time the expected average yield level could be increased considerably (i.e. 40-135%) with a better fine tuning of the sowing dates. In Mopti neither much reduction in crop yield variability nor increase in yield level is to be expected by selecting an alternative sowing date. The erratic rainfall pattern in Mopti precludes yields with low CVs for this type of cropping system. Other systems have to be developed that are less susceptible to the erratic moisture supply during the growing season, resulting in reduced CV of water-limited yields.

The second example focuses on the design of such systems. Here, systems were assessed that included measures to improve water availability during the growing season. Construction of tied ridges creates depressions that retain rain water, increasing the surface water storage capacity of a system, thus reducing surface runoff and increasing crop water availability. Therefore, water-limited yields have been re-calculated with adjusted parameters controlling maximum surface water storage capacity. They have been set to 2 cm for both soil types. The original sowing dates, other data and settings of WOFOST have not been changed.

The frequency distribution of yields of millet systems with tied ridges in the four physical environments (Fig. 4.7) shows that particularly on soil type A, the variability in yields was reduced. More than 60 (Mopti) and 90% (Koutiala) of the yields were within ± 50% of the average yields. For soil type B, these percentages remained low (± 30-35%). These systems in all physical environments resulted in higher average yields, from 40 (Mopti – soil type B) to 230% (Mopti – soil type A). CVs of yields were

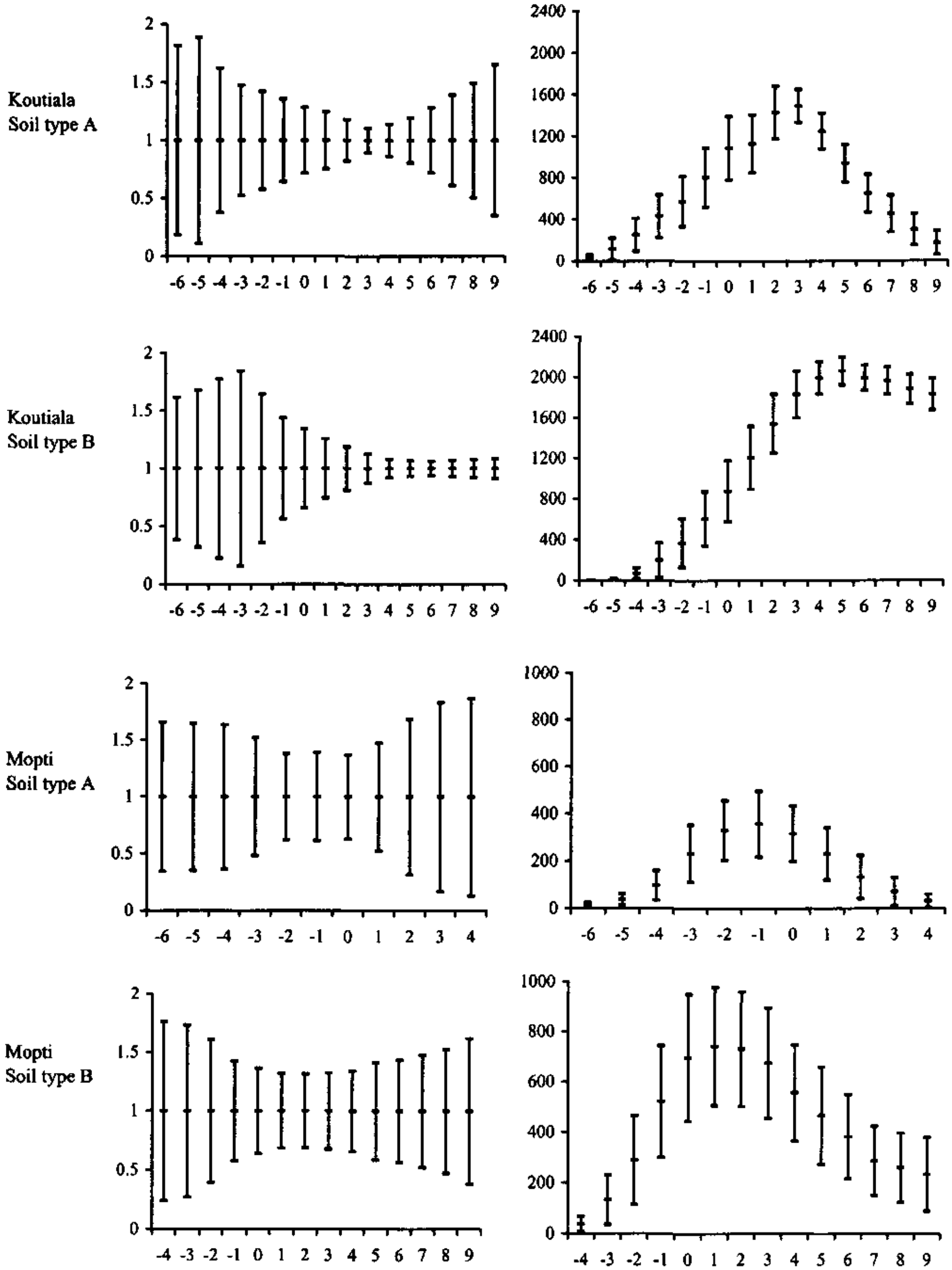

Fig. 4.6

On the left hand side the 95% confidence interval relative to the average millet yield for weekly sowing dates. On the right hand side average millet yields (in kg dm ha^{-1}) and their 95% confidence interval for weekly sowing dates. The X-axis shows week numbers with '0' as the original sowing dates, June 15 and July 16 for Koutiala and Mopti, respectively. Only sowing dates are shown for which the 95% confidence interval relative to the average yield is between 0 and 2.

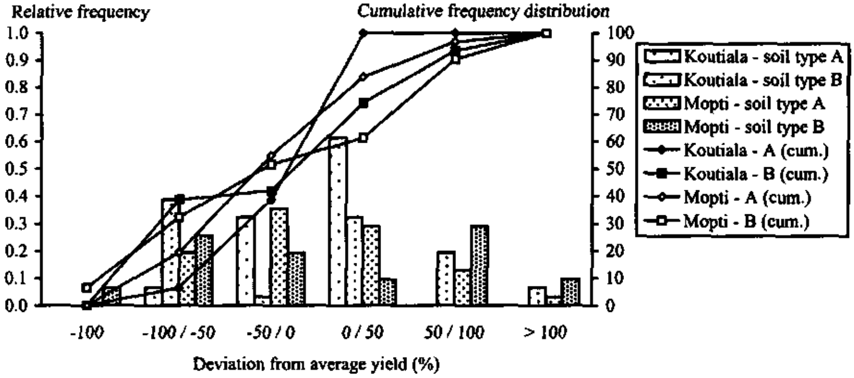

Fig. 4.7

Distribution of simulated yields of millet systems with tied ridges in four physical environments: Columns indicate the relative frequency in each deviation bin and lines the cumulative frequency distributions.

considerably lower. Compared to the values shown in Table 4.2 these were at soil type A reduced with 50 and 43% for Mopti and Koutiala, respectively. On soil type B, the reductions were smaller, but still about 28% in both regions. A well-balanced decision concerning application of such a water retention technique is only possible if labor required for construction and maintenance of ridges is taken into account. These labor requirements are high and animal traction is generally required for actual implementation of tied ridges (Shapiro and Sanders, 1998).

4.3.3 Future perspectives

A promising direction of research attempts to relate the variation in seasonal rainfall to the Southern Oscillation phenomena that are associated with changes in ocean temperatures and resulting atmospheric circulation (Mc Bride and Nicholls, 1983). In the arid areas of Australia, indicators of these phenomena correlate well with rainfall in subsequent months, which allows application as basis for rainfall probability forecasts which enable fine-tuning of tactical management of crops (Hammer et al., 1996). For West Africa, however, this method has shown mixed results and requires further research (Adiku and Stone, 1996). Analyses as presented fit well in this type of research. Future-oriented cropping systems may be screened under expected temporal conditions, so that cropping systems can be selected that best meet a set of predefined (performance) criteria. However, temporal variation is just one source of variation in cropping systems. Other sources (e.g. weed infestation, incidence of pests and diseases, fluctuations in prices, etc.) should also be taken into account in assessments of the performance of future-oriented cropping systems. The interactions among many related and often stochastic factors are among the reasons that the degree of variability caused by these factors is difficult to determine. Operational engineering tools are urgently needed that enable quantification of the magnitude of variation caused by such factors so that decision-makers can also manage and reduce these sources of variation.

The high variability in performance of future-oriented cropping systems can easily be misinterpreted as risk and considered a limitation for agricultural development. However, variation not necessarily contributes to risk, particularly unexpected variation causes risk (Fleisher, 1990). Therefore, timely information on the source and degree of variability is of utmost importance in agriculture. Engineering tools help to identify such sources of variability and to quantify their consequences at different spatial scales, so that variability can be reduced or better managed.

4.4 Conclusions

Erratic rainfall patterns in the (semi-) arid areas of the Sudano-Sahelian zone cause highly variable performances of cropping systems, as illustrated by the simulated water-limited production of millet in four physical environments and associated inputs (i.e. labor requirements) and other outputs (i.e. N-loss). Though some differences exist among physical environments and among inputs and outputs analyzed, CVs are without exception very high, i.e. exceeding 50%. Therefore, in designing future-oriented cropping systems for (semi-) arid areas, uncertainty in system performance should explicitly be taken into account. As tailoring of inputs to outputs of future-oriented cropping systems usually is based on well-controlled environments, the target-oriented approach should be operationalized for low-yielding conditions, including assumptions on interactions among various growth factors under such conditions.

Both examples, tuning of sowing dates and improving water availability with conservation measures, show that it is possible to reduce variability in yield of the analyzed cropping systems, but not to the same degree and not in all situations. Combination of various cultivation methods at the field level may further reduce variability of future-oriented cropping systems in the Sudano-Sahelian zone. The contribution of such methods to the variability in inputs and outputs of future-oriented cropping systems can be rapidly explored using the tools presented. In addition, systematic analysis using available engineering tools, allows explicit analysis of trade-offs between gains and costs of such alternatives, so that decision makers can take these into account while developing or implementing land use strategies.

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Chapter 5

Implementing a target-oriented approach for engineering N dynamics of future-oriented crop rotations

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5 Implementing a target-oriented approach for engineering N-dynamics of future-oriented crop rotations

Abstract

Increasingly, target-oriented and computer-aided approaches are applied to design and quantify technically feasible land use systems. Such land use systems can be used in decision support models aimed at exploring policy options or guiding empirical farming systems research. These approaches often assume equilibrium conditions with respect to soil resources when quantifying inputs and outputs, while this condition is often not met or the ultimate aim. Hence, the dynamics of future-oriented systems are insufficiently dealt with. In this chapter, future-oriented systems are engineered as a sequence of crops, while interactions between N-input and output of succeeding crops are explicitly accounted for. A simple N-balance model is used describing major processes affecting soil N-dynamics. In a test with long-term field data, the model showed satisfactory performance under moderate input conditions.

The model calculates the annual amount of N required to realize target crop N-uptake taking into account losses and the supply via rainfall, biological fixation and mineralization from the soil N-pool. For the Koutiala region in West Africa five crop rotation scenarios are defined that differ in target crop yields, crop choice, crop residue management and external N-source.

Consequences of explicit modeling of the N-cycle in future-oriented cropping systems are discussed for decision support models based on linear programming techniques. Finally, an outline of a modeling approach is given aimed at identification of management strategies required to realize simultaneously multiple goals, including a required soil N-stock.

5.1 Introduction

Worldwide, agriculture faces an array of interrelated problems. In developing countries, for example, production must be increased to feed a rapidly growing population in a situation of increasing scarcity of land, water and agricultural labor resources, and growing environmental and nature concern (Pinstrup-Andersen and Pandya-Lorch, 1994). Exploitation of the limited resources requires, therefore, a well-balanced consideration of multiple interests.

Empirical research methods only are not sufficient to analyze the problems at stake and to contribute to their solution. Increasingly, computer-aided engineering approaches are applied to disentangle the complex problems that agriculture is facing and to identify alternatives. Engineering approaches are based on mathematical representations of established agro-ecological relationships, while taking into account the available resources and land-related objectives in a given area (Hengsdijk and Van

Ittersum, 2001). These approaches allow to identify future-oriented land use systems and to quantify such systems in outputs and the inputs required for realizing such outputs. These quantified descriptions can be used in decision support models, e.g. using linear programming, to guide empirical farming systems research (Ten Berge et al., 2000) or to explore policy options (Bakker et al., 1998).

In future-oriented land use systems, inputs and outputs are calculated in a target-oriented way, i.e. first a crop output is determined and subsequently, the required inputs to realize that output. Often, such systems are designed assuming an equilibrium situation with respect to soil resources (e.g. Van Duivenbooden and Veeneklaas, 1993; De Koning et al., 1995; Rossing et al., 1997), i.e. changes in soil qualities (e.g. pH and soil organic matter content) due to system's performance are not explicitly accounted for. Such a static approach limits analysis of the interactions between inputs and outputs over time. Consequently, the performance of engineered systems in the long term is poorly dealt with, since their production potential may change. At the same time, such a static approach hampers the design of systems aimed at improving soil quality characteristics. Particularly in the Sudano-Sahelian zone, soil degradation is one of the major problems threatening the livelihood of millions. In such situations, new systems may be required enabling the restoration of, for example, soil organic matter content or soil pH (Breman et al., 2001). Other systems, for example, in The Netherlands, require a decrease in phosphorus stocks after years of accumulation and consequently leaching problems (Aarts et al., 2000).

The aim of this chapter is to explore how to implement a target-oriented approach under non-equilibrium conditions. Consequences of engineering land use systems as sequences of crops are analyzed while interactions among growing seasons are explicitly taken into account. Nitrogen (N) dynamics are used as an illustration. Selected crop rotations from the semi-arid area of West Africa are simulated, their long-term effect on N-dynamics compared, and consequences of explicit modeling of N-dynamics for decision support models discussed. Finally, an outline is given of a modeling approach aimed at identification of management strategies required to realize multiple goals simultaneously, including targets with respect to soil stocks.

First, the target-oriented approach is described that is applied in various land use studies to determine N-requirements of future-oriented land use systems. Subsequently, a summary model simulating long-term crop response to fertilizer and soil N is briefly described and validated with a long-term data set from Saria, West Africa. This model is used to calculate N-dynamics of various crop rotation scenarios varying in target yield, crop choice, crop residue management and external N-source. Consequences of explicit modeling of N-dynamics for decision support models based on linear programming techniques are discussed and finally an outline is given of an alternative modeling approach that may be elaborated to deal with dynamic input-output relationships.

5.2 N-requirements of future-oriented cropping systems

Following the target-oriented approach, external N-input requirements are determined by comparing total crop N-uptake with N-supply from natural sources (e.g. deposition and biological fixation) and unavoidable N-losses (e.g. leaching and gaseous losses). The difference between both must be supplied from external sources while taking into account unavoidable losses associated with their application. The result of this procedure is often called N-requirement, since it represents the minimum input of external N required to realize a pre-defined target output. Nitrogen requirement is a generic term for all human-supplied N and may be met from various sources, such as fertilizers, manure, compost or any combination. Basic assumption in the approach is that mineralization associated with soil organic matter decomposition compensates any losses of supplied nutrients due to immobilization. Provided invariable cropping pattern and management, this assumption is plausible in exploring long-term options (Jenny, 1941). Consequently, characterizations of future-oriented cropping systems in terms of N-inputs and outputs are static and do not account for their effect on soil fertility status.

Depending on location-specific conditions, data availability and/or assumptions, this generic procedure may be implemented in different ways. For example, crop residue N is subtracted from the final N-requirement (e.g. Hengsdijk et al., 1999) or a fixed mineralization rate of soil N is accounted for on the supply side of the N-balance (e.g. Rossing et al., 1997). However, in none of these approaches soil stocks are modeled explicitly which is required to account for nutrient transfers between growing seasons and to determine accurate N-input-output relationships of crop sequences over time.

To analyze carry-over effects between growing seasons, to take into account changes in soil N-stocks and N-requirements of crops, or to use a particular change in soil N-stock (or organic matter) as a target, an approach is required that includes processes affecting soil N-dynamics. Therefore, a simple N-balance model has been applied that describes major processes and enables analysis of long-term changes in soil N-stocks and N-requirements.

5.3 The model

Many processes governing N-dynamics in crop rotations cannot (yet) be described mechanistically in most crop growth simulation models, since these models have been primarily focussed on the crop component, disregarding soil physical, chemical or microbiological processes that determine production in the long-term (Bowen et al., 1998). Application of comprehensive simulation models that have incorporated such soil-related processes, for example, EPIC (Sharpley and Williams, 1991), APSIM (McCown et al., 1996) and DNDC (Li et al., 1992), often has major limitations (Van Keulen, 1995): (i) They have extensive data requirements, (ii) validation is difficult, as many parameters have not been measured, certainly not over the time-span required to evaluate their long-term behavior, (iii) partial knowledge of many of the underlying processes leads to unbalanced descriptions, i.e. detailed descriptions of well-known processes are combined with simplifications of poorly understood processes. Therefore, in this study a choice has been made for a simple descriptive model with modest data requirements of which most can be derived from commonly measured characteristics of soil-plant systems. Wolf et al. (1989) give a comprehensive description of the model that has been used in this study. In this chapter, the general structure is discussed, followed by a validation procedure that also illustrates the model parameterization and calculation procedure. Subsequently, initialization of the model parameters for the Koutiala region in Mali is described and the different rotation scenarios for which the model is applied.

5.3.1 Model structure and data requirements

In the model, a labile organic N (LON) and a stable organic N (SON) pool are distinguished (Fig. 5.1). The model operates with time steps of one year or a growing season and annual N-transfers between both pools are described as fixed fractions of their size. The values of these fractions are the reciprocals of the time constants of conversion of each of the two pools. Stable organic N is converted into labile organic N, while crop N-uptake (NCROP) and losses (NLOSS) deplete the labile pool. In addition, a fraction of the labile pool is transferred to the stable pool, characterizing all processes involved in formation of stable organic N components.

In addition to N from the SON-pool, four other sources supply N to the LON pool: rainfall (NRAIN), biological fixation (NFIX) including N-fixation by algae and symbiotic and free-living bacteria, inorganic fertilizer (NFERT) and organic amendments (NORG), such as straw and farmyard manure.

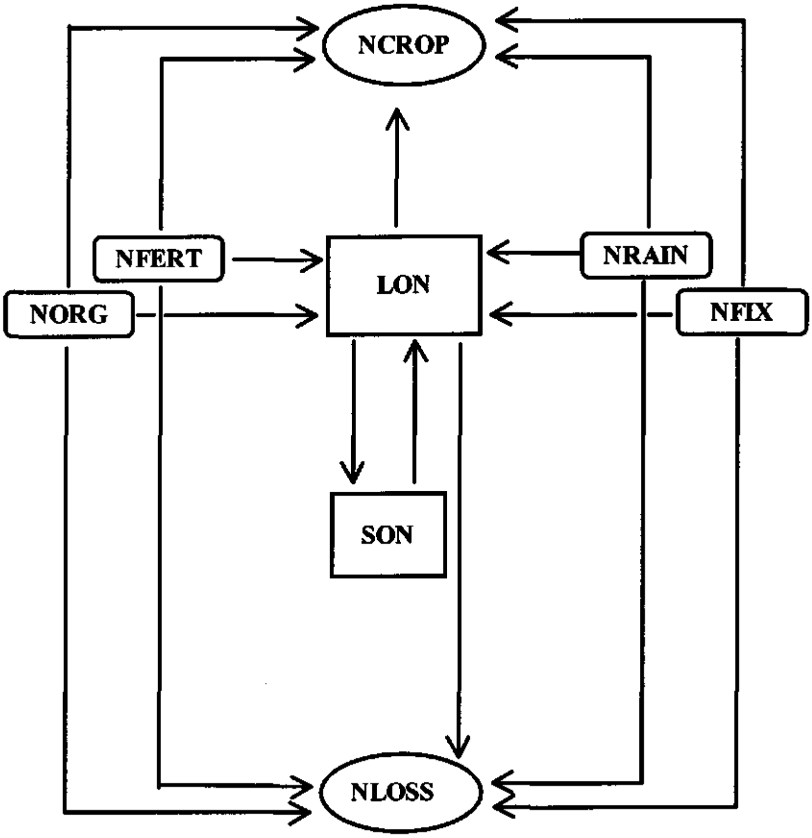

Fig. 5.1
Model structure, with in the center a labile and stable organic nitrogen pool, LON and SON, respectively. Nitrogen inputs from biological fixation (NFIX), fertilizer (NFERT) and organic matter applications (NORG), rainfall (NRAIN), and from mineralization of LON are partitioned over crop uptake (NCROP), incorporation in the labile pool, and losses (NLOSS).

Required data include the rates of N applied in NFERT and NORG, and N supplied via NRAIN and NFIX, initial sizes of the LON and SON pools, and the time constants of conversion of both pools. For each external N-source and for the mineralized N from the LON pool, partitioning or transfer factors, governing distribution of N-sources among crop N-uptake, incorporation in the LON pool, and losses due to leaching, etc. are required. These factors depend on environmental conditions and management and have to be derived from empirical data sets, literature or expert knowledge. Since uptake and losses from soil organic N only occur at the expense of LON, corresponding partitioning fractions are used for the LON pool. The fraction of N in the LON pool partitioned to the SON pool is set to 0.15 and the ratio between the time constants of conversion of the LON and SON pool to 20. Both parameter values are difficult to determine empirically but in simulations of long-term experiments, these values showed satisfactory results (Wolf and Van Keulen, 1989). The size of the LON and SON pools is derived from total initial soil organic N and the equilibrium ratio between both pools. If initially transfer rates between both pools are identical, the equilibrium ratio is 3 (SON over LON), based on the transfer coefficient from the LON to the SON pool (0.15) and the ratio between both time constants of conversion (1/20).

5.3.2 Validation

Wolf and Van Keulen (1989) validated the model with data from long-term field trials in Germany, United Kingdom and Japan. In this chapter, the model is applied for semi-arid conditions in West Africa, and is tested with a long-term data set from Saria (12° 15′ N, 02° 10′ W) in Burkina Faso with an average annual rainfall of 850 mm (Pichot et al., 1981). We used 14 years (1960-1974) of sorghum (*Sorghum bicolor*) yields from four treatments: (i) unfertilized, (ii) inorganic fertilizer (average N-rate of two experiments was 44 kg N ha^{-1} y^{-1}), (iii) a combination of inorganic fertilizer (24 kg N ha^{-1} y^{-1}) and 5 t manure (estimated at 80 kg N ha^{-1} y^{-1}), and (iv) a combination of inorganic fertilizer (64 kg N ha^{-1} y^{-1}) and 40 t manure (estimated at 640 kg N ha^{-1} y^{-1}). Total crop N-uptake has been calculated using standard dry matter partitioning factors and N-content of crop parts. Transfer coefficients are based on literature (e.g. Christianson et al., 1990; Van Duivenbooden et al., 1996; Carsky et al., 1999) and expert knowledge about the processes involved (Table 5.1). Nitrogen supply via rainfall (NRAIN) and biological N-fixation (NFIX) are based on Penning de Vries and Djitèye (1982).

The initial pool sizes of LON and SON and their time constants of conversion are based on total initial soil N and N-uptake of an unfertilized crop, taking into account the contribution of N via rain and biological fixation. Initial total soil N in the 0-0.5 m layer is estimated at 1353 kg ha^{-1}, based on a bulk density of 1400 kg m^{-3}, soil carbon content of 0.29% and C/N ratio for soil organic matter of 15. Applying an equilibrium ratio of 3 for the LON and SON pools (section 5.3.1), the initial size of the labile and stable pool is 338 kg and 1015 kg, respectively. The time constant of conversion of N from the labile pool is based on the average crop N-uptake of the unfertilized treatment. Average yields and N-uptake of the unfertilized treatment were low, 150 kg dry matter ha^{-1} and 6.4 kg N ha^{-1}, respectively. Part of crop N-uptake originates from NRAIN and NFIX, taking into account the fractions transferred to various components

Table 5.1

Annual N-inputs (kg ha^{-1}) via rain (NRAIN) and biological fixation (NFIX) and the fractions transferred to crop, labile and stable pool, and lost N-input via inorganic fertilizer (NFERT), organic material (NORG), biological fixation (NFIX), rain (NRAIN) and mineralized soil organic matter (LON) used in the validation procedure of the N-cycle in sorghum field experiments in Saria, Burkina Faso.

	Crop	Loss	Labile pool	Stable pool	NRAIN	NFIX
NFERT	0.30	0.40	0.30			
NORG	0.20	0.50	0.30			
NFIX	0.15	0.15	0.70			2.5
NRAIN	0.40	0.40	0.20		5.7	
LON	0.425	0.425		0.15		

of the N-cycle (Table 5.1). Actual crop uptake minus N transferred to the crop from NRAIN and NFIX results in the amount of N taken up from the LON pool: 6.4 – 0.40*5.7 – 0.15*2.5 = 3.7 kg N ha^{-1}. Since the initial size of the LON pool is 338 kg ha^{-1} and 0.425 of its annually mineralized N is transferred to the crop (Table 5.1) the time constant of conversion of the LON pool is (338 / (3.7 / 0.425) =) 38.4 year. Applying the ratio between the time constants of conversion between the LON and SON pool, i.e. 20 (section 5.3.1), the time constant of conversion of the stable pool is (20 * 38.4 =) 768 year.

Subsequently, annual available N for crop uptake in the four treatments is simulated with the model and their average is compared with the average actual sorghum N-uptake over 14 years (Table 5.2).

Actual N-uptake of the unfertilized and inorganic fertilizer treatments shows close agreement with the calculated available N for crop uptake. The treatment with inorganic fertilizer and 5 t manure is also closely approximated with the model, despite its high variability in yield, actual yields varied between 300 kg ha^{-1} and 2040 kg ha^{-1} (coefficient of variation = 47%). Actual N-uptake of the treatment with high fertilizer gift and 40 t manure is, however, only half the calculated available N for crop uptake.

Table 5.2

Actual N-uptake and calculated available N for crop uptake according to the model for four different treatments. Between brackets the experiment codes used in Pichot et al. (1981).

	Unfertilized (T)	Fertilizer (fm + FM)	Fertilizer + 5 t manure (fmo)	Fertilizer + 40 t manure (FMO)
Actual N-uptake	6.4	19.2	30.4	62.7
Calculated N available for crop uptake	6.1	19.0	31.4	138.7

Apparently, very high application rates of N can not be treated with this simple model, which was also concluded by Wolf and Van Keulen (1989) in their validation procedure. At these extremely high N-doses (about 704 kg N ha^{-1} y^{-1}), recovery and loss fractions as defined in Table 5.1 are not constant and less N is available for crop uptake than calculated by the model, or more probably, available N exceeds crop N-uptake capacity. However, the performance of the model for the other treatments gives confidence that for moderate N-doses the model can be applied in West Africa to approximate long-term effects of crop rotations and soil and crop management on N-dynamics.

5.3.3 Initialization of model parameters

The model is applied for conditions in the Koutiala region (12° 24′ N, 05° 28′ W), an important cotton producing area in Mali with average annual rainfall of 1000 mm (σ = 189 mm). Crops taken into account in the crop rotations are cowpea (*Vigna unguiculata*), cotton (*Gossypium hirsutum*), sorghum (*Sorghum bicolor*), millet (*Pennisetum glaucum*) and maize (*Zea mais*) for which different transfer coefficients were identified (Table 5.3). For NORG two transfer coefficients are defined, one for crop residues (straw) and one for animal manure, since they differ in composition ('quality') and crop residues are incorporated in the soil long before sowing of the following crop, while manure can be applied shortly before sowing. Soil characteristics are similar to those in the long-term experiments in Saria (section 5.3.2). Hence, the initial size of the labile and stable pool is set to 338 kg and 1015 kg, respectively. However, the time constants of conversion of both N-pools are different from those in Saria. The time constant of conversion of N from the labile pool is estimated from unfertilized millet and sorghum yields in the Koutiala region (Giraudy, 1995). Average yield and N-uptake of unfertilized fields were 671 kg ha^{-1} and 18.1 kg N ha^{-1}, respectively. Crop N-uptake from mineralization of the labile pool is total N uptake minus N from rain and biological fixation. Using the annual supply via NRAIN (5.8 kg ha^{-1}) and NFIX (1.8 kg ha^{-1}) and their transfer fractions as shown in Table 5.3, N-supply by the labile pool is: 18.1 – 0.40*5.8 – 0.15*1.8 = 15.5 kg ha^{-1}. Thus, the time constant of conversion of the LON pool is (338 / (15.5 / 0.425) =) 7.6 year and the time constant of conversion of the SON pool is (20 * 7.6 =) 152.7 year.

Table 5.3

Nitrogen fractions transferred to crop, losses, and labile and stable pool, via inorganic fertilizer (NFERT), organic material (NORG), biological fixation (NFIX), rain (NRAIN) and mineralized soil organic matter (LON) used in the simulation of N-dynamics in Koutiala for (i) cowpea and (ii) millet, sorghum, maize and cotton.

	Crop	Loss	Labile pool	Stable pool
Cowpea:				
NFERT	0.30	0.40	0.30	
NORG				
Crop residues	0.25	0.25	0.50	
Manure	0.20	0.40	0.40	
NFIX	0.15	0.15	0.70	
NRAIN	0.40	0.40	0.20	
LON	0.425	0.425		0.15
Millet, sorghum, maize and cotton:				
NFERT	0.40	0.40	0.20	
NORG				
Crop residues	0.10	0.20	0.70	
Manure	0.30	0.30	0.40	
NFIX	0.15	0.15	0.70	
NRAIN	0.40	0.40	0.20	
LON	0.425	0.425		0.15

5.3.4 Using the model in a target-oriented mode and scenario definition

In this chapter, the model is used in a target-oriented way to simulate N-requirements of various crop rotation scenarios differentiated by crop choice, target yield, residue management and external N-source. Pre-set yields, dry matter partitioning factors and N-content of crop parts determine target N-uptake. Subsequently, the required N to realize target uptake is calculated with the model, taking into account the supply of N via rainfall, biological fixation, mineralization from the labile pool and losses. To illustrate the effect of some relevant factors on N-requirements and N-dynamics of crop rotations, different scenarios have been defined:

A. Current crop rotation, consisting of millet-sorghum-cotton-maize with target yields based on actual yield levels (Table 5.4). After harvest of the economic product, crop residues are burned in the field.

B. Similar to scenario A, but with higher target yields (Table 5.4). After harvest of the economic product, crop residues are burned in the field.

C. Similar to scenario B, but after harvest of the economic product, crop residues are incorporated.

D. Crop rotation consisting of millet-cowpea-cotton-maize with high target yields. After harvest of the economic product, crop residues are incorporated.

E. Similar to scenario D, but N-requirement of crops is met by manure instead of inorganic fertilizer as in the other scenarios.

Scenario A best represents the actual situation, as we only use current yields as targets for determining N-requirements. Current N-doses in the region are ± 10 kg ha^{-1} (Van der Pol, 1992). Here, the required N for these actual yields is calculated taking into account soil N-dynamics. Comparison of scenarios A and B shows the consequences of a higher target yield and N-uptake on N-requirement and soil N. Scenarios B and C differ only in crop residue management. Since crop residues in scenario C are incorporated each year, more N is recycled, as during burning a substantial proportion of the nitrogen is lost in gaseous form (Crutzen and Andreae, 1990). Scenario C represents an N saving strategy, while scenario D characterizes a strategy that adds N to the system, since sorghum is replaced by a legume, cowpea. The beneficial effect of legumes in crop rotations has frequently been confirmed in field experiments (e.g. Bationo and Ntare, 2000) and comparison of scenarios C and D enables approximation of its impact in the long term. Scenario E generates information on the consequences of using manure to meet N-requirements instead of inorganic N-fertilizer.

In scenarios A and B, it is assumed that 80% of crop residue N is lost via burning. Actual crop yields are based on rainfed conditions in the Koutiala region (Giraudy, 1995). High target yields have been based on, but are well below, yields realized in field experiments (e.g. Blondel, 1971; IRAT, 1975; Lombin, 1981) and water-limited yields as estimated from crop growth simulation models applied in the semi-arid area of West Africa (e.g. Van Keulen and Van Diepen, 1990). It is assumed that in scenarios with high yields, other growth factors, such as phosphorus availability, are not constraining realization of these target yields.

Table 5.4

Target yields (in kg dm ha^{-1}) of five crops that have been used in different rotation scenarios.

	Actual yields	Increased target yields
Cotton	1123	2000
Cowpea	395	1000
Maize	1238	3000
Millet	655	1500
Sorghum	733	2000

5.4 Results

Model results of the scenarios are discussed in pairs, so that the impact of specific changes in crop choice, target yields, residue management and external N-source can be examined. The moving average N-requirement of crop rotations and the size of the LON pool at the end of each growing season are presented graphically (Fig. 5.2). An equilibrium situation is assumed when the average N-requirement or size of the LON pool of two subsequent growing seasons differs less than 1%.

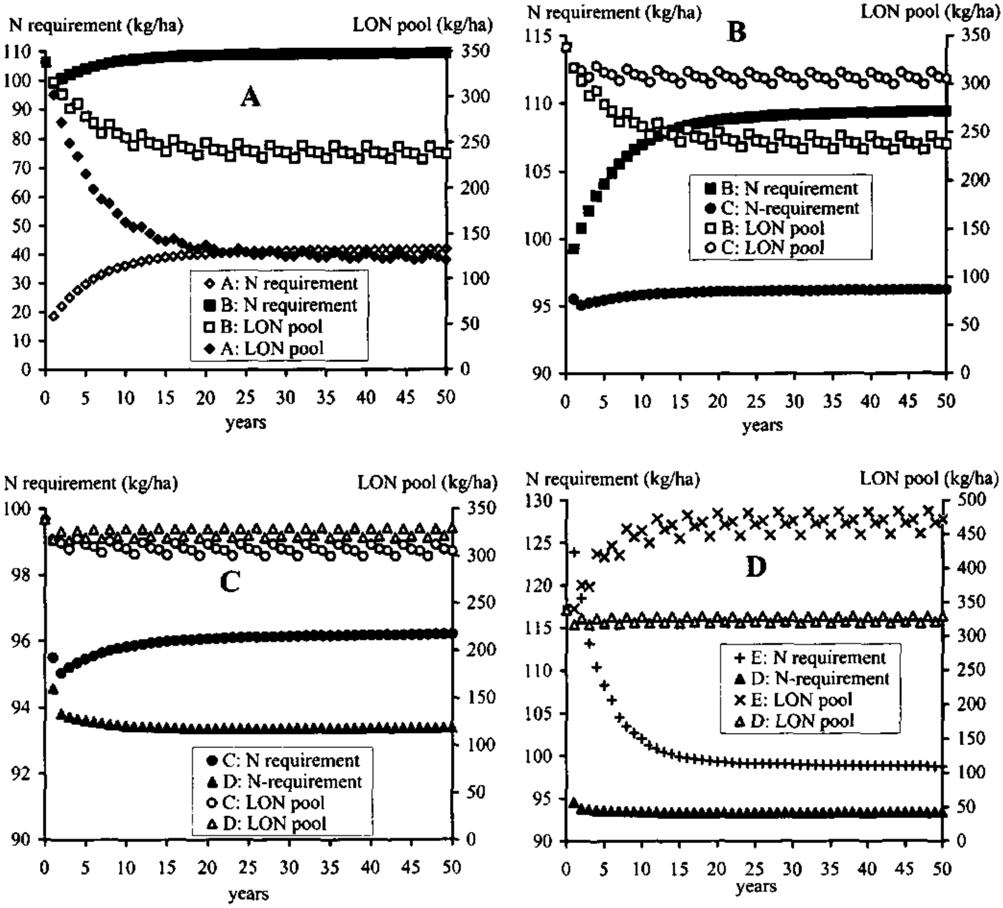

Fig. 5.2

The development of N-requirement and the LON pool over time in different scenarios. Capitals in the legends refer to scenarios as described in the text. Notice the different scales of Y-axes.

5.4.1 Scenarios A and B

Both scenarios differ only in productivity. Since yield targets are set higher in scenario B, biomass production and total crop N-uptake are higher. In scenario A, a large part of the N-uptake is furnished by mineralized N from the LON pool resulting in a rapid depletion of this pool (Fig. 5.2A), and a corresponding increase in N-requirement from 18 kg ha^{-1} in year 1 to ± 40 kg ha^{-1} in year 17, when the LON pool reaches an equilibrium situation. The size of the LON pool decreases by 63% after 50 years.
To realize the higher target yields, N-requirement is much higher in scenario B. Consequently, a considerable amount of the applied fertilizer N is transferred to the LON pool each year, resulting in a lower depletion rate. After 7 years, the LON pool reaches an equilibrium situation and after 50 years, the LON pool is 29% smaller than its initial size. Due to the larger time constant of conversion of the stable pool, total soil N (LON and SON) in both scenarios decreases less rapidly than LON: In scenario A, total soil N is reduced by 27% and in scenario B by 13% after 50 years.

5.4.2 Scenarios B and C

In scenario B, most of the crop residue N is lost during burning of the residues, while in scenario C crop residues are recycled and part of the incorporated N is available for crop uptake in the subsequent growing season. Hence, part of the N-requirements is transferred via crop residues to the next crop, so that the efficiency of utilization of externally applied N increases. Consequently, average N-requirement in scenario C stabilizes at a lower level than in scenario B, 96 and 109 kg ha^{-1}, respectively (Fig. 5.2B). Effects on the depletion rate of the LON pool exceed those on N-requirements, because the major part of crop residue N in scenario C is transferred to the LON pool each year (Table 5.3). After 50 years, the LON pool is reduced by 10% in scenario C compared to 29% in scenario B. Total soil N decreases over the same period by 4% in scenario C, compared to 13% in scenario B.

5.4.3 Scenarios C and D

The concept underlying scenario D is that N fixed by cowpea contributes to nitrogen inputs into the system, and thus reduces the N required from other external sources to realize specified target yields. Scenario D reaches an equilibrium situation in a very short time in which average N-requirement stabilizes at ± 93 kg ha^{-1} (Fig. 5.2C). The size of the LON pool decreases by 4% over 50 years, while total soil N is reduced by 2% over the same period. Although the LON pool in scenario C decreases by 10% and total soil N by 4% in 50 years, absolute differences between both scenarios are small as also illustrated by the average N-requirement in scenario C that is about 96 kg ha^{-1}.

5.4.4 Scenarios D and E

In scenario E, the change in N-requirement and in the LON pool over time is distinct from the other scenarios (Fig. 5.2D). Here, the size of the LON pool increases, while at the same time N-requirement drastically decreases. Since required N is applied in the form of manure, a large part is transferred to the LON pool each year (Table 5.3). As a consequence, mineralization of LON increases over time and less N from external sources is required to realize the target yields. The LON pool and total soil N increase by 38 and 17%, respectively, in 50 years. At the end of that period, N-requirement in scenario E is 6 kg ha^{-1} higher than in scenario D. Assuming 2% N in manure, the equilibrium N-requirement of ± 100 kg ha^{-1} can be supplied with approximately 6 t manure ha^{-1}, within the range of validity of the model (section 5.3.2).

5.4.5 Synthesis

Maintenance of soil N-stocks requires a great effort according to the scenario results. Nitrogen fertilizer to increase productivity is not sufficient to compensate for depletion trends, although it has the greatest impact (scenario B, Fig. 5.2A). A change in crop residue management, incorporation instead of burning, reduces soil N-depletion still further (scenario C, Fig. 5.2B). Ignoring practical difficulties of incorporating residues under West-African conditions, alternative uses of crop residues, such as animal feed during the dry months, are not possible in such scenario. The additional effect of incorporated legume residues on N-depletion is small (scenario D, Fig. 5.2C), while their use as animal feed is more attractive than that of the low quality residues from other crops. An N saving strategy (scenario C) is almost as effective in preventing soil N-depletion than a strategy that adds N via legume (scenario D), though neither of the two suffices to maintain initial (low) soil organic matter stocks. In scenario C and scenario D, organic matter stocks have decreased by 4 and 2%, respectively, after 50 years (Fig. 5.2C). Only a strategy aiming at high productivity in combination with incorporation of crop residues and supply of large quantities of external organic N prevents soil N-depletion completely and result in an increase in total soil N (scenario E, Fig. 5.2D). A conclusion in line with De Ridder and Van Keulen (1990) who investigated the role of organic matter in the semi-arid tropics. Also in scenario E, incorporation of crop residues limits animal feed availability and, thus, manure production, while current manure availability is already constraining its widespread application (Williams et al., 1995). In addition, increase in total soil N in scenario E is associated with considerable emissions to the environment. Total N-losses from the

LON pool, NRAIN, NFIX, and NORG during 50 years are 18% (± 500 kg N ha^{-1}) higher than in scenario D.

5.4.6 Conclusions

In this chapter, the dynamics of the N-cycle have been explicitly modeled for rotations that differ in target yields, residue management, crop composition and type of external N-source. Such analyses are helpful in engineering future-oriented land use systems, since they illustrate N-dynamics and their consequences for calculated N-requirements. Since the system is governed by a feedback mechanism between LON and SON, all rotations tend to equilibrium soil N-stocks and requirements, though at a different pace (Ferrari, 1982). Scenario A requires most time to reach equilibrium (17 years) and during that period, N required to realize target yields gradually increases to twice the initial requirements. For other scenarios, equilibrium is reached much faster, but total soil N after 50 years differs from the initial situation from which transfer coefficients have been estimated. A change in total soil N is associated with changes in soil organic matter content which influences N-recovery and losses, i.e. the values of transfer coefficients as defined in Table 5.3. Such changes in coefficients can not be handled without adjustment of this simple model.

5.5 Consequences for future-oriented land use studies

The target-oriented approach, which is used in an important number of land use studies (e.g. Bakker et al., 1996; Ten Berge et al, 2000), uses well-defined objectives to determine yield and emission targets and generally assumes soil equilibrium conditions, resulting in static input-output relationships (section 5.2). Explicit modeling of soil N-dynamics, as in this study, shows that aiming at steady target yields may result in changing input requirements (external N) over time, i.e. input-output relationships become dynamic. What are the consequences of such dynamic input-output relationships for decision processes with respect to strategic policy-making or the development of farming systems? Existing models supporting such decision processes are often based on linear programming techniques that do not (easily) allow incorporation of dynamic input-output relationships as identified in this study. To match the dynamic descriptions of land use systems to the specifications of linear programming techniques, two options are available: (i) averaging the changing N-requirements for a relevant period or (ii) to calculate an annuity based on the sum of discounted future N-requirements (Schipper et al., 2000). In financial analyses, the latter approach is often applied to value a series of equal future payments (annuity) that are discounted to a single equivalent present value.

Consequences of both calculation methods, averaging and annuity, are illustrated for scenario A and D (Table 5.5). The annuity of N-requirements (ANREQ) is determined as:

$$ANREQ = \frac{r}{(1-(1+r)^{-i})} * \sum_{y=1}^{i} \frac{NREQ_y}{(1+r)^y}$$

in which r is the discount rate (here set to 7% per year), $NREQ_y$ is the N-requirement in year y, and i is the length over which N-requirements are discounted (here set to 15 year).

The difference between average N-requirement and annuity is small in both scenarios. When the change in N-requirement over the given period is small, such as in scenario D, both an average N-requirement and an annuity give a fair approximation. When the average or annuity refer to a period covering a large change in N-requirements (e.g. in scenario A), both an average and annuity may result in considerable under- or overestimation, depending on the direction of change. When large deviations in input are unacceptable, only crop rotations should be incorporated in the analysis in which the change in N-requirement over a given period is modest so that an average or annuity is an adequate approximation. Identification of such rotations is difficult using a deterministic or data-driven model, such as the one used in this chapter, since it is a priori not known which rotations satisfy that condition. Such rotations can only be identified using trial and error. Alternatively, when crop rotations are designed with the aim to increase the soil N-stock and deviations in N-requirements are acceptable, a data-driven model does not necessarily identify the most appropriate rotations. In general, data-driven models do not allow calculating input requirements for a pre-defined output value which limits decision-makers as well as researchers in identifying and developing new systems aimed at realizing a priori user-specified goals.

Table 5.5

N-requirement (in kg ha^{-1}) of scenario A and D in year 1, year 15, the average N-requirement for 1 to 15 year, and its annuity for the same period.

	year 1	year 15	average	annuity
Scenario A	19	39	32	31
Scenario D	95	93	94	94

5.6 Perspectives for engineering cropping systems with dynamic input-output relationships

Recently, Li and Yost (2000) described a so-called 'goal-driven' modeling approach that allows identifying management strategies (i.e. rates and times of fertilizer application and irrigation) that are required to simultaneously maximize yields and economic profit, while minimizing N-leaching targets of a single crop. Three modules, i.e. a generator, a simulator and an evaluator, match in an iterative search process the strategy (from the numerous possible management strategies) that best meets the three objectives. The generator defines a set of management alternatives and the simulator executes the management strategies and calculates their effects on the three objectives. Subsequently, the evaluator examines the simulation results to find the management strategy that best satisfies the user-specified objectives, while this information can be fed back to the generator to adjust the management strategies.

A similar goal-driven modeling approach of crop rotations with multiple targets, for example, maximizing yields and minimizing changes in soil N-stock is conceivable. Implementation of such an approach for rotations requires that certain conditions have to be met of which a few are discussed. First, a generator is required, that produces plausible management strategies that are complete but non-redundant. Since many management variables affect soil N-stock in crop rotations, for example, crop choice, crop residue management, amount and type of external N-source, a selection of management variables must be made that a generator may adjust. Too many variables make the iterative procedure of generation, simulation and evaluation much too complex and time-consuming.

Second, the approach requires an adequate simulation model of the soil-plant-atmosphere system enabling to simulate, for example, the effects of relevant management operations, but also processes that take place between the actual cropping seasons. In the present chapter, a simple descriptive model with time steps of one year is used, but to simulate management strategies in an explanatory fashion smaller time steps are required.

Finally, an evaluator is required that analyses the simulation results and guides the generation of new management options. The design of an evaluator, for example, depends on the time horizon in which targets must be realized. Only aiming at realization of targets at the end of a given time horizon may result in 'postponed payments', i.e. a target soil N-stock is realized in the last year of the time horizon while in the preceding years large soil N deficits are created (Kuiper, 1997). Targets imposed at periodic intervals may help to overcome this problem.

Although far from operational yet, and more choices and focusing is required to obtain an operational lay-out, such a goal-driven modeling approach, theoretically, may help to identify cropping systems that result in realization of multiple output targets simultaneously, including outputs related to the use of natural resources.

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Chapter 6

Quantification of land use systems using technical coefficient generators: a case study for the northern Atlantic zone of Costa Rica

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6 Quantification of land use systems using technical coefficient generators: a case study for the northern Atlantic Zone of Costa Rica

Abstract

This chapter describes two generic so-called technical coefficient generators, PASTOR (Pasture and Animal System Technical coefficient generatOR) and LUCTOR (Land Use Crop Technical coefficient generatOR), that quantify land use systems in terms of inputs and outputs based on the integration of systems-analytical knowledge, empirical and standard agronomic and animal husbandry data, and expert knowledge. PASTOR quantifies livestock systems while LUCTOR is geared towards cropping systems. Main inputs quantified include costs, labor requirements, fertilizer use and application of biocides. Outputs are production and a number of associated environmental indicators. Although both PASTOR and LUCTOR were developed to generate input data for land use models, they are also useful as stand-alone tools to explore the technical efficiency of land use systems, to perform cost-benefit analyses, and to quantify the trade-off among socio-economic, agronomic and environmental indicators at the field level. PASTOR and LUCTOR are illustrated with data from the northern Atlantic zone in Costa Rica. Tools such as PASTOR and LUCTOR integrate different types of knowledge, including non-documented knowledge from field experts and make that knowledge transparent and open to critical review and discussion by others.

6.1 Introduction

During the last decade, various land use modeling studies have been executed to support policy decision making with respect to agricultural land use at different scale levels, varying from farm (e.g. Kruseman et al., 1995), settlement (e.g. Schipper et al., 1995), regional (e.g. Van Keulen and Veeneklaas, 1993), national (e.g. Veldkamp and Fresco, 1996), supra-national (e.g. Rabbinge and Van Latesteijn, 1992) to global (e.g. Penning de Vries et al., 1995). Though these studies have different aims and use different spatial and temporal scales of analysis, they all analyze economic, social and environmental aspects of land use in an integrated way by using tools based on quantitative systems analysis. Important building blocks of these tools are quantitative descriptions of land use systems which may be any type of agricultural land use under specific biophysical and technological conditions associated with inputs and outputs (Fresco et al., 1992), which are called technical coefficients (TCs) in the current chapter. For each land use system, e.g. cropping, timber plantation, cattle grazing, etc., a unique quantitative combination of inputs results in a unique mixture of outputs. Inputs may include external nutrients (e.g. fertilizer), biocides, labor use and agricultural implements. Typically, outputs are production items in physical or financial terms, but may also include indicators related to natural resource use, such as changes in soil stocks (e.g. soil nutrients, soil organic matter), waste loss and emissions to the environment, such as nutrients, biocides and trace and greenhouse gasses. Quantifying the trade-off among socio-economic, agronomic and environmental objectives of land use systems is an important goal of many recent land use studies (Rabbinge and Van Latesteijn, 1992; Bouman et al., 1998a).

Whereas land use studies received ample attention in literature, the issue of how to formalize quantification of land use systems has only been addressed to a limited extent. In this chapter, agro-ecological concepts and principles are presented and operationalized to quantify land use systems in terms of TCs, which can be used in different types of land use studies. A generic framework is introduced which is implemented in two so-called Technical Coefficient Generators (TCGs): PASTOR (PASture and livestock Technical coefficient generatOR) for cattle systems, and LUCTOR (Land Use Crop Technical coefficient generatOR) for cropping systems. PASTOR and LUCTOR were developed in the Research Program on Sustainability in Agriculture (REPOSA) with the northern Atlantic zone (NAZ) of Costa Rica as case study. PASTOR and LUCTOR build upon experiences gained in previous phases of REPOSA (Jansen and Schipper, 1995; Stoorvogel et al., 1995) and upon methodologies developed in related studies in The Netherlands (Habekotté, 1994), Europe (De Koning et al., 1995) and West Africa (Hengsdijk et al., 1996).

This chapter focuses on the underlying, generic concepts used in PASTOR and LUCTOR, describing briefly their functioning, illustrating their use as stand-alone tools in the *ex-ante* analysis of land use systems, and discussing some benefits of the developed methodology.

6.2 Main concepts used in PASTOR and LUCTOR

Some of the terminology that is used in this section is summarized in Table 6.1.

6.2.1 Type of land use systems in different types of land use studies

Different types of land use models exist, each with their own purpose and spatial and temporal scales. The combination of both (i.e. purpose and scale) determines largely which type of land use systems must be quantified. In *long-term explorative studies*, e.g. as described in Bouman et al. (1998a), biophysical sustainable land use options are explored given societal objectives related to land use. Such studies require *alternative* land use systems that are technically feasible and sustainable from a biophysical point

Table 6.1

Summary of terminology relating to the quantification of land use systems (adapted from Van Ittersum and Rabbinge, 1997).

Terminology	Description
Land use system	Agricultural land use under specific biophysical and technological conditions associated with inputs and outputs
Alternative land use system	Land use system that represents technically feasible means of production already available or in the R&D pipeline but not (yet) widely applied.
Actual land use system	Land use system that represents the current means of production
Target-oriented approach	Identification of a technically optimal combination of inputs to realize a particular output level
Production level	Level of primary output per unit of area
Production technique	Complete set of inputs to realize a particular output level
Formal knowledge	Standard data, measured data and derived, reproducible calculation rules.
Informal knowledge	Subjective expert knowledge
Standard data	Well-accepted knowledge and published information

of view, but most likely not yet widely practiced. Such systems use inputs more efficiently than current systems due to supposed future efficiency gains in agricultural production (De Wit et al., 1987). Biophysical sustainability of alternative land use systems is mainly operationalized in terms of a zero change in soil nutrient stock: all nutrients withdrawn from the system (via product removal, but also via unavoidable losses) are balanced by various external inputs (e.g., fertilizer and natural deposition). This implies that soil productivity of such alternative land use systems, as determined by nutrient stocks in the soil, is maintained over time.

Land use studies aimed at identification of possible *short-term* effects of policy instruments related to land use have a shorter time horizon than explorative studies (e.g. Kruseman et al., 1995). This shorter time horizon requires that land use systems representing current means of production need to be included in the analysis. Often, though not necessarily, such land use systems are unsustainable in terms of depleting soil nutrient stocks. In this case, land use systems should represent *actual* land use systems and incorporate changes in production techniques that can be expected to be realized in the short-term only.

6.2.2 Quantifying TCs

In both LUCTOR and PASTOR, the so-called 'target oriented' approach (Van Ittersum and Rabbinge, 1997) is used to quantify *alternative* production systems: target production levels are predefined and various combinations of inputs required to realize these target levels are subsequently quantified. For example, target production levels for crops and pastures may vary from maximum (i.e. potential), close-to-actual situations to very low yields, resulting in simulated high and low external input levels per hectare (e.g. fertilizers, biocides) for the first and the last case, respectively. Substitution between different types of inputs is reflected by changes in labor and capital inputs (De Wit, 1979). This implies that production techniques can be quantified using either herbicides or manual weeding methods, or using either manual or mechanized field preparation methods.

For quantification of *actual* production systems a descriptive approach is used. Primary data regarding inputs and physical production are obtained from field surveys, while remaining data gaps are estimated using standard agronomic and animal husbandry data, supplemented by expert knowledge.

Both PASTOR and LUCTOR generate three categories of TCs: 1) input requirements in physical and economic terms, i.e. labor, fertilizers, biocides, implements and costs, 2) physical production (i.e. crop yield, meat and milk) and 3) environmental indicators: change in soil nutrient stock (Δ stock) for nitrogen (N), phosphorus (P) and potassium (K); nutrient losses to the environment via leaching, volatilization and denitrification/nitrification; and use of biocides. Environmental indicators are calculated by book keeping of biocides and nutrients in the system. Nutrient efficiencies and loss fractions are based on a combination of systems-analytical knowledge and expert judgement. Input and outputs are expressed per hectare and are scale independent.

Costs for movable inputs (e.g. implements) are based on rent prices. To calculate the cost of immovable inputs (e.g. on-farm post-harvest processing unit and drainage canals) it is implicitly assumed that the scale on which such inputs are used is economically optimal. These costs are expressed as an annuity factor to take the investment costs of materials with a life span exceeding 1 year into account. Annuity costs are calculated using the capital recovery factor (Gittinger, 1984) with a discount rate specified by the user.

6.2.3 Complementary information sources

TCs are mostly based on standard data regarding agronomic and animal husbandry relationships, empirical data and systems-analytical knowledge of physical, chemical, physiological and ecological processes. In situations where data are incomplete, lacking or where processes are poorly understood, expert knowledge is used as a complementary information source. Often decisions relating to land use are necessarily (partially) based on this type of knowledge since adequate formal knowledge is insufficient. For example, process-based models predicting the complex interactions between pests and crops and their effect on yields are not yet sufficiently developed for the useful generation of TCs (Kropff et al., 1995). This is due to the stochastic and location-specific nature of crop-pest complexes, which make effects on yields highly diverse and difficult to model. Crop experts with years of location-specific field experience, on the other hand, are often able to make reliable predictions with sufficient accuracy for use in the generation of technical coefficients. In the development of both PASTOR and LUCTOR, teams of experts were consulted because of their knowledge on livestock and cropping systems in the NAZ, resulting in many debates and well thought-through relationships to quantify TCs.

6.3 PASTOR

PASTOR (Bouman et al., 1998b) contains separate modules for the calculation of TCs for pasture, herd and feed supplement systems.

6.3.1 Pasture

The pasture module in PASTOR is able to quantify three types of pastures: (1) fertilized pastures; (2) grass-legume mixtures; and (3) unfertilized pastures. (1) and (2) represent *alternative* systems that are sustainable in the sense that their soil-nutrient balances are in equilibrium (zero Δ nutrient stock). (3) are a proxy for *actual* pasture management in the NAZ and that may be unsustainable in terms of soil nutrient stock. Pasture systems are characterized by a combination of environmental and management criteria: botanical composition (species), soil type, stocking rate, weeding manner and production level as determined by fertilizer application rate. Table 6.2 gives an example of implementation for the NAZ as used in a regional land use study (Bouman et al., 1998a).

For fertilized grasses, TCs are calculated with a predefined allowable loss of soil nutrient stock, i.e. maximum quantities of N, K and P that are allowed to be removed from the soil stock are predefined by the user. For *alternative* sustainable pasture systems, these losses in soil nutrient stock are zero. The procedure for calculating TCs is rather complex and involves a number of steps (Fig. 6.1). First, for each grass species, upper and lower production boundaries are estimated for each soil type in the study area in terms of biomass and contents of metabolisable energy (ME), crude protein (CP) and P. The upper boundary corresponds to the maximum attainable production with no nutrient constraints (Bouman et al., 1996), whereas the lower boundary corresponds to the minimum production level attained on exhausted soils where the grass just manages to survive.

Table 6.2

Design criteria and variants for pasture systems as implemented in PASTOR for the northern Atlantic zone (NAZ) of Costa Rica.

Design criteria	Maximum number of variants
Botanical composition	6 (improved grasses *Cynodon nlemfuensis*, *Brachiaria brizantha*, and *Brachiaria radicans*; grass-legume mixtures *B.brizantha-A.pintoi* and *B.humidicola-A.pintoi* mixture; 'Natural' which represents a mixture of the naturalised and native grasses *Ischaemum ciliare*, *Axonopus compressus* and *Paspalum* spp.)
Soil type	3 (fertile well drained, fertile poorly drained, infertile well drained)[a]
Stocking rate	21 (from 1 to 6 animal units per hectare, in steps of 0.25. For the grass-legume mixtures and the natural pasture, stocking rates varied only from 1-3)
Weeding manner	3 (only herbicides, only manual, mixed herbicides and manual)
Fertilizer application	11 (from 0 to 100% to reach maximum attainable production, in steps of 10%)

[a] Defined as major soil units in the NAZ (Hengsdijk et al., 1998).

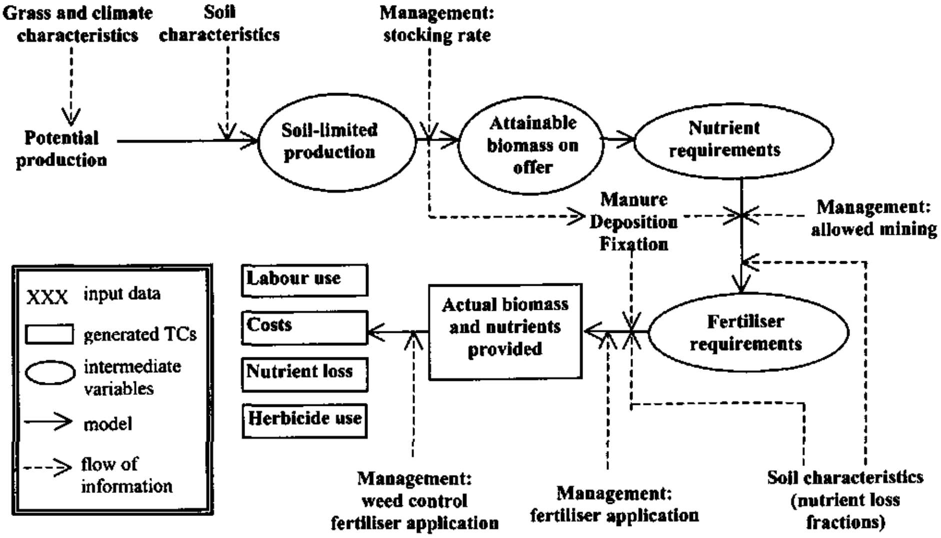

Fig. 6.1

Schematic representation of the procedure for calculating technical coefficients (TCs) by PASTOR for fertilized, *alternative* pastures.

On the basis of the maximum attainable production, PASTOR calculates attainable feed (i.e. biomass and amount of ME, CP and P) produced as a function of a range of (user-defined) stocking rates. With increasing stocking rate, less of the pasture biomass can be eaten by grazing cattle because of trampling and deposition of faeces and urine (Van de Ven, 1992). Changes in soil nutrient (N, P and K) stocks are calculated using an adapted version of the model presented by Stoorvogel (1993). The calculations are based on estimates/calculations for all inputs, namely atmospheric deposition, fixation by micro-organisms, weathering, manure and urine (from the grazing stock), and all outputs, namely the attainable amount that may be removed by grazing and losses by erosion, leaching, volatilization, denitrification/nitrification, and fixation (only for P). A negative balance (i.e. loss of soil nutrient stock) indicates the net amount of fertilizer that is needed to sustain the attainable amount of biomass that may be removed by grazing. Gross fertilizer input is calculated from the required net amount by taking account of loss fractions specified per nutrient type. Next, a user-defined range of fertilizer application levels is specified, ranging from 0-100% of the amount needed to sustain this amount of attainable feed. For each combination of fertilizer application level and stocking rate, the actual amount of feed on offer is calculated on the basis of total amount of nutrients available (from fertilizer, manure and all other external sources) and non-linear energy and nutrient concentrations in the pasture biomass as function of nutrient availability. For example, with 0% fertilizer application, the amount of feed cannot be higher than the amount that is produced using only external inputs from atmospheric deposition, fixation by micro-organisms, weathering and faeces and urine. In case of 100% fertilizer gift, the amount of feed equals the maximum attainable production. When pasture production is not sufficient to sustain cattle intake (e.g. as in the combination of relatively low fertilizer application rates with high stocking rates), it is assumed that the shortage is balanced by feed supplements. The required amount of feed supplements in terms of ME, CP and P are TCs for each pasture system. In a last step, the amount of available feed at the various fertilizer application rates is compared to the uptake capacity of the cattle at the various stocking rates. Since cattle can not remove more feed than their intake capacity, the actual amount of pasture removed by grazing is limited to the intake capacity of grazing cattle. Any over-production of pasture is assumed to recycle into the soil.

For unfertilized pastures, the calculation procedures are relatively simple. Since no fertilizer is applied by definition, actual available feed is specified by the user as function of a range of feasible stocking rates. In the case of grass-legume mixtures, the soil-nutrient balance model takes account of the additional input of N by the legume. The soil-nutrient balance is merely the result of book keeping of all nutrient inputs and outputs, and may be in equilibrium, as it is in grass-legume mixtures, or have a negative value, as it does for most *actual* grass-only systems. For all pastures, i.e. fertilized and unfertilized, costs and labor requirements are related to material inputs such as fences, tools and herbicides, as well as operations such as establishment, weeding, fertilizer application (if any) and maintenance. Different modes of weeding may be specified by using different combinations of herbicides and manual weeding techniques.

6.3.2 Herd

The herd module in PASTOR is able to quantify TCs for breeding and fattening systems, each with a low and a high target growth rate representing *actual* and *alternative* systems, respectively. A breeding system is defined as a system where calves are bred and subsequently sold at a certain age or liveweight. No animals are bought externally. A fattening system is defined as a system where young animals are bought, fattened for a period of time, and sold afterwards. No animals are bred internally. In land use studies replacement of animals may be modeled using the offspring of breeding systems as input for fattening systems. For both types, the modeled herds are 'stationary', which means that there are no changes in herd size and composition over the year(s) (Upton, 1989; 1993). Production and feed requirements of the herd are computed, based on a specification of herd structure characteristics, target growth of the animals and target buying/selling strategy, total composition. The (stationary) composition of the herd, i.e. the number and type of animals per age class, is calculated using the method presented by Hengsdijk et al. (1996). The production of the herd is obtained by summing the user-specified target live weight gains and milk production over all animals in the herd, using the user-defined buying/selling strategy. Feed requirement calculations are based on equations as presented by the National Research Council (NRC, 1989; 1996). Calculations were performed for each animal in the herd according to sex and age group, and for females according to stage of pregnancy and lactation, and then added to obtain total herd requirements. Costs and labor requirements of herds are related to construction, buying and maintenance of corrals, feed troughs, various equipment, vaccinations, assistance at birth and animal health care. Costs and labor requirements are quantified for each of these items and operations and summed to obtain herd totals.

6.3.3 Feed

The feed supplement module of PASTOR merely converts data on supplements into feed characteristics (ME, CP and P), costs and labor use. For the NAZ, these supplements included: green rejected bananas, sugar cane molasses, two types of chicken-dung based concentrates, and a P mineral salt.

6.4 LUCTOR

LUCTOR (Hengsdijk et al., 1998) generates TCs for annual cropping, perennial cropping, timber plantation and managed natural forest systems. These systems are characterized in terms of the complete operation sequences involved and all the quantified inputs and outputs of these operations (Stomph et al., 1994). For annual cropping systems, periods are defined for each well-defined operation (e.g., field preparation, sowing, etc.) to take into account the timeliness of operations and to identify labor peaks. For perennial cropping, timber plantation and managed natural forest systems, no such periods are identified since these systems require different operations throughout the entire year, as a result of the relatively uniform climate conditions in the NAZ, and since such operations typically occur simultaneously. Therefore, labor requirements for these systems are spread evenly over the year.

Actual and *alternative* cropping systems are characterized by design criteria, which relate to the physical environment and the production technique. The most important criteria and their variants are shown in Table 6.3 and discussed below. Based on user-defined combinations of variants, LUCTOR calculates for each unique land use system, its requirements of inputs in physical terms and total costs of input use, as well as associated indicators of natural resource use and emissions to the environment.

6.4.1 Crop type

LUCTOR generates land use systems for the following crops: banana, black bean, cassava, maize (grain and fresh cobs), melina and teak tree plantation, palm heart, pineapple (one for export, and one for local market), plantain, rice, and managed natural forest. These crops are chosen based on a representative sample of suitable crops in the NAZ (Hengsdijk and Van Ittersum, 2001). For maize and pineapple, two types of crops are considered since their marketable products have different economic values and market outlets. In addition, since their crop characteristics and growth cycles are distinct, their input-output relations differ as well. For all other crops, only one single crop type is defined.

Table 6.3
Design criteria and variants for cropping systems as implemented in LUCTOR for the northern Atlantic zone (NAZ) of Costa Rica.

Design criteria	Maximum number of variants
Crop type	13 (Black bean, cassava, maize-grain, maize-cobs, rice, pineapple-export, pineapple-local, banana, plantain, palm heart, teak, melina and managed natural forest)
Soil type	3 (Fertile poorly drained, fertile well drained, infertile well drained)[a]
Yield level	11 (10 Target yields for alternative systems, 1 yield level for actual systems)
Mechanization level	2 (Low and high)
Crop residue strategy	2 (Harvesting, left in the field)
Herbicide level	2 (Low and high)
Pesticide level	2 (Low and high)

[a] Defined as major soil units in the NAZ (Hengsdijk et al., 1998).

6.4.2 Soil type

Soil characteristics determine which soils are suitable to grow a certain crop, the maximum yield level, suitability for mechanization (which is a function of stoniness and slope) and nutrient recoveries. Identification of feasible crop-soil type combinations is based on a qualitative land evaluation procedure. The fertile, well drained soil type (SFW) is suitable for all crops, although banana, plantain, timber, and pineapples for export all require the construction of a drainage system. The poorly drained soil type (SFP) can be used in its natural state for natural forest management, and is suitable after the construction of a drainage system for both banana and plantain. The infertile soil type (SIW) is unsuitable for banana, plantain, beans and maize, mainly because of high soil acidity. Costs of construction and maintaining drainage systems for crop-soil type combinations are included in the description of the relevant land use systems. The land characteristics of slope and stoniness determine the feasibility of mechanized cropping systems. Soil types having either slopes of more than 25% and/or more than 1.5% stones are considered unsuitable for cropping systems that require machinery.

6.4.3 Yield level

Yield levels of actual land use systems are based on surveys. Ten target yields are defined for alternative land use systems. The maximum target yield level, being the maximum attainable production without nutrient constraints (Bouman et al., 1996), is stepwise reduced by reducing nutrient inputs so that the lowest yield is 10% of the maximum attainable production. The maximum attainable production level takes into account quality characteristics that are required for some crops. For example, most cassava cultivated in the NAZ is for export, which markets demand relatively small tubers that are harvested before the maximum crop biomass is attained. Yields may include as many as three product qualities for annuals and two for perennials, all of which may have their own price and market outlets.

6.4.4 Mechanization level

Mechanization levels refer to soil preparation operations and the application of biocides (subdivided into pesticides and herbicides). Other mechanized field operations are limited in view of the high rainfall intensities in the NAZ combined with soil compaction risk, as well as because of certain specific crop characteristics (i.e. narrow passage in perennials). In the high mechanization option field preparation is mechanized while application of biocides, depending on the type of crop, may be applied with a boomspray or spray plane (for pesticides only) instead of a backpack sprayer.

6.4.5 Crop residue strategy

Crop residues may either be left in the field after harvesting or be harvested and used, for example, for fodder purposes. Both options affect labor requirements and nutrient relationships of cropping systems.

6.4.6 Herbicide and pesticide level

Biocides are divided into herbicides and other pesticides, the latter including fungicides, insecticides and nematicides. In the low herbicide option, herbicides are completely substituted by manual weeding, which requires more labor and reduces the emission of active ingredients into the environment. In the low pesticide option, insecticides and fungicides are reduced by a crop-dependent percentage to a level lower than the high pesticide option. It is assumed that with better crop monitoring and hygienic measures – both of which require additional labor – the use of insecticides and fungicides can be reduced. Lower pesticide use reduces emissions of active ingredients but may also lower yields, since yield losses, in general, are inevitable when insecticide and fungicide use is lowered. The extent of these yield losses is estimated on the basis of expert knowledge.

6.4.7 *Alternative and actual cropping systems*

For the quantification of *alternative* cropping systems, yield levels are based on field experiments and on discussions with field experts. Furthermore, these systems aim at nutrient balances of N, P and K that are in equilibrium; this requirement implies that the annual nutrient uptake and losses due to erosion, leaching, volatilization, denitrification and fixation (only for P) are replenished with nutrients from natural resources (atmospheric deposition, crop residues and fixation by micro-organisms), in addition to a certain amount of fertilizer that is calculated by LUCTOR. In case of black beans, the additional input of fixed N by the crop is taken into account. The procedure of determining fertilizer requirements is straightforward and is based on the same book keeping procedure used in PASTOR. Loss fractions by type of nutrient are based on a combination of systems-analytical knowledge and expert judgement. For some perennial and timber plantation systems, nutrient balances may show a positive result, soil nutrient stocks are enriched. In these systems, nutrient turnover in different years of the crop cycle (i.e. the time during which the land is planted with a crop) is taken into account. Nutrients in crop residues left in the field after harvesting as well as nutrients in the standing crop are discounted in the following year. At the end of a crop cycle, a large flush of nutrients from decomposing crop residues is released, and is available at the start of a new crop cycle. In such situations the inputs of nutrients may exceed the sum of the crop uptake and nutrient losses, thus resulting in positive changes in soil nutrient stock.

Although yield levels of alternative cropping systems are defined at an equidistant range, other outputs and inputs are not; a practice that is justified since higher yield levels are usually associated with higher crop nutrient concentrations (Van Keulen and Wolf, 1986). In this way non-linear (i.e. diminishing return) relationships are determined between fertilizer requirements and yield levels. It is assumed that the use of all insecticides and fungicides decrease proportionally with diminishing yield levels; a number of fungal diseases and insects pests require less effort to be controlled under less favorable growing conditions (De Wit, 1994). Finally, it is assumed that inputs in alternative cropping systems are applied in a more technically efficient manner than in actual cropping systems, which may be expressed in: (1) crop characteristics that are geared towards higher yields compared to actual systems (i.e. higher harvest indices); (2) a shift in the distribution of quality class towards a higher fraction prime quality as a result of better crop management (e.g. in fruits such as pineapples); (3) higher planting densities, and (4) higher frequencies of fertilizer applications.

For *actual* cropping systems, the calculation procedures are to a large extent similar to those for alternative systems. However, in the case of actual cropping systems survey data on yield and use of inputs such as nutrients, labor and biocides are used to determine associated environmental indicators. Any missing value is estimated using standard agronomic knowledge and expert judgement. Unlike the approach for alternative systems – where nutrient balances are in equilibrium by design – nutrient balances of actual cropping systems are simply the result of summing all outputs (nutrient losses) and inputs (nutrient gains). Actual cropping systems do not necessarily have lower yields than alternative cropping systems. However, alternative cropping systems, at least theoretically, can be practiced without depleting soil nutrient stocks, while most actual cropping systems deplete the soil nutrient stock and are, therefore, not sustainable in the long run.

6.5 Use of pastor and LUCTOR in *ex-ante* analysis

6.5.1 PASTOR

The following example shows how PASTOR can be used as a stand-alone tool at the field scale to identify the trade-off among various environmental indicators of land use systems. This type of analysis supports the design of new land use systems that on the one hand are economically viable while on the other hand meet environmental criteria. PASTOR was used to quantify TCs for fertilized Estrella pasture (*Cynodon nlemfuensis*) on a well-drained, fertile soil type with a stocking rate of three animal units per hectare (Fig. 6.2). Production levels ranged from the minimum to the maximum attainable level on that soil type, by varying fertilizer applications from 0-100% of the amount needed to realize the maximum yield level. Soil nutrient balances were in equilibrium at all production levels.

In Fig. 6.2A, the trade-off among economic and environmental indicators is illustrated. The horizontal axis gives pasture production, and the vertical axes give the associated use of herbicides and nitrogen loss via denitrification. An increase in pasture production is associated with an increase in denitrification losses, which is clearly an economic-environmental trade-off. However, herbicide use diminishes with increasing production. At higher production levels pastures are more competitive (De Wit, 1994), and thus less herbicides are needed for weed control. Thus, in this example, there exists not only an economic-environmental trade-off, but also a trade-off between environmental indicators: increased yields are associated with increased denitrification losses but with decreased herbicide use. Fig. 6.2B shows that costs of production and labor requirements increase rapidly with increasing production, even though labor requirements grow less rapidly than costs. The explanation for this phenomenon can be found in Fig. 6.2C which shows that both fertilizer requirements and frequency of N-applications increase with higher (target) production levels; Thus labor requirements increase. Since the use of herbicides decreases at higher production (Fig. 6.2A), and hence the required labor for weeding as well as total labor requirements increase less rapidly than total production costs (Fig. 6.2B).

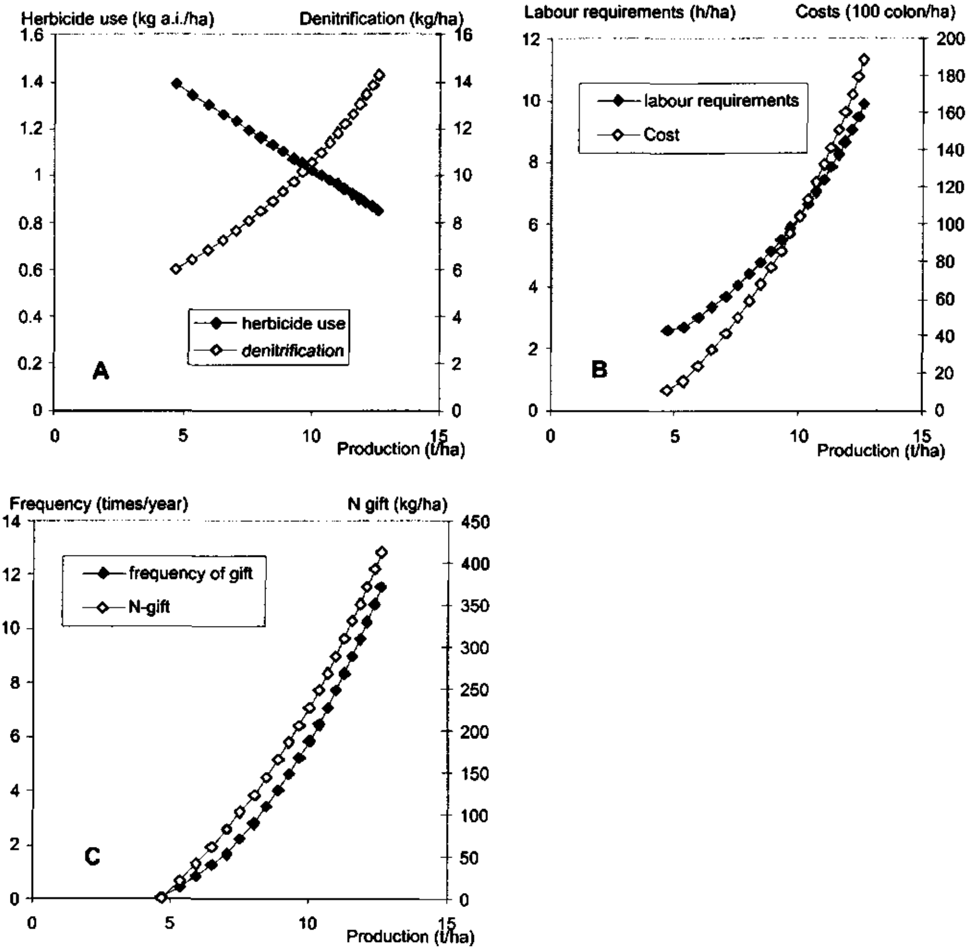

Fig. 6.2

Generated technical coefficients (TCs) by PASTOR for fertilized *Cynodon nlemfuensis* on a well-drained, fertile soil with a stocking rate of three animal units per hectare. (A) shows relationships among production, herbicide use and denitrification; (B) among production, labor requirements and costs of production, and (C) among production, frequency of fertilizer and N applied. All data are annual values.

6.5.2 LUCTOR

This section illustrates the use of LUCTOR as a stand-alone tool for cost-benefit analysis of individual cropping systems by showing how LUCTOR can be used to identify the relative importance of a number of input prices for several cropping systems. This may support priority setting with regard to the implementation of efficiency improvements in cropping systems and as such may be useful for both research and extension efforts.

The effect of a 10% price increase for three inputs (biocides, fertilizers and labor) on total production costs of grain maize, cassava, pineapple for export purposes, banana and palm heart systems is shown in Table 6.4. Production costs were calculated for alternative cropping systems with a maximum attainable yield level, on fertile well-drained soils, using high levels of mechanization, herbicides as well as pesticides. Total production calculations were performed using 1996 prices prevailing in the NAZ and relative changes in total production costs were compared to this base situation. Costs are discounted costs per hectare per year averaged over the length of the crop cycle, which is 1 year for maize and cassava, 2.2 years for pineapple and 15 years for banana and palm heart. Total production costs include both variable costs and fixed costs required for crop establishment and infrastructure (e.g. drainage, on-farm post-harvest processing unit).

The large differences in average annual discounted costs among cropping systems in the base situation are striking. Production costs of banana and export pineapple are seven to 12 times higher than those of other crops. This is largely due to post-harvest costs and associated establishment costs for an on-farm processing unit, as well as costs for drainage and infrastructure in general.

Generally, the effects of higher input prices are limited, even though effects of the various input price changes for production costs of cropping systems are evident. In all cropping systems, with the exception of pineapple, total production costs are most sensitive to changes in fertilizer costs.

Costs of biocides are particular high in banana, pineapple and maize, while much lower in cassava and palm heart. This can be explained by the fact that cassava and palm heart use virtually only herbicides without hardly any other biocide. On the other hand, banana, pineapple and maize require substantial amounts of fungicides, insecticides and/or nematicides.

The sensitivity of total production costs of cassava and palm heart to changes in wages highlights the relative importance of labor in these crops.

Table 6.4

Relative change in total production costs of five alternative cropping systems compared to the base situation (average prices in 1996 colones) for a 10% increase in the price of biocides, fertilizers and labor, respectively (207.38 colones = 1 US$).

Crop	Base situation (colones ha^{-1} y^{-1})	+10% price biocides (% change)	+10% price fertilizers (% change)	+10% price labor (% change)
Cassava	328.965	0.3	3.3	3.2
Grain-maize	291.661	1.6	3.1	1.5
Banana	2.530.783	1.8	1.8	1.2
Palm heart	201.652	0.2	4.4	3.4
Pineapple-export	2.429.993	1.5	0.8	0.8

6.6 Conclusion and discussion

The presented concept of TCGs to generate TCs for a large number of land use systems integrates systems-analytical knowledge, empirical and standard agronomic and animal husbandry data, as well as expert knowledge. Both PASTOR and LUCTOR have been successfully used to systematically generate the necessary input data for various land use studies of the NAZ of Costa Rica (Bouman et al., 1998a; Sáenz et al., 1998; Bouman and Nieuwenhuyse, 1999). The development as well as the application of TCs in these land use models has already resulted in fruitful discussions with users about expert-based assumptions. Since both PASTOR and LUCTOR are highly generic and modular, their parameters can easily be adjusted to reflect such location-specific conditions as those shown in another case study area (Hengsdijk, 1999; Sáenz et al., 1999).

In addition to their traditional role as generators of input data for land use models, PASTOR and LUCTOR are useful tools for decision support as well. For example, both TCGs can be used to quantify the trade-off among socio-economic and environmental indicators at the field level, or to explore the relative importance of inputs in land use systems through cost-benefit analysis. While cost-benefit analysis may support decisions (e.g. with respect to the efficient application of different inputs), the trade-off among different production objectives can be made explicit to identify new options and to allow a more balanced decision-making with regard to new land use systems.

Generation of TCs in both PASTOR and LUCTOR is based as much as possible on systems-analytical knowledge of the physical, chemical, physiological and ecological processes involved. For a number of processes, however, the required knowledge is lacking or insufficiently developed to formalize it into process-based models. In such cases, knowledge of experts has been used. Examples include estimates of attainable production in both PASTOR and LUCTOR and the relationships between stocking rate and dry matter use by the cattle in PASTOR. Though expert knowledge is sometimes considered to be an unreliable source of information in land use studies (Van Diepen et al., 1991), generic expert systems such as PASTOR and LUCTOR thus stimulate field experts (which often are also users) to be explicit about their knowledge, and to make that knowledge transparent and open to critical review and discussion by other experts. The advantage is that such important knowledge is not left unused, simply because it cannot (yet) be formalized into process-based models. Moreover, there always remains the issue of the balance between expected return from expensive collection of empirical field data and time-consuming development of process-based models, versus the low costs involved with tapping knowledge of field experts. Considered in this way, both PASTOR and LUCTOR as applied in the NAZ are also important tools to store, order and integrate formal and informal agro-ecological knowledge, that is currently not readily available or accessible.

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Chapter 7

General discussion

7 General discussion

This thesis is a methodological study in order to realize other goals, i.e. the exploration of regional land use options and the development of new farming systems. The overall objective of the study was to contribute to the development of a formalized approach to identify and engineer future-oriented land use systems at the field level that are able to fulfill well-defined objectives. In Chapter 2, a systematic framework is presented including general guidelines for selecting manageable sets of land use alternatives with appropriate quantitative descriptions. Such alternatives can be used to explore options for strategic decision-making with respect to land use policy and for ex-ante assessment of farming systems to be further tested or developed in experimental settings. In subsequent chapters, important aspects of the framework were examined, such as consequences of limited data availability and lack of knowledge about processes involved (Chapter 3) and uncertainty due to random variability in processes (Chapter 4). In Chapter 5, the performance of alternative cropping systems over time and their consequences for the resource base is made explicit. In Chapter 6, two operational tools are described that incorporate various concepts and scientific methods discussed in the previous chapters.

The results presented in this study can be evaluated from different viewpoints. First, the approach developed should be examined as part of the demand for a formalized method to engineer land use systems for future-oriented purposes. Does the approach comply with the a priori specified requirements? Does the approach really generate *future* options or does it exclude possibilities, deliberately or not? The appropriateness of underlying concepts used in the approach, such as *best technical means* and *production orientation* is not dealt with since they have been extensively discussed elsewhere (e.g. Van Ittersum and Rabbinge, 1997; Van Latesteijn, 1999).

Second, engineering of future-oriented land use systems heavily hinges on numerical methods of which several have been applied in the study. Numerical tools as such were not the focus of this study, but were applied to illustrate concepts. In this final chapter, their role is explicitly addressed because of their importance for systems engineering. What types of tools are available and what are problems associated with their application?

Third, I look ahead. What are the bottlenecks for widespread implementation of engineering approaches to land use analysis? Are additional remarks to be made after having developed an approach that has been applied in various future-oriented land use studies? Additionally, what future directions of research are needed or may be considered based on the knowledge and insights gained in this study?

7.1 The goal-oriented approach in retrospective

One of the major dilemmas systems engineers have to deal with in land use studies is the number of alternative land use systems that should be taken into account and their specification. The potential number of alternatives is much higher than most land use studies need and – a practical problem – can handle. Despite the rapid development in information technology, the number of alternatives that can be screened in land use studies using linear programming techniques is often still limited by model size and computation time (e.g. Jansen et al., 1995; Bessembinder, 1997). More important is that with increasing numbers of alternatives, the differences among alternatives are so small that they often have little relevance for strategic decision-making. In addition, consistency and error checking of incorporated relationships becomes increasingly complex with increasing number of alternatives. A priori, only alternatives should be considered that are possible from a biophysical point of view, feasible from a technical point of view and that may contribute to the required objectives.
The goal-oriented approach combines existing scientific knowledge and methods and value-driven aims related to location-specific land use problems. Value-driven aims direct the specification and number of alternatives, which in combination with current agro-ecological knowledge generalized in numerical tools, results in appropriate quantitative specification of alternatives in their inputs and outputs. New is that various elements are integrated in general guidelines for identification and engineering of alternative land use systems for future-oriented studies. Systems approaches to land use analysis benefit from such a formalized and consistent procedure since underlying choices are made transparent and open to discussion by others. In addition, application of standardized procedures has the advantage that different land use studies can be compared resulting in better understanding of possibilities and limitations for agricultural development.

Do the alternatives identified and engineered according to the goal-oriented approach really represent *future* options? Here, two viewpoints can be distinguished. The first claims that alternatives identified and engineered in the described way are not sufficiently innovative, while the second argues that they are far too optimistic and go beyond any reality. Alternative land use systems engineered according to the goal-oriented approach are based on current knowledge of the underlying biophysical processes of plant and animal production and present technical insights. What is important, is that the approach gives clear guidelines that can be implemented according to the location-specific situation in identifying contrasting alternatives allowing realization of various (possibly conflicting) land-related objectives.

A recurring task in future-oriented land use studies is the quantification of alternatives that are (i) conceivable and perhaps already in the R&D pipeline or (ii) already practiced in some parts of the world, but not yet in the area under study. In both cases, although more profound in the first case, knowledge about the performance of such alternatives in the given situation is limited, and data are often scarce. This uncertainty in underlying process knowledge and data hampers quantification of alternatives in sound input and output relations, and easily evokes discussion about the possibilities to identify true innovative systems for a given area. It is the continuous challenge for systems engineers to generalize the latest knowledge on agro-ecological processes into generic calculation rules that allow wide ex-ante evaluation of alternatives. Attempts at generalization of knowledge may identify the need for research aimed at a better understanding of underlying processes allowing true exploration of alternatives. The approach may also serve to set a research agenda aimed at the development of more futuristic and novel technologies that enable realizing objectives better or in a different way. Alternatively, many technological developments that are currently feasible in some parts of the world can be specified in terms of outputs and inputs for other areas taking into account the location-specific conditions. In other parts of the world, such developments have not come to complete fruition and, therefore, such technologies are highly innovative.

This brings us to the other group of critics that consider future-oriented alternatives far beyond reality. Their criticism is largely based on the large difference in performance between current and future-oriented land use systems in many situations (Bouma et al., 1998). Is it realistic to assume that farmers will be able to realize optimal use of the synergistic properties of agricultural inputs required to fully exploit the qualities of the prevailing natural resources? It is important to realize that this question can also be reversed: are there sound arguments to claim that certain farmers are not able to perform in a technically optimal way and to realize production levels set by the natural resource base? This question is often answered positively by referring to current developments with associated inefficiencies in resource use, inappropriate knowledge and skills, and institutional and structural barriers. Such developments, however, are deliberately ignored in engineering approaches since they prevent identification of discontinuities and exploration of future options in terms of technical feasibilities rather than plausibilities and probabilities (Van Latesteijn, 1999).

Though the exploration of technical feasibilities is the core of engineering approaches, in many future-oriented land use studies concessions are made with respect to the considered alternatives based on prevailing cultural, social and/or economic conditions. Systems engineers making value-driven concessions easily enter the domain of the decision-maker or stakeholder. For example, the West African case study discussed in Chapter 2 does not consider alternative systems using motorized mechanization, i.e. tractors and accompanying implements. The decision not to consider such alternatives was based on the assumption that motorized mechanization would result in high agricultural unemployment. Since off-farm employment opportunities in West Africa are scarce, such scenarios would result in socially unacceptable developments. In other future-oriented land use studies, water-limited productivity levels were arbitrarily reduced with 20% to keep such levels within the realm of reality (Van Duivenbooden and Veeneklaas, 1993). In both cases, engineers took over the role of the decision-makers since they used prevailing skills and social and economic constraints as motives for offering only a subset of the full scope of available alternatives. Personal desires and aims of engineers may well foster such inappropriate adjustments of the goal-oriented approach. Future-oriented studies easily degenerate from exploring feasibilities into describing plausible future developments. Preferably, normative user goals with respect to the future use of available resources should direct the identification of future options from the full range of alternatives. Realization of such options actually involves a profound analysis and understanding of current systems that, however, is not the topic of this study.

7.2 Numerical tools for engineering future-oriented land use systems

Knowledge about land use systems increases continuously, and concurrently the possibilities to quantify at least parts of such systems with reasonable accuracy. Systems engineers have a palette of tools at their disposal to quantify inputs and outputs of future-oriented systems. These can be roughly divided into:

1. Models to formalize knowledge about agro-ecological processes. Such models are often developed for specific purposes and describe only well defined parts of cropping systems.
2. Databases, comprising electronically stored information that can be geo-referenced, published standard agronomic information in handbooks (e.g. PAV, 1997; Nix and Hill, 1994), survey data and formalized expert knowledge, which in data poor environments is an important and often only source of information.
3. Technical coefficient generators that are used to integrate and synthesize different databases and models or their results, and make knowledge about land use systems explicit, transparent and reproducible (Hengsdijk and Van Ittersum, 2000).

Since the advent of computer-based tools more than 30 years ago, agro-ecological research has put much energy in the development and refinement of crop growth simulation models, particularly for crops in temperate zones. These models have greatly contributed to explanation and understanding of crop growth. The emphasis on development of crop growth simulation models allowed estimating productivity ceilings of crops as defined by prevailing environmental conditions, i.e. temperature, radiation, CO_2 and water availability. These yield-defining and limiting factors determine the biological possibilities for agricultural production and, thus, the *biophysical* feasibilities for the future (Van Ittersum and Rabbinge, 1997). These intrinsic productivity characteristics of agricultural systems are a starting point for exploration of options that go beyond current developments but remain within the boundaries defined by the system properties. Understanding of the biological processes governing plant production has resulted in a large number of crop growth models and studies demonstrating their applicability (e.g. Van Keulen and Wolf, 1986; Seligman, 1990; Stöckle et al., 1994; Tsuji et al., 1998). By now, they are widely accepted tools in different fields of agro-ecological research, including engineering of future-oriented cropping systems to estimate production potentials of agricultural systems (Bouman et al., 1996). However, in an era of growing public attention for the side effects of agricultural production, such as emission of nutrients and biocides or loss of biodiversity and/or modification of nature and landscape values, quantification of these effects becomes increasingly important for a well-balanced identification of trade-offs between production and other objectives of agricultural systems. In addition, formalized process-knowledge about perennials, mixed cropping systems and rotations is scarce, due to insufficient documented information about such systems. Generic and easily operational tools enabling quantification of all relevant systems characteristics are scarce since many of the underlying processes are poorly understood. Therefore, the final products, i.e. the input-output relationships of future-oriented land use systems are often based on a poorly balanced description of the objectives. Some characteristics are described with more accuracy than others, which is fostered by the personal interests of involved researchers for understanding of specific processes.

Simulation models have recently become available allowing quantification of land use systems from agronomic, economic and environmental points of view by answering 'what if?' questions (e.g. McCown et al., 1996; Tsjui et al, 1999). However, such simulation models are not (yet) able to support a target-oriented approach of alternatives that is required to contribute to widely acceptable systems. At the end of Chapter 5 an outline of a tool is presented that enables the application of simulation models in a truly target-oriented and iterative manner to realize multiple objectives simultaneously. Three modules, i.e. a generator of management strategies, a crop growth simulation model, and an evaluator of the simulation results form the core of the tool. The generator defines a set of management alternatives and the simulator executes these management strategies and calculates their effects for user-specified objectives. Subsequently, the evaluator examines the simulation results to find the management strategy that best satisfies the objectives, while this information can be fed back to the generator for adjustment of the initial management strategies. Although far from operational yet, such a goal-driven use of simulation models may help to efficiently identify cropping systems that result in realization of multiple objectives simultaneously.

In addition to calibration and validation problems of individual tools, integration of tools (or their results) is a challenging task (Dent et al., 1995). So far, few tools have a generic structure that is simply exchangeable among locations, nor are model inputs geared to one another. Many tools have been developed for specific purposes, and assumptions or initial conditions used in one tool do often not match with those used in other tools. Recently, progress has been made with data standardization (Hunt et al., 2001) and modular model development (Jones et al., 2001) for crop growth simulation modeling. In addition, comprehensive and accessible databases with systematically compiled quantitative information on crop, soil and climate characteristics, and economic and agronomic attributes are hardly available in many places. In some cases, the only way for systems engineers is trying to capture relevant data and processes with expert estimates to make assumptions transparent and open to discussion (Chapter 6). 'Hard' and 'soft' information sources are often complementary, and their integration in computer-aided tools may on the one hand improve theoretical insights and on the other hand demonstrate options that otherwise would not have come to the fore. However, over-reliance on expert knowledge in agro-ecological engineering may result in biased designs towards prevailing production systems. Recently formulated objectives and new priorities may not be recognized or rejected as unfeasible since they do not correspond to the experts' perception about the current situation (De Ridder et al., 2000).

Considering the identified problems related to available tools, agro-ecological engineering also serves as a catalyst to stimulate collection and storage of agro-ecological information in a structured manner and formalization of knowledge about agro-ecological processes in generic and easily accessible models. The partial analysis presented in Chapter 3 showed the large impact of three N relationships and their uncertainty, on input-output relationships. Full insight in the degree to which incomplete and uncertain knowledge and data affect the performance of engineered systems may also be used to prioritize (disciplinary) research aimed at better understanding of involved processes or data sets that are more complete.

7.3 Future developments

A starting point in discussing future prospects of engineered land use systems is analysis of their most important application domains, i.e. exploring strategic policy options at regional scale and ex-ante assessment of farming systems. In the first domain, engineered land use systems are used as theoretical building blocks to explore options for and trade-offs among land-related policy objectives that for reasons of scale are difficult to identify experimentally. The robustness and accuracy of quantified inputs and outputs of future-oriented land use systems determine whether the generated information is a reliable basis for decision-making. Implementation of such land use systems in practice is often not the main purpose, but rather exploring the possibilities to realize well-defined objectives and identifying trade-offs among these objectives and, thus, making choices in the debate on land use transparent.

In the second domain, ex-ante assessment of new farming systems is a pre-stage of testing farming systems ('prototypes') in cooperation with commercial farmers or at experimental farms. Here, in contrast to the first domain, the aim is to identify favorable and technically feasible land use systems to be tested in practice. How do such systems perform under the conditions of tactical and operational decision-making? And does the mix of production systems allow realizing the required farm-objectives? In experimental settings, theoretically derived performances of engineered land use systems are used as targets, since input-output relationships generated according to the goal-oriented approach are not blueprints for crop cultivation. Confrontation of engineered systems with reality may require revision of theoretical insights or adjustment of traditional tactical or operational decision-making. In this way, interaction between future-oriented land use systems and experimental testing results in improvement of their mutual knowledge bases (Ten Berge et al., 2000). The use of engineering approaches in developing new agricultural systems does not replace the need for empirical work, but should be complementary to analyze those aspects that for various reasons are difficult to derive empirically (Aarts, 2000). However, their complementary value is until now scarcely recognized and has not (yet) been fully capitalized.

Both application domains of future-oriented land use systems would greatly benefit from engineering approaches that incorporate temporal phenomena such as long-term effects of interactions between system performance and soil resources. The conceptual engineering framework is based on equilibrium conditions of soil resources. In Chapter 5, this framework is expanded with a modeling approach that explicitly takes into account the interaction between system performance and soil resources and, hence, allows addressing the performance of systems in the long-term. A more dynamic approach to characterize future-oriented land use systems would give insight in the rate of change of such systems which is important when insight in the possible pace of agricultural development is required (Barbier, 1998; Bouman et al., 1999).

Particularly, strategic decision making at regional or higher scale would benefit from engineering approaches that incorporate spatial phenomena such as briefly indicated in Chapter 2. At aggregate scale, characteristics of land use are not a summation of inputs and outputs of individual land use systems. This is not only caused by the likely increase in variation with increasing spatial scale, but more important is that at each spatial scale the relative importance of processes changes (De Ridder, 1997). For example, erosion, hydrological processes and the dispersal of airborne pests can only be analyzed at scales beyond the scale of land units, while taking into account the interactions among different land units.

In physical environments characterized by high spatial and temporal variability, engineering of land use systems must consider consequences of this variability. Chapter 4 shows that under West African conditions the performance of land use systems strongly varies among years. The failure of explorative studies to affect the policy debate in this region may perhaps partly be explained by insufficient acknowledgment of this variation. Ignorance of years with complete crop failure while emphasizing the high yield performance of alternative land use systems does not match the common perception of West Africa. As shown in Chapter 4, tools exist to make this variation explicit, and to manage and reduce it. The analysis showed that fine-tuning of the sowing date to seasonal water availability could reduce coefficients of variation of yields from more than 50% to 20-30%. At the same time, long-term average yields could be increased with 40 to more than 130%. Also other sources of variation, for example, weed infestation and incidence of pests, should be taken into account in assessing future-oriented systems. Development of operational tools that enable quantification of the magnitude of variation by such factors is, therefore, urgently needed. Especially the design of systems based on so-called organic farming principles (CEC, 1991) may benefit from such tools. Due to a priori rejection of chemical fertilizers and biocides, fine-tuning of inputs to systems requirements is difficult, and various yield-limiting and yield-reducing factors may affect yields concurrently. Hence, organic farming systems are susceptible to various sources of variation that need to be addressed in order to improve the performance of such systems. One of the challenges for the future application of agro-ecological engineering approaches will be the formulation of such organic farming systems in appropriate model specifications allowing a well-balanced consideration of different objectives.

Agro-ecological engineering for the design and exploration of alternative systems has not (yet) materialized as an independent discipline within agricultural sciences and is, therefore, still in its infancy. The body of work developed in this field of study thus far has been largely uncoordinated. A small group within the agricultural science community attempts to identify and organize concepts, principles and methods that are required for engineering future-oriented systems in a transparent and reproducible way (e.g. Van Ittersum and Rabbinge, 1997; Rossing et al., 1997; Tsuji et al., 1998). This study contributes to these shared aims but it is realistic to state that currently agro-ecological engineering is still mainly in a theoretical stage. Development of agro-ecological engineering as a field of study in its own right requires a broad and in-depth discussion with researchers from different disciplines, such as agronomy, soil sciences, economics, and plant pathology. Dovetailing information and concepts from various disciplines can only begin when the need for a joint approach is widely acknowledged. Agro-ecological engineering is a means to improve communication among research disciplines, empirical and theoretical researchers, and stakeholders and researchers. It bridges gaps that exist among many different groups. Only their joint effort allows to develop systems that can take up the challenges that agriculture faces in the 21st century, both in developing and developed countries.

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Summary

Both in developing and developed countries, agriculture faces an array of interrelated challenges and constraints with respect to the management of natural resources, production of sufficient food of a high quality, and employment for a decreasing part of the rural population. To solve these problems, development of new production systems is required. A revision of existing systems must explicitly take into account the multiple and possibly conflicting needs of mankind in the 21st century. Agro-ecological engineering approaches aimed at design and exploration of alternative systems may help to characterize the complex problems that agriculture faces, and to identify options that contribute to their solution. Typically, engineering approaches address the future and explore *possible* options and not *plausible* or *probable* developments. Such engineering approaches are fundamentally different from methods that build on extrapolation of knowledge from historical and existing land use. Engineering methods are based on mathematical representations of well-founded agro-ecological principles, taking into account available resources and required land-related objectives. Using a variety of numerical tools, engineering approaches integrate and synthesize knowledge of physical, chemical, physiological and ecological processes, empirical data and expert knowledge regarding agronomy and livestock.

This study explicitly addresses agro-ecological approaches to engineer land use systems at the field level. The goal of this study is to contribute to the development of a formalized approach to identify and engineer future-oriented land use systems at the field level enabling the systematic exploration of land use options at farm or regional level. Formalization of concepts and procedures is required to efficiently engineer alternative land use systems that are consistent with the objectives at stake while at the same time no option is excluded in an early phase of development. A formalized approach enables the development of operational tools to engineer relevant and manageable sets of land use systems in terms of outputs and inputs. Case study data and information from the northern Atlantic zone of Costa Rica and (semi-) arid West Africa are used to develop, test and elaborate the approach. Subsequently, the approach and its underlying concepts are implemented into two operational tools.

In Chapter 2, a *goal-oriented* approach is introduced to identify and engineer future-oriented land use systems. The approach encompasses three steps:

(i) goal-oriented identification and design of land use systems,
(ii) quantification of biophysical production possibilities, and
(iii) identification of the optimal mix of inputs, i.e. the production technique, required to realize production possibilities.

The goal-oriented identification and design depends on required objectives of a system

under study, whereas plant, animal and environmental characteristics determine biophysical production possibilities. Characteristics of the production technique determine the realization of these production possibilities. Hence, quantification of future-oriented land use systems starts with determining outputs followed by defining the inputs required for the realization of these outputs. In general, several combinations of inputs are possible to realize a given output. However, a relevant set of inputs can only be identified if the required objectives are explicit. Land use systems engineered according to the goal-oriented approach are future-oriented, since not (yet) practiced but technically feasible systems are explored using accepted goals. These systems are based on available resources and take into account the latest developments in agricultural sciences and well-founded agro-ecological principles guaranteeing technically optimal resource use.

Engineering of future-oriented land use systems requires process knowledge and data that are subject to uncertainty affecting quantification of land use systems in their inputs and outputs. In Chapter 3, the effects of uncertainty in three important N-relationships relevant for quantification of inputs and outputs of future-oriented cropping systems are analyzed:

(i) N-leaching as function of crop characteristics, i.e. uncertainty as to crop characteristics affecting N-leaching,

(ii) crop N-concentration as function of yield level, i.e. uncertainty as to the development of N-concentrations in the crop over the entire yield range, and

(iii) the recovery of crop residue-N, i.e. uncertainty as to the fraction of crop residue-N that is available for uptake by a subsequent crop.

Based on validated assumptions, consequences of uncertainty in these three N-relationships are specified in terms of N-loss and production costs for different cropping systems in the northern Atlantic zone of Costa Rica. All three relationships and their uncertainty have a major impact on N-loss of cropping systems; the maximum relative change compared to the base calculations is 70% for all crop types. Effects on costs are limited; the maximum relative change compared to the base calculations is 12% for all crop types, and depends on the share of costs for fertilizer management in the total production costs. The analyses enable a better management or reduction of uncertainty through the identification of cropping systems with smaller uncertainty margins, and identification of research aimed at a more complete understanding of involved processes.

Uncertainty in performance of future-oriented cropping systems due to temporal variation creates difficulties in strategic decision-making based on such systems. In Chapter 4, the degree of variation in inputs and outputs of future-oriented millet systems is quantified using a generic dynamic crop growth simulation model and a static technical coefficient generator that has been developed to quantify various inputs and outputs of land use systems in West Africa. Weather data for 31 years characterize two sites in (semi-) arid West Africa, while at each site two soil types with contrasting properties are considered. Economic yield, N-loss and labor requirement are used as benchmarks for outputs and inputs of millet systems. In all cases, inputs and outputs of millet systems have coefficients of variation (CV) exceeding 50%. Engineering tools are identified that help policy makers to quantify consequences of variability at different scale levels so that variability can be reduced or better managed. Examples are given of how engineers of future-oriented cropping systems can apply crop growth simulation models to engineer cropping systems aimed at less variable yields. At one site, fine tuning of the sowing date to seasonal water availability reduced CVs of yield to 20-30%, while long-term average yields increased with 40 to more than 130%. Water conservation measures increased yields with 40 to 230% and reduced their CVs with 28-50% in all cases.

To be able to determine input-output relations, often equilibrium conditions with respect to soil resources are assumed, while this condition is often not met, nor the ultimate aim. In Chapter 5, land use systems are quantified as a sequence of crops, while interactions between system performance and soil N-resources are explicitly taken into account and equilibrium conditions in soil N-stocks are not a premise. A simple and validated N-balance model is used describing major processes affecting soil N-dynamics. The model calculates the annual amount of N required for realizing a target crop N-uptake taking into account losses and the supply via rainfall, biological fixation and mineralization from the soil N-pool. Five crop rotation scenarios, typical for semi-arid West Africa, are defined that differ in target crop yield, crop choice, crop residue management and external N-source. With exception of the scenario in which N-fertilization is via manure, all scenarios result in a decline in total soil N-stock varying from 27 to 2% after 50 years and, thus, increasing need to supply N via fertilization over time. Consequences of this changing need to supply N in future-oriented cropping systems are discussed for decision support models based on linear programming techniques. In addition, an outline of an alternative modeling approach is given aimed at identification of management strategies required to realize multiple goals simultaneously, including a required soil N-stock.

In Chapter 6, two operational tools are presented, PASTOR (Pasture and Animal System Technical coefficient generatOR) and LUCTOR (Land Use Crop Technical coefficient generatOR), that enable the engineering of land use systems in terms of inputs and outputs based on the integration of systems-analytical knowledge, empirical and standard agronomic and animal husbandry data, and expert knowledge. PASTOR quantifies livestock systems while LUCTOR is geared towards cropping systems. Both

PASTOR and LUCTOR were developed for the generation of input data for explorative and predictive land use models for the northern Atlantic zone of Costa Rica. In addition, they are also useful as stand-alone tools to explore the technical, economic and environmental efficiency of land use systems, to perform cost-benefit analyses, and to quantify the trade-off among socio-economic, agronomic and environmental objectives at the field level. Tools such as PASTOR and LUCTOR integrate different types of knowledge, including non-documented knowledge from field experts so that this knowledge becomes transparent and open to critical review and discussion by others.

In Chapter 7, the goal-oriented approach, required numerical tools and its future-prospects for development of new systems are discussed on the basis of the knowledge and insight gained in this study.

Do the alternatives engineered according to the goal-oriented approach really represent *future* options? Here, two opinions are distinguished, i.e. the goal-oriented approach is either insufficiently innovative or too optimistic. The former opinion indicates the continuous challenge for researchers to generalize the latest agro-ecological knowledge into generic calculation rules that allow wide ex-ante evaluation of alternative land use systems. With respect to the claim that the approach produces options that are too optimistic, the conclusion is that current developments with, for example, institutional barriers are deliberately ignored since explorations of options should be based on *feasibilities* and not on *probable* and *plausible* developments.

Available numerical tools to quantify input-output relationships of future-oriented land use systems are biased towards models quantifying production characteristics of a limited number of crops. Less attention is given to formalization of knowledge involving other important characteristics of land use systems, for example, their long-term effects on resource use. Agro-ecological engineering may serve as a catalyst to stimulate collection and storage of agro-ecological information in a structured manner and formalization of knowledge about agro-ecological processes in generic and easily accessible models. The degree to which incomplete or uncertain knowledge and data affect the performance of engineered systems may be used to prioritize (disciplinary) research aimed at a better understanding of involved processes or the collection of data sets that are more complete.

With respect to prospects of engineering approaches for the development of new systems, it is concluded that the complementary value of engineering approaches and empirical research until now has been scarcely recognized and has not (yet) been capitalized. In addition, more attention should be given to temporal and spatial phenomena in engineering approaches. Examples of these are long-term effects of outputs on the system's performance, variability in the system's performance due to erratic weather patterns, and processes that show interactions at scales beyond the field level, such as erosion, hydrological processes and the spread of airborne diseases and pests.

Agro-ecological engineering should be used to help improve communication among research disciplines, empirical and theoretical researchers, and stakeholders and researchers, enabling the development of truly new systems. It bridges gaps that exist among many groups, but that have to be closed to realize widely acceptable systems. Only the joint effort of these groups allows the development of systems that can take up the challenges that agriculture faces in the 21st century, both in developing and developed countries.

Samenvatting

Zowel in ontwikkelings- als ontwikkelde landen staat de landbouw voor een aantal samenhangende uitdagingen en problemen op het gebied van beheer van natuurlijke hulpbronnen, de productie van voldoende voedsel van hoge kwaliteit, en werkgelegenheid voor een afnemend deel van de plattelandsbevolking. Teneinde die problemen op te lossen is de ontwikkeling van nieuwe productiesystemen vereist. Bij een herziening van bestaande landbouwsystemen moet expliciet rekening worden gehouden met de verschillende en veelal conflicterende behoeften van mensen in de eenentwintigste eeuw. Ingenieursbenaderingen gericht op het technisch ontwerpen en verkennen van alternatieve systemen kunnen helpen bij het karakteriseren van de problemen waarvoor de landbouw staat, en bij het identificeren van opties die bijdragen aan hun oplossing. Kenmerkend van deze ingenieursbenaderingen is dat zij zich richten op de toekomst en het verkennen van *mogelijkheden* en zich niet richten op *aannemelijke* of *waarschijnlijke* ontwikkelingen. Deze benaderingen zijn fundamenteel verschillend van benaderingen die gebaseerd zijn op extrapolatie van kennis over historisch en huidig landgebruik. Ingenieursbenaderingen zijn gebaseerd op wiskundige beschrijvingen van valide agro-ecologische principes, terwijl rekening wordt gehouden met de beschikbare hulpbronnen en de gewenste doelstellingen met betrekking tot landgebruik. Zij integreren en synthetiseren met behulp van verschillende numerieke methodieken enerzijds proceskennis over betrokken fysische, chemische, fysiologische en ecologische processen, en anderzijds empirische gegevens met betrekking tot agronomie en veehouderij, inclusief kennis van experts.

In deze studie staan landgebruiksystemen op perceelsniveau centraal. Het doel van deze studie is om bij te dragen aan de ontwikkeling van een geformaliseerde benadering om toekomstgerichte landgebruiksystemen op perceelsniveau te ontwerpen en te kwantificeren in termen van inputs en outputs. Deze kunnen worden gebruikt bij systematische verkenningen van landgebruikopties op bedrijfs- of regionaalniveau. Formalisering van concepten en procedures is nodig voor het op een efficiënte wijze ontwerpen en kwantificeren van alternatieve landgebruiksystemen die consistent zijn met de doelstellingen van belanghebbenden, terwijl tegelijkertijd geen enkele optie wordt uitgesloten in een vroegtijdig stadium van ontwikkeling. Een geformaliseerde benadering maakt het mogelijk operationele computer-programmatuur te ontwikkelen waarmee relevante en hanteerbare sets van landgebruiksystemen ontworpen en gekwantificeerd kunnen worden in termen van outputs en inputs. Gegevens van de noordelijke Atlantische zone van Costa Rica en het (semi-) aride West-Afrika zijn gebruikt om de benadering te ontwikkelen, te testen en uit te werken. Vervolgens zijn de benadering en haar onderliggende concepten geïmplementeerd in twee operationele modellen.

In Hoofdstuk 2 wordt een doelgerichte benadering geïntroduceerd om toekomstgerichte landgebruiksystemen te identificeren, te ontwerpen en te kwantificeren. De benadering bestaat uit drie stappen:

(i) doelgerichte identificatie en ontwerp van landgebruiksystemen,

(ii) kwantificering van de biofysische productiemogelijkheden, en

(iii) bepaling van de optimale combinatie van inputs, dat wil zeggen de productietechniek benodigd om productiemogelijkheden te realiseren.

De doelgerichte identificatie en het ontwerp hangen af van de nagestreefde doelstellingen voor het bestudeerde systeem, terwijl plant-, dier- en omgevingseigenschappen de biofysische productiemogelijkheden bepalen. Kenmerken van de productietechniek bepalen de realisatie van deze productiemogelijkheden. Kwantificering van toekomstgerichte landgebruiksystemen begint dus met het bepalen van de outputs, gevolgd door het definiëren van de inputs die nodig zijn om deze outputs te realiseren. In het algemeen zijn diverse combinaties van inputs mogelijk voor het realiseren van een bepaalde output, maar een relevante combinatie van inputs kan alleen geïdentificeerd worden als de gewenste doelen expliciet zijn. Landgebruiksystemen die ontworpen worden volgens de doelgerichte benadering zijn toekomstgericht omdat (nog) niet bestaande maar technisch wel uitvoerbare systemen worden verkend op basis van gangbare doelen. Deze systemen zijn gebaseerd op beschikbare hulpbronnen en houden rekening met de laatste ontwikkelingen in de landbouwwetenschappen en valide agro-ecologische principes die een technisch optimaal gebruik van hulpbronnen garanderen.

Het ontwerpen en kwantificeren van toekomstgerichte landgebruiksystemen vereist proceskennis en data die onderhevig zijn aan onzekerheid en zo de berekende inputs en outputs van landgebruiksystemen beïnvloeden. In Hoofdstuk 3 worden de effecten geanalyseerd van onzekerheid in drie relaties voor stikstof (N) die belangrijk zijn voor het kwantificeren van inputs en outputs van toekomstgerichte gewassystemen:

(i) N-uitspoeling als functie van gewaskarakteristieken, dat wil zeggen onzekerheid over de mate waarin gewaskarakteristieken N-uitspoeling beïnvloeden;

(ii) N-concentratie in het gewas als functie van het opbrengstniveau, dat wil zeggen onzekerheid met betrekking tot het verloop van N-concentraties in het gewas bij verschillende opbrengstniveaus;

(iii) De benutting van gewasresidu-N, dat wil zeggen onzekerheid met betrekking tot de fractie N in gewasresiduen die beschikbaar komt voor het volgende gewas.

Gebaseerd op valide aannames worden consequenties van onzekerheid in deze drie N-relaties gespecificeerd in termen van N-verlies en productiekosten voor verschillende gewassystemen in de noordelijke Atlantische zone van Costa Rica. Alle drie relaties en hun onzekerheid hebben een groot effect op het N-verlies, dat wil zeggen het N-verlies verschilt maximaal 70% met het N-verlies volgens de basisberekening voor alle gewassystemen. Hun effecten op de kosten zijn beperkt: de productiekosten verschillen maximaal 12% met die volgens de basisberekening, en hangen af van het aandeel van de kosten van het nutriëntenmanagement in de totale productiekosten. De analyses maken het mogelijk onzekerheid beter te hanteren en te reduceren door het identificeren van gewassystemen met kleinere onzekerheidsmarges, en het identificeren van onderzoek gericht op beter begrip van de betrokken processen.

Onzekerheid over de resultaten van toekomstgerichte gewassystemen ten gevolge van temporele variatie veroorzaakt problemen bij het nemen van strategische beslissingen gebaseerd op zulke systemen. In Hoofdstuk 4 wordt de mate van variatie in inputs en outputs van toekomstgerichte gierstsystemen gekwantificeerd met behulp van een generiek dynamisch gewasgroei simulatiemodel en een statische technische coëfficiënten generator die is ontwikkeld om verschillende soorten inputs en outputs van landgebruiksystemen in West-Afrika te kwantificeren. Weersgegevens van 31 jaar karakteriseren twee gebieden in het (semi-) aride West-Afrika, terwijl voor elk gebied berekeningen worden uitgevoerd voor twee bodemtypes met verschillende eigenschappen. Gewasopbrengst, N-verlies en arbeidsbehoefte worden gebruikt als voorbeeld voor outputs en inputs van gierstsystemen. Alle inputs en outputs van gierstsystemen hebben variatiecoëfficiënten (VC) van meer dan 50%. Methodieken zijn geïdentificeerd die beleidsmakers helpen de consequenties van variabiliteit op verschillende schaalniveaus te kwantificeren zodat deze variabiliteit gereduceerd of beter beheerst kan worden. Aan de hand van voorbeelden wordt geïllustreerd hoe agro-ecologische ingenieurs met behulp van gewasgroei simulatiemodellen gewassystemen kunnen ontwerpen met een minder variabele opbrengst. In één gebied konden door het beter afstemmen van het zaaitijdstip op de waterbeschikbaarheid gedurende het seizoen VCs van de opbrengsten tot 20-30% worden teruggebracht, terwijl gemiddelde langetermijnopbrengsten toenamen met 40 tot meer dan 130%. Met waterconserveringsmethoden namen de opbrengsten toe met 40 tot 230% en verminderden hun VCs met 28-50% onder alle omstandigheden.

Om input-output relaties te kunnen bepalen worden vaak evenwichtssituaties met betrekking tot bodemhulpbronnen verondersteld, hoewel zulke situaties zich vaak niet voordoen en vaak niet het ultieme doel zijn. In Hoofdstuk 5 worden landgebruiksystemen gekwantificeerd die bestaan uit een reeks van gewassen, terwijl expliciet rekening wordt gehouden met de interactie tussen systeem outputs en de bodem N-voorraad, en er niet wordt uitgegaan van een evenwichtssituatie. Een eenvoudig en gevalideerd N-balans model wordt gebruikt om de belangrijkste processen te beschrijven die de bodem N-dynamiek beïnvloeden. Het model berekent de jaarlijkse hoeveelheid N die nodig is om een bepaalde gewas N-opname te realiseren waarbij rekening wordt gehouden met de verliezen en aanvoer via regenval, biologische stikstofbinding en mineralisatie van de bodem N-voorraad. Er zijn vijf gewasrotatie scenario's gedefinieerd, die kenmerkend zijn voor het semi-aride West-Afrika. Deze scenario's verschillen in gewenste gewasopbrengst, gewaskeuze, gewasresidu-management en type toegediende N. Met uitzondering van het scenario waarin de N-behoefte door dierlijke mest wordt gedekt, resulteren alle scenario's in een afname van de totale bodem N-voorraad met 2 tot 27% na 50 jaar, en dus, in een toename van de vereiste N-toevoer via bemesting met de tijd. De consequenties van deze veranderende N-behoeften in toekomstgerichte landgebruiksystemen worden bediscussieerd voor beslissingsondersteunende modellen gebaseerd op lineaire programmeringtechnieken. Daarnaast wordt een alternatieve modelbenadering gepresenteerd ter identificatie van managementstrategieën waarmee meerdere doelen tegelijkertijd gerealiseerd kunnen worden, inclusief een gewenste bodem N-voorraad.

In Hoofdstuk 6 worden twee operationele computermodellen gepresenteerd, PASTOR (*Pasture and Animal System Technical coefficient generatOR)* en LUCTOR (*Land Use Crop Technical coefficient generatOR)*. Deze modellen maken het mogelijk landgebruiksystemen te ontwerpen en te kwantificeren in termen van inputs en outputs gebaseerd op de integratie van systeemanalytische kennis, empirische en standaard agronomische en veehouderij gegevens, en kennis van experts. PASTOR kwantificeert veehouderij-systemen terwijl LUCTOR is gericht op het kwantificeren van gewassystemen. PASTOR en LUCTOR zijn ontwikkeld om input gegevens te genereren voor verkennende en voorspellende landgebruikmodellen voor de noordelijke Atlantische zone van Costa Rica. Ze zijn daarnaast ook bruikbaar als zelfstandig instrument om de technische, economische en milieukundige efficiëntie van landgebruiksystemen te verkennen, om kosten-baten analyses uit te voeren, en om uitruilwaarden tussen sociaal-economische, agronomische en milieukundige doelen op perceelsniveau te kwantificeren. Instrumenten zoals PASTOR en LUCTOR integreren verschillende typen kennis, inclusief ongedocumenteerde kennis van experts zodat deze kennis transparant wordt en kritisch beoordeeld kan worden door derden.

In Hoofdstuk 7 worden de doelgerichte benadering, de benodigde numerieke instrumenten en de vooruitzichten voor de ontwikkeling van nieuwe systemen bediscussieerd aan de hand van kennis en inzicht verkregen met deze studie.

Representeren de alternatieven die ontworpen en gekwantificeerd zijn volgens de doelgerichte benadering werkelijk *toekomstige* opties? Hier kunnen twee contrasterende opvattingen worden onderscheiden: de eerste is dat de doelgerichte benadering onvoldoende innovatieve systemen genereert, terwijl de tweede stelt dat deze systemen juist te optimistisch zijn. De eerste opvatting wijst op de voortdurende uitdaging voor onderzoekers om de meest recente agro-ecologische kennis te generaliseren in algemene wetmatigheden waardoor een uitgebreide ex-ante beoordeling van alternatieve landgebruiksystemen mogelijk wordt. Met betrekking tot de opvatting dat de benadering opties genereert die veel te optimistisch van aard zijn, wordt beargumenteerd dat huidige ontwikkelingen met bijvoorbeeld institutionele belemmeringen opzettelijk zijn genegeerd omdat verkenningen van opties moet gebeuren op basis van *technische mogelijkheden* en niet op basis van *waarschijnlijke* of *aannemelijke* ontwikkelingen.

De meeste instrumenten om input-output relaties van toekomstgerichte landgebruiksystemen te kwantificeren zijn computermodellen gericht op het kwantificeren van productiekarakteristieken van een beperkt aantal gewassen. Veel minder modellen zijn beschikbaar waarin kennis is geformaliseerd omtrent andere belangrijke karakteristieken, zoals bijvoorbeeld het langetermijneffect van landgebruiksystemen op het gebruik van hulpbronnen. Ingenieursbenaderingen zoals beschreven in deze studie kunnen het gestructureerd verzamelen en opslaan van agro-ecologische informatie stimuleren, evenals de formalisering van agro-ecologische proceskennis in generieke en eenvoudig toegankelijke modellen. De mate waarin incomplete kennis en gegevens het functioneren van toekomstgerichte systemen beïnvloeden kan dienen om prioriteiten vast te stellen voor (disciplinair) onderzoek gericht op een beter begrip van de betrokken processen of het complementeren van onvolledige gegevensbestanden.

Met betrekking tot de vooruitzichten van ingenieursbenaderingen voor de ontwikkeling van nieuwe systemen is de conclusie dat de complementaire aard van deze benaderingen en empirisch onderzoek tot op heden nauwelijks is onderkend en (nog) niet is benut. Bovendien moet meer aandacht worden gegeven aan temporele en ruimtelijke verschijnselen en interacties in ingenieursbenaderingen. Voorbeelden hiervan zijn langetermijneffecten van outputs op het functioneren van het systeem, variabiliteit in het systeem ten gevolge van variatie in het weer, en processen die interacties vertonen op hogere schaalniveaus dan het perceelsniveau, zoals erosie, hydrologische processen, en de verspreiding van ziekten en plagen door de lucht.

Ingenieursbenaderingen kunnen worden gebruikt om communicatie te verbeteren tussen onderzoeksdisciplines, tussen empirische en theoretische onderzoekers, en tussen belanghebbenden en onderzoekers zodat werkelijk nieuwe systemen kunnen worden ontwikkeld. Ingenieursbenaderingen maken het mogelijk om bestaande kloven tussen vele groepen te overbruggen wat noodzakelijk is om breed geaccepteerde systemen te realiseren. Slechts met de gezamenlijke inspanning van deze groepen is het mogelijk systemen te ontwikkelen die de uitdaging aankunnen waar de landbouw voor staat in de eenentwintigste eeuw, zowel in ontwikkeling- als ontwikkelde landen.

Curriculum Vitae

Huib Hengsdijk was born June 7, 1962 in Rheine, Germany. He studied at Wageningen University from 1980 till 1988, where he graduated as agronomist with majors in agronomy and theoretical production ecology and a minor in weed science. After his graduation, he worked at the *Wetenschappelijke Raad voor het Regeringsbeleid* (WRR) in The Hague where he was assigned to the project team that prepared the report '*Grond voor keuzen: vier perspectieven voor de landelijke gebieden in de Europese Gemeenschap*'. In 1990, he started to work for the *Proefstation voor de Akkerbouw -en Groenteteelt in de Vollegrond* (PAGV) in Lelystad where he was responsible for countrywide experiments on the use of manure in arable cropping systems. Subsequently, he worked at the *Instituut voor Agrobiologisch en Bodemvruchtbaarheidsonderzoek* (AB-DLO) in Wageningen within the research programme 'Sustainable land use and food security in developing countries'. In the beginning of 1997, he started to work for the 'Research Program on Sustainabililty in Agriculture (REPOSA)' in Guápiles, Costa Rica which is also known as *Steunpunt Costa Rica* of Wageningen University. Two years later, in 1999, he started his dissertation work at the Group Plant Production Systems of Wageningen University. Currently, he is working for Plant Research International in Wageningen as a senior research scientist.

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