UNCERTAINTY AND TEMPORAL ASPECTS IN LONG-TERM EXPLORATIONS OF SUSTAINABLE LAND USE

with reference to the Northern Atlantic Zone of Costa Rica

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UNCERTAINTY AND TEMPORAL ASPECTS IN LONG-TERM EXPLORATIONS OF SUSTAINABLE LAND USE

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Janette Bessembinder

Proefschrift
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STELLINGEN

1. Voor een eenduidige kwantificering van nieuwe productieactiviteiten ten behoeve van landgebruiksstudies, bieden de concepten "target-oriented approach" en "productieorientatie" een betere ingang dan de gegevens van huidige productieactiviteiten.

   - Van Ittersum, M.K. & R. Rabbinge, 1997. Concepts in production ecology for the analysis and quantification of agricultural input-output combinations. *Field crops research* 52, pp. 197-208.
   - dit proefschrift

2. Het gebruik van het concept "best technical means" binnen langetermijnverkenningen heeft tot gevolg dat de waarden van coëfficiënten met betrekking tot nutriënten en biociden sterk gecorreleerd zijn.

   - dit proefschrift

3. Door waarschijnlijkheidsverdelingen te gebruiken voor de beschrijving van alle typen onzekerheden wordt onzekerheid ten onrechte gelijkgesteld aan risico.

4. Door te spreken over "minimum data sets" voor landgebruiksstudies wekt men de indruk dat de omvang van de gegevensbestanden van meer belang is dan de kwaliteit van de gegevens, dat wil zeggen dat informatie over onzekerheden voor handen is.

5. De meerwaarde van een meer-perioden LP-model ten opzichte van een 1-periode LP-model binnen langetermijnverkenningen rechtvaardigt niet de benodigde inspanning om tijdsaspecten expliciet te beschrijven.

   - dit proefschrift

6. Technisch efficient gebruik van inputs zoals water en nutriënten kan veel duurzaamheidsproblemen verminderen of zelfs oplossen.

   - De Wit, C.T., 1992. Resource use analysis in agriculture. *Agricltural systems* 40, pp. 125-151.

7. Bij interdisciplinair onderzoek wordt te veel de nadruk gelegd op het aantal personen dat er aan meewerkt, en te weinig aandacht besteed aan de communicatie tussen en de integratie van de verschillende disciplines.

8. Het gebruik van GIS garandeert niet dat de spatiale componenten van landgebruik worden meegenomen.

9. Afwijzing van genetische manipulatie staat gelijk aan het ontkennen van honderden jaren "ontwikkeling" door middel van veredeling.

10. De verschuiving naar meer noodhulp binnen het Nederlandse ontwikkelingsbeleid, duidt er op dat men nog altijd meer waarde hecht aan de kwantiteit dan aan de kwaliteit van het leven.

11. Dat Nederland "vol" zou zijn is even perceptie-gebonden als wat "duurzaam" is.

12. Het imago van de Nederlandse boer is nog niet zo slecht, gezien de popularitieit van "boeren"-karnemelk, "boeren"-kaas, etc.

Behorende bij het proefschrift:

UNCERTAINTY AND TEMPORAL ASPECTS IN LONG-TERM EXPLORATIONS OF SUSTAINABLE LAND USE - with reference to the Northern Atlantic Zone of Costa Rica.

Janette Bessembinder

Wageningen, 14 november 1997

Supplementary sheet

Table 2.4 Feasible combinations of forms of land use and production techniques in the MGLP-model for the NAZ.

		Production technique					
	Mechanization	yes	yes	yes	*no*	no	*no*
	Chemical pest and disease control	yes	no	yes	yes	no	yes
	Reduced N-loss	no	no	yes	no	no	yes
Form of land use		*MBN*[a]	*MbN*	*MBn*	*mBN*	*mbN*	*mBn*
Banana[c]		+[b]	+	+	-	-	-
Cassava		+	+	+	+	+	+
Maize		+	+	+	+	+	+
Palmheart[c]		+	-	+	+	-	+
Grass pasture		-	-	-	+	-	+
Grass-legume pasture		-	-	-	+	-	+
Tree plantation		+	-	+	-	-	-

[a] explanation of codes for production technique: M = cultivation practices mechanized; m = no mechanized cultivation practices; B = chemical control of pests and diseases; b = alternatives for biocide use if possible; N = not aiming at reduced N-loss; n = 40 % lower N-loss compared with yield-oriented production;
[b] + = included; - = not included;
[c] construction of drainage systems in activities with techniques *MBN, MbN* and *Mbn* only.

Tables 4.1 and 6.1 Summary of indices used in the description of the single-period and multi-period MGLP-model[a]. Only those elements are specified that are used in figures.

Index	Description	Elements
ap	animal product	
au	animal unit	milking cow unit with calf for replacement ($_{au=mcu}$); beef cattle unit 1 ($_{au=bcu}$); beef cattle unit 2, with milk production included ($_{au=bcup}$)
c	cropping technique	
cp	crop product	
d	feeding pattern	100 % pasture ($_{d=po}$); 90 % pasture + 10% banana ($_{d=ba10}$); 80 % pasture + 20 % banana ($_{d=b20}$); 90 % pasture + 10 % maize ($_{d=m10}$); 80 % pasture + 20% maize ($_{d=m20}$); 90 % pasture + 10 % cassava ($_{d=c10}$)
l	form of land use (single-period)	banana ($_{l=ba5,\ l=ba10,\ l=ba15,\ l=ba20}$); cassava ($_{l=ca}$); maize ($_{l=ma}$); palmheart ($_{l=pa5,\ l=pa10,\ l=pa15,\ l=pa20}$); grass pasture ($_{l=gi5,\ l=gi10,\ l=gi15,\ l=gi20}$); grass-legume pasture ($_{l=gl5,\ l=gl10,\ l=gl15,\ l=gl20}$); tree plantations ($_{l=wt}$)
l	form of land use (multi-period)	banana ($_{l=ba1,\ l=bac}$); cassava ($_{l=ca}$); maize ($_{l=ma}$); palmheart ($_{l=pa1,\ l=pac}$); grass pasture ($_{l=gi1,\ l=gic}$); grass-legume pasture ($_{l=gl1,\ l=glc}$); tree plantations ($_{l=wt}$)
n	nutrient	
p	period	
s	terrain type	

[a] the indices in the single-period model and the multi-period model only show two differences: for forms of land use other indices are used and an index for periods is added in the multi-period model.

Table 2.2. Five tentative policy views for future land use in the NAZ, and the relevance of the objectives in each policy view.

Objective function	Code[a]	Free Enterprise (FE)	National Development (ND)	Regional Development (RD)	Environmental Protection (EP)	Nature Conservation (NC)
Environmental						
Area for agriculture	*ARM*	-[b]	-	-	-	min[b]
Total biocide leaching risk	*BLM*	-	-	-	-	min
Total biocide use	*BUM*	-	-	min	-	-
Biocide use per unit area	*BUHA*	-	-	-	min	-
Total N-loss	*NLM*	-	-	-	-	min
Social						
Total employment	*EMP*	-	max[b]	max	-	-
Economic						
Total economic surplus	*ESP*	max	max	-	-	-
Income per person	*INP*	-	-	max	-	-

[a] codes used in the single-period MGLP-model for the NAZ (Chapter 4);

[b] max=maximization; min= minimization; - = not considered very relevant in this policy view.

Table 2.3 Bounds on value-driven constraints per policy view for the NAZ.

Constraint [a]	Free Enterprise (FE)	National Development (ND)	Regional Development (RD)	Environmental Protection (EP)	Nature Conservation (NC)
Minimum area for nature	national parks	national parks, reserves, buffer zone	national parks, reserves, buffer zone	national parks	national parks, reserves, buffer zone
Minimum employment in agriculture (man years.y^{-1})	2,528	25,280	25,280	2,528	2,528
Minimum economic surplus (10^9 col.y^{-1})[b,c]	7.5	7.5	-	-	-
Minimum income from agriculture (10^4 col.$person^{-1}$.y^{-1})	4.5	8.9	8.9	4.5	4.5
Minimum export level	current[d] export	current export	-	-	-

[a] bound on objectives used as value-driven constraints, except export level;

[b] the colon (col.) is the currency of Costa Rica, in 1990 US$1=130 colon (Schipper 1996);

[c] estimated as GDP in 1992 (World Bank 1994) minus costs of labour;

[d] estimated current export from the NAZ per year: 1,780 10^3 tonne bananas; 17,000 tonne cassava, 2,246 tonne palmheart, 1,250 tonne beef.

ABSTRACT

Long-term explorations serve to widen the perspectives of decision makers. Biophysical and technical possibilities and constraints are confronted with the value-driven objectives of stakeholders in Multiple Goal Linear Programming (MGLP) models. Two methodological aspects of long-term explorations are elaborated in this thesis: uncertainty in agro-ecological coefficients and temporal aspects of land use. The effects of these aspects on generated land use scenarios are studied using data from the Northern Atlantic Zone of Costa Rica (NAZ).

Uncertainties in agro-ecological coefficients concerning nutrients and biocides were quantified. Only uncertainties caused by lack of knowledge of underlying biophysical processes or lack of data for quantification were considered. "Average", "pessimistic" and "optimistic" estimations of coefficients were generated, based on different perceptions of the influence of environmental factors. The estimations of the coefficients for various production activities are strongly correlated owing to the assumption of "best technical means" (i.e. inputs are used with the highest technical efficiency according to available knowledge and techniques). These coefficients were used in the single-period MGLP-model that was constructed for the NAZ. With the help of sensitivity analyses the effect of uncertainties on land use scenarios was determined for five tentative policy views, representing different perceptions of sustainability. It is concluded that, in long-term explorations, uncertainties in agro-ecological coefficients strongly affect the objective function values. However, they hardly affect the optimal land use allocation, because the ranking of production activities for the agro-ecological coefficients hardly changes when including uncertainties.

In long-term explorations the following temporal aspects are relevant: 1. Growth and ageing of crops and livestock, 2. Fluctuations in coefficients caused by variation in weather conditions, 3. Interactions in time. After an inventory of possibilities and limitations to describe these temporal aspects in LP-models, a multi-period version of the single-period model was constructed. In theory, all temporal aspects can be described in multi-period MGLP-models, although location-bound temporal interactions pose serious problems owing to the limitations of the LP-technique. In most cases, the relevant types of temporal aspects can also be included in single-period models with the help of predefined cropping sequences and additional coefficients and variables. It is discussed, that in long-term explorations the use of a multi-period model may have added value only if large differences in coefficients between periods and growth stages occur *and* if strong bounds are put on fluctuations over periods.

Based on the land use scenarios generated with the single-period and multi-period model it is concluded that there is considerable scope for policy in the NAZ. The differences between land use scenarios for the five policy views are large, regardless of the effects of the uncertainties in agro-ecological coefficients and the explicit inclusion of temporal aspects. By revealing the consequences and possibilities under particular land use objectives and constraints, this long-term exploration may help to structure and organize the discussion on desires for the future in the NAZ.

Keywords: long-term exploration, sustainability, Linear Programming, MGLP, uncertainty, sensitivity analysis, temporal aspects, multi-period model, policy views, Costa Rica.

PREFACE

The work reported here is part of the programme "A methodology for planning of sustainable land use: a case study in Costa Rica", started in 1991. The programme was carried out in the Atlantic Zone of Costa Rica by the Agricultural University of Wageningen (AUW) in cooperation with the *Ministerio de Agricultura y Ganadería* (MAG) and the *Centro de la Agronómia Tropical de Investigación y Enseñanza* (CATIE). Without the support of many people my research would not have resulted in this thesis.

First, I would like to thank my supervisors Louise Fresco and Rudy Rabbinge. You two took care of the steering of my research, although sometimes in a slightly different direction. In spite of your overfull agendas, you always found time for supervising my research in a pleasant way. I learnt a lot from you in the past years. Also special thanks to my co-promotor Martin van Ittersum. Martin, as my daily supervisor you took care I did not lose myself in details and you spent much time on revising my texts. Thank you for your patience and continuing support.

For such a broad subject as exploration of land use options, information from various disciplines is required. People from many departments and institutes assisted in obtaining the required data. I was pleasantly surprised that everyone wanted to make some time for my questions. Discussions were not always easy, owing to the differences in terminology and perspective between disciplines. On the other hand, contact with so many people and disciplines was very challenging and inspiring. To all of you, and to those I did not mention in particular, thanks for being so helpful: F. Penning de Vries and H. Van Keulen (AB-DLO); N. De Ridder, Th. Guiking, J. Neuteboom, L. 't Mannetje, J. Schoorl and J. Vos (Agronomy); L. Angulo (Agropalmito); J. Schiere and H. Udo (Animal husbandry); J. Arze, J. Jimenez, F. Lopez and B. Valverde (CATIE); R. Garcia, L. Perez, O. Torres, H. Sanchez, A. Vargas and R. Vargas (CORBANA); H. Hengsdijk and G. Kruseman (DLV); J. Arce, J. Celso, R. Russo and V. Villalobos (EARTH); N. de Graaf (Forestry); S. Abarcas, E. Aguilar, J. Carrillo and J. Von Dueszeln (MAG); F. Claassen and E. Hendrix (Mathematics); J. Van Bezooijen (Nematology); G. Reinds, E. Smaling, C. Van Diepen, N. Van Duivenbooden and F. Veeneklaas (SC-DLO); L. Arroyo (SENACSA); H. Booltink, R. Poels and T. Veldkamp (Soil science and geology); B. Janssen (Soil science and plant nutrition); P. Kooman, E. Lantinga, H. Naber and W. Rossing (Theoretical production ecology); G. Alink (Toxicology); E. Carazo, C. Jimenez and J. Sanchez (UCR); L. Castillo, M. Baayen and C. Ruepert (UNA); J. Garcia (UNED); M. Ridgeley and R. Yost

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TABLE OF CONTENTS

1 LONG-TERM EXPLORATIVE LAND USE STUDIES: AIM, METHODOLOGY AND SOME RESEARCH QUESTIONS

1.1 Explorative land use studies and land use planning

Land use planning is directed at finding the best use of land in view of accepted objectives, environmental and societal opportunities and constraints, and at determining appropriate future actions to reach this best land use (Fresco *et al.* 1990). By systematically evaluating current land use and alternatives, informed decisions about desired future land use can be made (Jordahl 1984; Dent 1993; Fresco *et al.* 1990; FAO 1993). Land use planning is mostly used to solve existing economic, social or environmental problems. Sustainability and sustainable development have several dimensions: ecological, technical and socio-economic. Attitudes towards sustainability diverge considerably, depending on the differing weights attached to facts, uncertainties and risks with respect to the environment and society (WRR 1995). Increasingly, the ecological aspects of sustainability and sustainable development receive attention, in addition to the socio-economic and technical aspects in land use planning and land use optimization studies (e.g. Miranowski 1984; Despotakis 1991; FAO 1993; Fresco *et al.* 1994; Van Lier *et al.* 1994; Schipper 1996; Barbier 1996).

Long-term explorative studies aim at showing options for future sustainable land use and trade-offs between objectives. Different perceptions of sustainability are operationalized by confronting fact-driven information on biophysical processes with value-driven objectives and bounds. This way, the options and limitations for future land use, caused by divergent priority setting can be determined. These long-term explorations can be used to support strategic choices. Figure 1.1 shows a simplified diagram of a land use planning process and the place of long-term explorations in this process. In the *descriptive* phase, the current situation (i.e. the start of the future) is analysed and the problems are defined. *Explorative* studies aim at showing decision makers alternatives for current land use. Short-term explorations examine the possibilities within the current socio-economic limits. Effects of small changes in these constraints are also studied. In long-term explorations it is assumed that these socio-economic constraints may be alleviated in a relatively short time span. Biophysical or agro-ecological limits can be assumed to be more stable in the next decades. Long-term explorations explore the possibilities within these biophysical limits. Exploring the biophysical possibilities for future agricultural land use is possible since considerable knowledge is available of processes underlying agricultural production. Short-term and long-term explorative studies often use a scenario approach to show the possibilities under different policy views. The combined information from descriptive and explorative studies provides the basis for well-founded choices for a "desired" future in the short term, as well as in the long term. Desires for the future are often based on one's image of the future and thinking of the future as a continuation of present developments is almost commonplace (Schoonenboom 1995). Results of long-term explorative studies, which do not take current socio-economic constraints for granted, may widen perspectives and, consequently, desires may change. In the *design* phase of a planning process, a compromise has to be reached between the desires of different stakeholders. In this phase identification of appropriate policy instruments to direct land use takes place. When the required policy measures to reach a certain desired future are not acceptable from an economic, social or environmental point of view, the desires for the future have to be adjusted. *Implementation* of the land use plan requires constant monitoring to find out whether the changes in land use occur at the desired rate, and whether objectives and policy measures need to be adjusted.

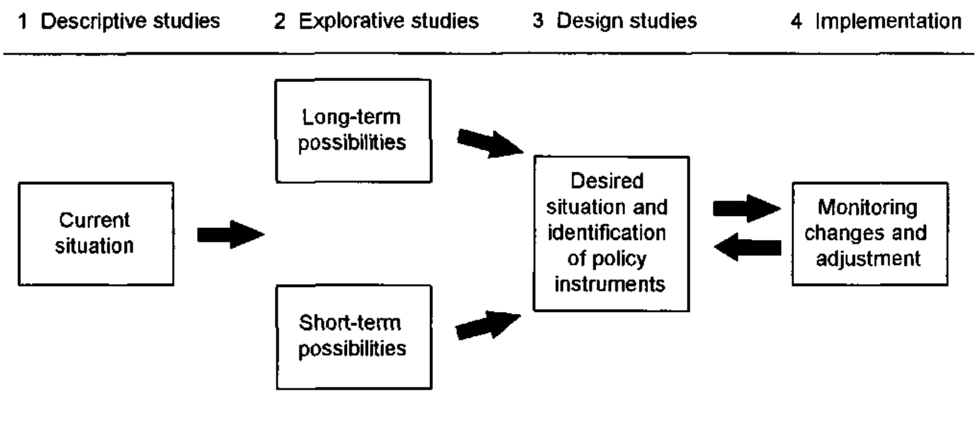

Figure 1.1 A simplified diagram of a land use planning process and the place of different types of land use studies, based on Dent (1993), FAO (1993), Hengsdijk & Kruseman (1993).

Current land use planning techniques are very much based on today's farmers' attitudes and production and production rates of the near past. Short-term explorations often use a projective approach, i.e. by extrapolating the past and the present to the future (Schweigman 1981; Csaki *et al.* 1984; Brown & Kane 1995). If more information is available on causality between land use drivers and land use, land use in the short term can be predicted (Van Ittersum *et al.* 1996). However, exploring long-term options in this way is virtually impossible. Changes in current trends are not only desirable, they are often also feasible. Exploration of long-term land use possibilities is needed to obtain insight into the options for agricultural land use (FAO 1991). An exploration of the long-term options for land use under different policy views helps to determine the "playing field" of policy makers for strategic choices. In long-term explorative studies this "playing field" is often determined with the help of Multiple Goal Linear Programming (MGLP).

Several examples of long-term explorative studies using MGLP have been published so far. The first studies focused on the regional level or higher levels: the Mariut region in Egypt (Ayyad & Van Keulen 1987), the Mediterranean Basin located in the northern Negev of Israel (Spharim *et al.* 1992), the fifth region of Mali (Van Keulen & Veeneklaas 1993), the rural areas of the European Community (WRR 1992), and at the global level (Penning de Vries *et al.* 1995; WRR 1995). Later studies also focused on farm level: small farms in the limestone area of East Java in Indonesia (Van Rheenen 1995), flowerbulb farms in The Netherlands (Rossing *et al.* 1997) and dairy farms in The Netherlands (Van de Ven 1996). All these studies aimed at increasing insight into the options to realize objectives and into the effects of constraints on technical options. They resulted in scenarios reflecting the viewpoints of different groups of stakeholders, each with different opinions on the relevance of various objectives.

Long-term explorative studies are relatively new and, compared with short-term explorations of land use, fewer methodological tools have been developed. In the next sections the methodology of long-term explorative studies and some relevant aspects are discussed.

1.2 Characteristics and methodology of long-term explorative studies

The aim of long-term explorative studies is exploring future land use options by confronting biophysical possibilities and constraints with the value-driven objectives of stakeholders. This aim has important consequences for the methodology and the required technical information. First, long-term explorations rely on *knowledge of underlying biophysical processes*, e.g. photosynthesis and effects of growth factors, to quantify new production techniques. Secondly, production is assumed to take place with the "best technical means", i.e. available knowledge and available means of production are optimally applied, which precludes any waste or inefficient use of resources. Neither current economic conditions, nor farm infrastructure present constraints to farming practices (WRR 1992; De Koning *et al.* 1995). Thirdly, value-driven and fact-driven aspects of land use are separated to enable distinction between technical possibilities and behaviourial factors that strongly influence the actual development policies (Spharim *et al.* 1992). In such long-term explorations the time span within which adopting the production activities could be technically feasible, is about 20 to 30 years. Being explicit about these assumptions underlying the long-term explorative study is important, because they affect the required input for such studies and the way in which results can be interpreted. Figure 1.2 shows a diagram of a land use optimization study. With the help of this figure the different elements of the methodology for long-term explorative studies are explained. This description is based on Bessembinder *et al.* (1997). In Table 1.1 the definitions of terms that are often used in long-term explorative studies are summarized.

The integrating technique is MGLP. With this optimization technique information on possible agricultural production activities is confronted with technical and value-driven constraints and a set of objective functions.

First, the various forms of soil-bound agricultural production that are feasible in the region are identified. For these forms of land use the physical production environments that are potentially suitable are identified in a qualitative land evaluation. The physical production environments are characterized by soil, terrain and climate. In the quantitative land evaluation, potential and water-limited yields are calculated for all suitable production environments with the help of crop growth simulation models. Such simulation models use knowledge of various growth processes, such as photosynthesis, to calculate plant growth under different climate and soil conditions (WRR 1992; Rabbinge 1993; Bouman *et al.* 1996).

Next, production activities are quantified. Production activities are characterized by their input-output combinations. These inputs and outputs differ per crop, production orientation, production technique and physical production environment (Rabbinge *et al.* 1994; Van Ittersum & Rabbinge 1997). The input-output relations are quantified using a "target-oriented" approach, which means that the inputs to realize a particular output level are quantified, using knowledge of the processes involved (De Wit *et al.* 1988; De Koning *et al.* 1992). Input-output relations are defined in such a way that they can be repeated many times with unchanged input-output relations, e.g. no depletion or accumulation of nutrients is allowed. This implies that no substitution is possible among inputs such as water and nutrients, which are taken up by the plant and which fulfill a specific and essential role. Other inputs such as biocides, labour, mechanization, can replace each other up to a certain degree. It is assumed that production takes place with the "best technical means", i.e. no more water, nutrients, biocides or labour to realize a particular production level are used than necessary. In other words, the inputs

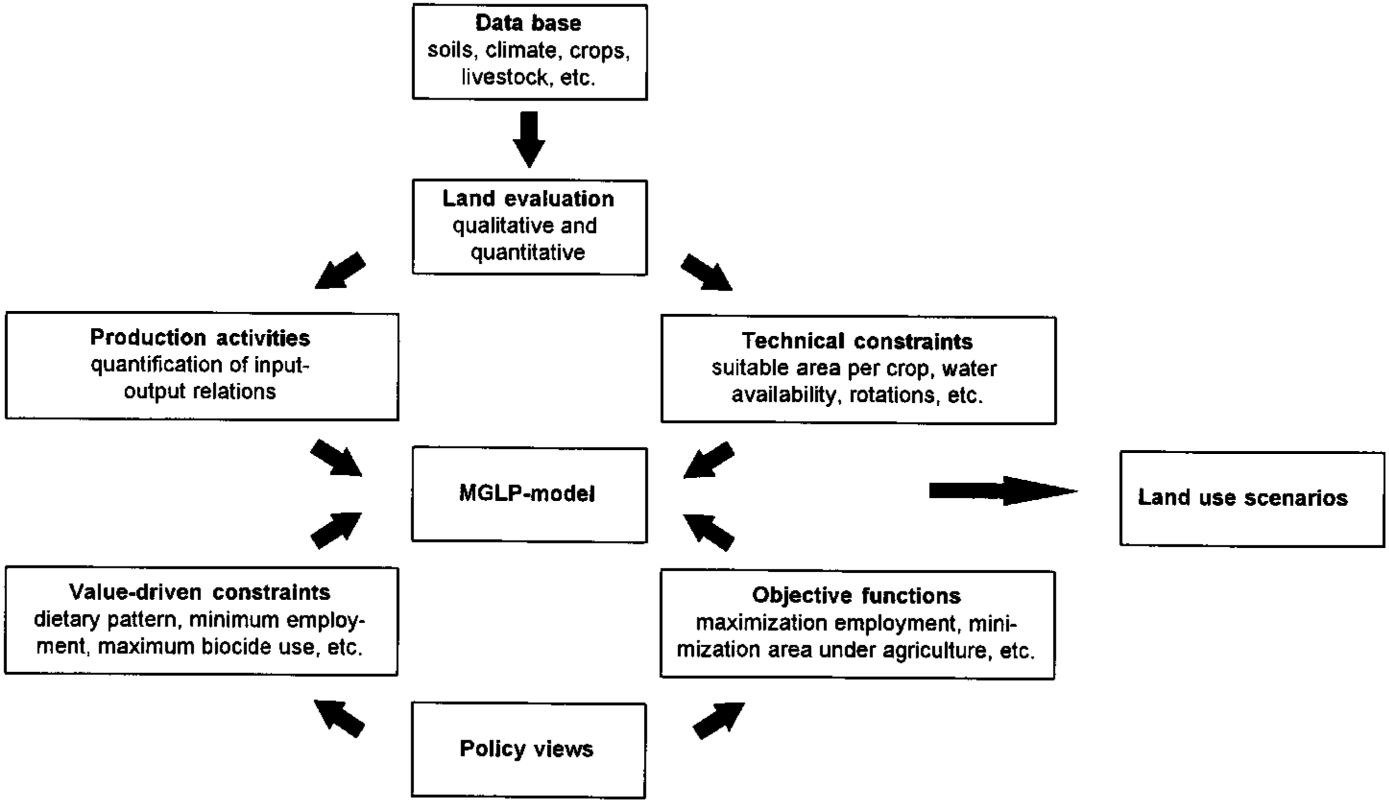

Figure 1.2 Diagram of the methodology for explorative land use studies.

are used with the highest technical efficiency according to the available knowledge and techniques. The choice of the various production techniques depends on the aim of the production activity, i.e. the production orientation: high soil productivity, low emissions of nutrients or biocides per unit product or per unit area, etc. The production orientation determines the combination of used inputs. For instance, in an activity oriented at high soil productivity, control of diseases and pests takes place in such a way that high productivity is achieved with efficient use of biocides. In an environment-oriented activity biocides are excluded as much as possible so there is minimum use per unit area. Lower yields per unit area are then accepted (WRR 1992).

The constraints of the MGLP-model can be divided into two groups. Technical constraints are determined by the biophysical and technical possibilities. An example is the suitability of a terrain unit for a particular form of land use or production technique, which is determined by climate and terrain conditions. For value-driven constraints no objective bounds can be formulated, because they are determined by the desires of man or society, e.g. the dietary pattern or the accepted unemployment rate. The bounds on these constraints often change with the policy view. Most value-driven aspects of land use are included as objective functions. When these objective functions are not optimized, they serve as value-driven constraints.

Decision makers or groups of stakeholders have different priorities for objectives (De Wit *et al.* 1988). Therefore, various policy views concerning land use problems are identified, e.g. views emphasizing self-sufficiency of food, free market and trade, nature conservation or environmental issues. These views are operationalized with one or more objective functions, such as maximization of cereal production, maximization of gross revenue of the region, or minimization of the area used for agriculture. Not all policy views can be quantified explicitly with objective functions. For instance, nature development and conservation have strong spatial components that are hard to catch in a MGLP model (WRR 1992).

Subsequently, land use options can be explored with the MGLP-technique in an interactive way (Spronk & Veeneklaas 1983; De Wit *et al.* 1988). First, the outer boundaries are determined by optimizing each of the objective functions in separate model runs, putting no or only light restrictions on the other objective functions. In this way, the initial freedom of choice (i.e. the worst and the best values) for each objective is made explicit to the stakeholders. In the next step, the stakeholders have to select the objective with the worst value that they consider most unacceptable. A tighter bound for that objective is then formulated. Next, the stakeholders are confronted with the results of a new series of optimization runs and then again, they have to select an objective with a value that is unacceptable to them. This procedure continues until the stakeholders are satisfied with the compromise between their objectives. The procedure can be repeated with different groups of stakeholders, resulting in different objective function values and land use allocations, i.e. land use scenarios. Comparison of the different land use scenarios shows the possibilities to realize objectives and the trade-offs between objectives.

Table 1.1 Summary of definitions of terms used in long-term explorations.

Term	Definition
Best technical means	Given a production aim, available knowledge and available means of production are optimally applied, which precludes any waste or inefficient use of resources. Neither current economic conditions, nor farm infrastructure present constraints to farming practices (WRR 1992; De Koning *et al.* 1995);
Input-output coefficient	Quantitative coefficient describing an input or output of a production activity;
Land use scenario	Result of optimization runs for one policy view, characterized by its objective function values and land use allocation;
Non-substitutable inputs	Inputs such as water and nutrients, which are taken up by the plant and which fulfill a specific and essential role (Van Ittersum & Rabbinge 1997);
Objective	Specific aim, expressing something to be achieved as part of a policy view;
Physical production environment	Condition characterized by soil, terrain and climate, under which production takes place and which is more or less a given fact for that production activity. These conditions affect the production level and the required inputs to realize a that production level (Van Ittersum & Rabbinge 1997);
Policy view	View on future land use representing a certain conception of sustainability. A policy view is described with one or more objective functions and bounds on value-driven constraints;
Production activity	A physical task or practice to produce a specific output, characterized by its input-output combination;
Production orientation	Aim of the production activity. The production orientation determines the combination of non-substitutable inputs;
Production technique	The way production activities are carried out;
Substitutable inputs	Inputs such as biocides, labour, mechanization, which can replace each other up to a certain degree (Van Ittersum & Rabbinge 1997);
Target-oriented approach	Inputs to realize a particular output level are quantified using knowledge of the processes involved (De Wit *et al.* 1988; De Koning *et al.* 1992);
Technical constraint	Biophysical and technical restrictions to land use;
Value-driven constraint	Restriction determined by the desires of man. Bounds on these constraints can differ per policy view.

1.3 Uncertainties

Data quality is important in quantitative models such as Linear Programming (LP) models. Knowledge of biophysical processes in various climates and for various soil types is not always sufficient for quantification of new production activities. Sometimes the knowledge of processes is there, while the data are lacking for proper quantification of processes. Consequently, analysis of model sensitivity should be part of land use studies. In the past, LP was mainly used for financial planning and, as a result, sensitivity to observed or intentional changes in product prices and input costs was tested.

Several diverging classifications for uncertainties exist (Beck 1988; Hendrix 1989; Funtowicz & Ravetz 1990; Pinter 1990; Cleaves 1994). Two main groups of uncertainties can be distinguished, each with three types or sources of uncertainties:

- Data uncertainties
  1. Inaccuracies or measurement errors;
  2. Randomness or natural variation;
  3. Lack of data for quantification of processes;
- Model uncertainties
  1. Errors in modelling of processes;
  2. Lack of knowledge of processes for modelling;
  3. Ignorance of processes.

In most land use studies using LP the six types of uncertainty are considered simultaneously, without discriminating between the different sources of uncertainty. Uncertainty does not necessarily imply low quality in scientific information and high quality does not require the elimination of uncertainty, but rather its effective management (Funtowicz & Ravetz 1990).

Qualitative or quantitative description of uncertainties, i.e. error bars, variation coefficients, probability distributions, ranges, is needed to be able to work with uncertainties. Methods for managing uncertainties can be divided into two main groups: explicit and implicit handling. Stochastic programming and fuzzy programming are examples of implicit managing of uncertainty. Uncertainties are put into these models, e.g. as probability distributions, and an "average best optimum" and ranges of possible values are calculated (Hof *et al.* 1993; Rossing *et al.* 1994). In "sensitivity" analyses of deterministic models uncertainty is handled more explicitly: specified changes in values of one or more coefficients are directly translated into new objective function values and land use allocations. Therefore, the coefficients and their uncertainties contributing most to the sensitivity of the LP-model can be identified. Several definitions are used in literature for the term sensitivity analysis (Kleijnen 1994). In the present study the term sensitivity analysis is used for all methods that study the effect of specified changes in the values of coefficients on the model output of deterministic LP-models, by changing one value at the time or by changing several values simultaneously. Most sensitivity analyses provide only partial information about the sensitivity of the optimal solution: only a limited range of possible values of coefficients are examined and higher order effects due to interactions between values of coefficients are normally ignored (Gardner *et al.* 1981). In LP the so-called shadow price is often used as a measure of model sensitivity. It tells us the increase in the value of the objective function when a particular constraint is relieved by one unit. Right-hand side ranging and reduced costs also give partial information about the sensitivity of a LP-model.

Until now analyses of the sensitivity of LP-models to uncertainties in agrotechnical coefficients have been limited, although in almost every project remarks on inaccuracies, uncertainties in coefficients, lack of data, uncertainties in model representations, etc. can be found, mainly in working documents or appendices (e.g. Ayyad & Van Keulen 1987; Sharifi 1992; Van Duivenbooden 1992). In the study on the fifth region of Mali the effects of alternative agrotechnical coefficients for livestock and reduced yields of inundated pastures after series of dry years were included in a sensitivity analysis (Veeneklaas *et al.* 1994). In the study on the rural areas of the European Community the effect of tighter constraints on N-use, biocide use and a change in diet were tested (Scheele 1992; WRR 1992). In the study on the limestone area of East Java effects of different farm sizes, labour availability, and allowed soil loss were analysed (Van Rheenen 1995). In all cases one coefficient was changed at the time.

Fresco (1994) and Bouma *et al.* (1995) mention data quality or uncertainty as one of the main problems in land use studies. For strategic choices on future land use objective information is needed. This means that information on the uncertainty associated with decision alternatives is needed (Spronk 1980; Environmental resources 1985; Schweigman 1985; Cleaves 1994; Rossing *et al.* 1997). The aim of long-term explorative studies is exploring future land use options, by confronting biophysical and technical possibilities and constraints with the value-driven objectives of groups of stakeholders each having a different perception of sustainability. To obtain an objective estimation of biophysical and technical options for land use in the long term, analysis of model sensitivity to uncertainties in coefficients, especially coefficients indicating the ecological dimension of sustainability, is needed.

1.4 Temporal aspects of land use

Land use has *temporal* and *spatial* aspects (Fresco & Kroonenberg 1992). The spatial aspects in land use optimization receive considerable attention through the use of different spatial units within LP-models and through the use of Geographic Information Systems (Fresco *et al.* 1994; Bouma *et al.* 1995; Stoorvogel 1995). Studies on temporal aspects of land use have almost entirely focused on past and present changes in spatial distributions of land covers (e.g. Sader & Joyce 1988; Veldkamp *et al.* 1992; Huising 1993; Stoorvogel 1995), or on extrapolations of past land use changes to the future (e.g. Veldkamp & Fresco 1996). Optimization of land use dynamics is hardly ever studied. In land use optimization studies mostly static single-period LP-models are applied. Such models suggest or imply that:

- Land use is the same each year and differences in inputs and outputs between years are not important or do not occur. Differences between years in coefficients and variables, e.g. fluctuations in crop yields caused by variation in weather conditions, are hardly ever included in the description of production activities for LP-models. Occasionally, differences within years are taken into account, e.g. for labour needs or forage production (Veeneklaas *et al.* 1991; Erenstein & Schipper 1993; Van Rheenen 1995). An exception is the study on the fifth region of Mali: in addition to production figures for years with average rainfall, figures for dry years were included (Veeneklaas *et al.* 1991);
- Land use scenarios can continue for many years. The land use scenarios generated with single-period LP-models can only continue for an infinite number of years if production activities do not affect the physical production environment or the input-output coefficients. Land use scenarios with negative nutrient balances do not satisfy this requirement: soil fertility depletion will affect input-output coefficients for future production activities;
- External factors remain constant. The effects of changes through the years in external factors are generally examined with the help of sensitivity analyses. For instance, land use scenarios can be generated for two different ratios between prices. Interactions between periods cannot be taken into account in this way.

In general, no distinction is made between types of temporal aspects, but the above-mentioned examples clearly illustrate that such a distinction would be of value. A possible classification of temporal aspects could be the following:

- Changing external factors (e.g. increased knowledge may lead to new production techniques, changing priorities or increased knowledge may lead to new policy views). This type represents developments in time, which will normally not reverse (type a);

- Growth and ageing of crops and animals (e.g. growth of timber stands; type b);
- Fluctuations (e.g. in prices, in weather conditions, in losses due to diseases). Many external factors and inputs and outputs show some random variation. This type represents fluctuations around an average, no developments in time occur (type c);
- Interactions (e.g. effects of soil degradation on crop yields, suppressing diseases by crop rotation). Land use in one year can affect the possibilities for land use in the next year, or it can affect the inputs and outputs in the next year (e.g. a leguminous crop provides N for the next crop). These interactions do not irreversibly change the physical production environment, unless certain threshold values are surpassed (type d).

Multi-period models are most often used to address the temporal aspects of land use explicitly. Examples are: Carter *et al.* (1977), Propoi (1977), Burgess (1981), Csaki *et al.* (1984), Dabbert (1986), Kennedy (1986), Nicholson *et al.* (1994), Leutscher (1995) for agricultural firm planning; Barbier (1996) for regional planning; Cox & Sullivan (1995), Hof *et al.* (1993) for timber harvest scheduling; Axsater *et al.* (1986) and Worm (1994) for other planning activities. These studies aimed at exploring or predicting short-term land use. They were either of a limited size, or only a limited number of temporal aspects were included.

The use of multi-period LP-models in long-term explorations may result in added value, as temporal aspects can be included more explicitly. The study of Spharim *et al.* (1992) can be considered as the only example of a multi-period model for a long-term exploration, but it only included a limited number of temporal aspects. According to Chapelle (1977) and O'Hara *et al.* (1989) it is entirely possible to accommodate temporal aspects using LP-techniques, although several authors mention limitations (Csaki 1977; Dykstra 1984; De Wit *et al.* 1988; Lohmander 1989; Hof *et al.* 1993) and no long-term explorations with strong spatial components have been carried out.

1.5 Objectives of this study

The research objectives of the present study follow from the problems identified in Sections 1.3 and 1.4.

The first research question concerns the handling of uncertainties in agro-ecological coefficients (i.e. coefficients indicating the ecological dimension of sustainability) in long-term explorations:

- Compare the uncertainty in agro-ecological coefficients with differences in

these coefficients owing to the form of land use, production technique and physical production environment;
- Analyse the consequences of uncertainties for optimum objective function values and land use allocation.

The second research question focuses on the inclusion of temporal aspects of land use in long-term explorations:
- Explore possibilities to include temporal aspects of land use in LP-models for long-term explorations of land use options;
- Evaluate advantages and disadvantages of including temporal aspects of land use in long-term explorations using LP.

The Northern Atlantic Zone (NAZ) of Costa Rica is used as case study area for elaborating the objectives.

1.6 Outline of the thesis

The following chapters deal with the different steps in the exploration of long-term possibilities for the NAZ, as described in Section 1.2. Chapter 2 describes the past and the present situation in the case-study area, the choices and assumptions underlying the long-term exploration of land use options in the NAZ, and the methods used to elaborate the research objectives. In Chapter 3 the quantification of the input-output coefficients of production activities is presented. The quantification of uncertainties in agro-ecological coefficients related to nutrients and biocides and the changes in input-output coefficients during the growth cycle of crops receive particular attention. Chapter 4 presents the mathematical description of the single-period MGLP-model for the NAZ. Chapter 5 contains the results of the land use optimization with this single-period MGLP-model. For five different policy views, i.e. different perceptions of sustainability, optimal land use scenarios are presented. The model sensitivity to uncertainties in coefficients relating to nutrients and biocides is compared with the model sensitivity to uncertainties in prices. Chapter 6 explores the possibilities to include temporal aspects of land use in multi-period LP-models. In this chapter the results of the single-period model for the NAZ are compared with the results of a multi-period version to demonstrate advantages and disadvantages. Finally, Chapter 7 presents a general discussion and recommendations for future research.

2 DESCRIPTION OF THE CASE-STUDY AREA, SYSTEM DELIMITATION AND METHODOLOGICAL APPROACH

In the last decades rapid changes have taken place in the Northern Atlantic Zone (NAZ) of Costa Rica, the case-study region of my project. The infrastructure has changed drastically, the deforestation rate and population growth were high, the cultivation of bananas has expanded enormously, price subsidies were abolished and several new crops were introduced. Ecologists, small-scale farmers, banana plantation owners, politicians, etc. are all imposing particular claims on the use of the available resources in the NAZ and increasingly conflicts arise (De Oñoro 1990; Fresco 1991; Roldan *et al.* 1991; Anonymous 1992a; Anonymous 1992b; Jansen *et al.* 1996). Many decisions were made without *ex ante* exploration of possibilities. As a result unforeseen conflicts arose. This situation underlines the need for strategic, well-informed choices for land use.

With the help of a long-term exploration the options and boundaries for future land use in the NAZ are examined. In this long-term exploration, biophysical and technical possibilities and constraints are confronted with value-driven objectives of groups of stakeholders. This may widen the perspective of decision makers on future land use options, and provide important information for strategic choices. Section 2.1 describes the current situation in the NAZ. System delimitation, and choices and assumptions underlying the exploration of the long-term possibilities are specified in Section 2.2. Section 2.3 deals with the methodology to address the research questions.

2.1 Description of the case-study area

2.1.1 The physical environment

The NAZ is situated in the eastern part of Costa Rica (Figure 2.1) and covers about 5430 km^2. This region constitutes the transition of the central volcanic mountain range to the Caribbean Sea. The major land forms from the South-West to the North-East are:

- Sloping areas of the central mountain range with lava and lahar deposits;
- Slightly inclined plains at the foot of the volcanoes with fine-grained fluviolaharic deposits;
- Coastal plain with fine-textured to peaty deposits and inundated depressions.

Some volcanic deposits with deep-weathered soils are also found. The soils in the region are predominantly classified as Andosols and Inceptisols. The younger deposits have nutrient-rich and non acid soils, whereas the older deposits are covered with nutrient-poor and acid soils. The younger lava and lahar deposits can be extremely stony. The soils of the coastal plain are fertile, but often suffer from impeded drainage. Very recent fluvial deposits are shallow and sandy (Huising 1993; Wielemaker & Vogel 1993; Stoorvogel 1995).

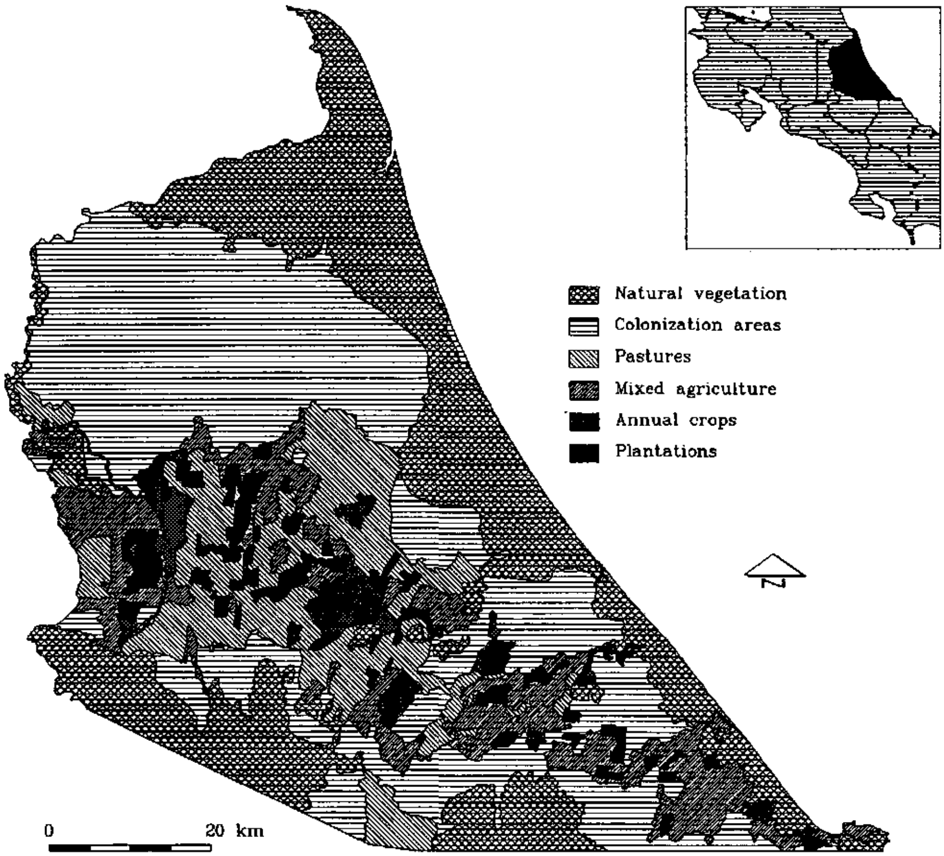

Figure 2.1 The Northern Atlantic Zone of Costa Rica and the 1984 land cover (Sources: Stoorvogel 1995; Stoorvogel & Eppink 1995).

The climate is characterised by abundant rainfall (3,000-7,000 mm.y^{-1}), well distributed throughout the year. Every month the precipitation is higher than the potential evapotranspiration, although in February, March and April dry spells of some days up to some weeks may occur. The relative humidity is 70 - 100 %. The average temperature is about 26 °C and varies little throughout the year (Figure 2.2). Table 2.1 shows some long-term average weather data for six weather stations in the NAZ. The variation is basically the same for all weather stations.

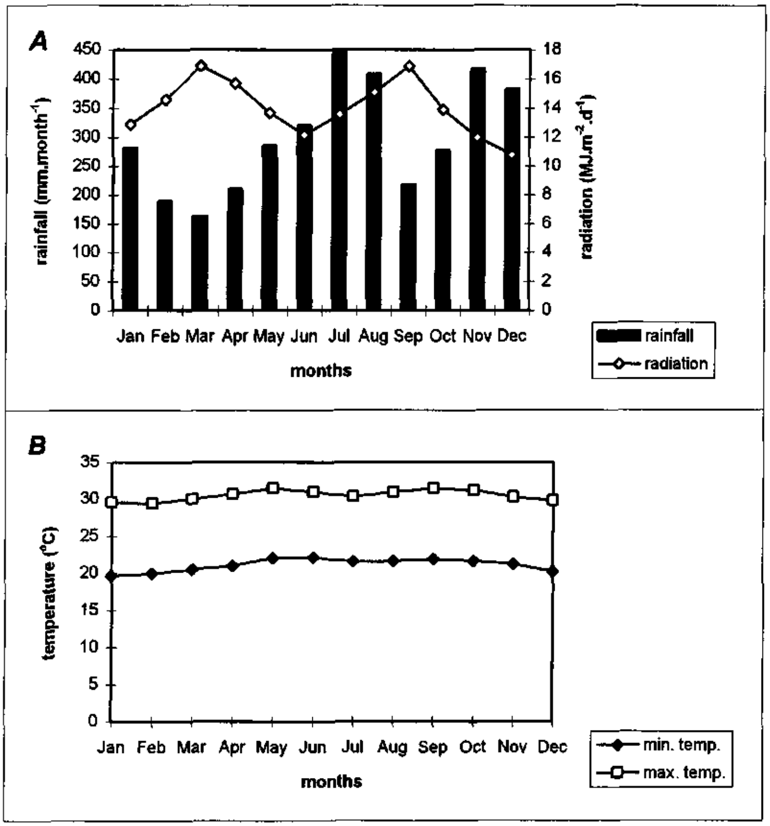

Figure 2.2 Variation in weather data throughout the year for weather station Carmen. A: radiation and rainfall; B: minimum and maximum temperatures.

Table 2.1 Long-term average weather data for six weather stations in the Northern Atlantic Zone of Costa Rica.

Weather station	Weather data from/to	Average maximum temp. °C	Average minimum temp. °C	Average radiation[a] $MJ.m^{-2}.d^{-1}$	Average rainfall $mm.y^{-1}$	Average vapour pressure kPa	Average wind speed $m.s^{-1}$
Carmen	1974-91	30.6	21.2	14.0	3,604	21.0	5.5
Cobal	1971-76	30.9	20.2	12.9	3,948	21.1	3.2
Diamantes	1971-91[b]	28.4	20.0	13.4	4,379	19.7	3.7
Lola	1973-90	30.2	20.1	12.0	3,548	20.6	5.8
Limon	1970-90	30.1	21.7	15.3	3,475	21.7	6.9
Mola	1980-89	28.0	21.2	13.0	3,735	21.1[c]	3.7

[a] average radiation data were based on three to nine years with daily data;
[b] data from 1975-1977 were missing;
[c] data from the Cobal weather station were used.

The original vegetation of the NAZ consisted of tropical rainforest (Holdridge 1987). By 1986, 54 % of the total area had been deforested. The deforestation rate in Costa Rica as a whole is decreasing, but after 1986 most of the deforestation in Costa Rica has taken place in the NAZ (Van Leeuwen & Hofstede 1995). Now, most of the natural vegetation outside the protected areas in the NAZ (National Park Tortuguero, Forest reserve Barra del Colorado, National Park Braulio Carillo) has disappeared. Of the deforested land 60 % is occupied by grasslands, although only 25 % was classified as "pasture land" by Huising (1993). Figure 2.1 shows the land cover map of 1984, the most recent map covering the entire NAZ. After 1984 land use has changed. The most important changes in land use were caused by continued deforestation and colonization, and the doubling of the area under bananas, which covered about 44,000 ha in 1992 (Stoorvogel & Eppink 1995).

2.1.2 Historical setting and socio-economic conditions

The development of the NAZ started with the construction of the railroad from the Central Valley to Limon at the end of the 19th century. The construction company (Soto Keith, later called United Fruit Company) received concessions for 404,000 ha and the right to exploit the railway for 99 years (Salas & Barahona 1980). To profit from these concessions, bananas were planted. The first bananas were exported in 1880. Owing to the "Depression" and the Panama disease the banana industry collapsed in the 1930s. Jobless plantation workers became farmers and began pushing towards the frontier regions. At the end of the 1950s, new resistant banana varieties were introduced and production increased again. The cultivation expanded rapidly, particularly since the early eighties. In the sixties, the colonization of areas situated further from the railway started with the immigration of people from other regions. They came to work at the plantations, bought farms, occupied new lands or underutilised lands. The population started to increase at a faster rate, pressure on the land increased, and large parts of the forest were cut. This colonization was also promoted by the *Ley de Tierras y Colonización* from 1961. The purpose of this law was to increase production and promote more equal distribution of land to improve social and economic conditions of farmers with small to intermediate sized farms (De Oñoro 1990; Van Sluys *et al.* 1992; Huising 1993). The traditional export crops of Costa Rica are coffee and banana. During the last decade considerable changes have taken place in the agricultural sector owing to Structural Adjustment Programmes. Price support for maize, beans and rice was abolished and the production of non-traditional export crops, such as palmheart, roots and tubers, macadamia, pineapple, and ornamentals was promoted (Jansen *et al.* 1996).

Costa Rica's average population density is 63 inhabitants per square kilometre; in the NAZ it is only 28. However, the population growth in the NAZ (4.0 %; Lok 1992) is much higher than in Costa Rica as a whole (2.2 %; INICEM-Market Data 1994). In Costa Rica 35 % of the population is economically active, and 22 % of the working force is employed in the agricultural sector, while in the NAZ more than 50 % is employed in the agricultural sector. In 1990, the unemployment rate in the NAZ was 5.7 % (MIDEPLAN 1991). The World Bank (1994) classified Costa Rica as a middle-income country based on its average annual per capita income (i.e. Gross Domestic Product per person) of US$1960 in 1992. About 15 % of the Gross Domestic Product is obtained from agriculture by 22 % of the working force. Therefore, it was assumed that in the NAZ, with about 50 % of the working force employed in the agricultural sector, 35 % of the Gross Domestic Product is obtained from agriculture.

2.2 System delimitation and assumptions underlying the long-term explorative study

2.2.1 System delimitation

Area

The explorations in this study are executed at the regional level. From 1986 onwards, research has taken place in the NAZ and, consequently, a large amount of information is available for this region.

Time horizon

In long-term explorations no fixed time horizon can be defined. The production activities included in the MGLP-model are not practised yet in the NAZ. However, within a time span of 20 to 30 years it would be technically feasible to adopt the described production activities, depending on the differences between the described production techniques and the currently available production techniques. Moreover, the alleviation of all current socio-economic and institutional constraints implies a considerable time horizon.

Interactions between economic sectors, production activities and regions

The study focuses on the agricultural sector, because only for this sector long-term potentials can be calculated with the help of knowledge on biophysical processes. In the MGLP-model for the NAZ, the only interaction with other economic sectors is through the need for labour: the maximum employment available for agriculture, in terms of percentage of economically active population, was assumed to be the same as the current percentage working in the agricultural sector. Interaction within the agricultural sector between crop activities and livestock activities concern the use of crop products (maize, banana and cassava) for livestock production and the uptake of nutrients from manure in pastures. Interactions with other regions take place through immigration of people and export and import of agricultural products. Self sufficiency of the NAZ for agricultural products was not considered. Other regions can affect conditions in the NAZ, for instance through transport of sediment by rivers, leaching of biocides, or decreased demand for products. These interactions between regions were not considered in the present study. Influences of other regions, e.g. on the demand for crop products, were taken into account only as exogenous factors. Changes in these exogenous factors can be relatively easy analysed with the MGLP-technique.

Technical and value-driven constraints
The technical constraints included in the MGLP-model concern land suitability for production activities and land use sequences. Value-driven constraints, other than objective functions, concern minimum population, dietary pattern, export level, and maximum area per form of land use. No restrictions were put on input use, production and immigration. For the quantification of production activities production with "best technical means" was assumed. This implies that no restrictions were put on credit availability, infrastructure, information availability, etc. It also implies technically efficient production: no more nutrients, biocides, water, labour, etc. are used than necessary for the required production level.

Sustainability indicators
Economic surplus, income per person, and employment are used as indicators of the socio-economic dimension of sustainability. Biocide use, biocide leaching and N-loss are used as measures of the ecological dimension of sustainability of land use in this study. Information on biodiversity, soil compaction, organic matter content, etc. was insufficient to operationalise these aspects as sustainability indicators in this study.

2.2.2 Policy views for future land use in the NAZ

Land use in the NAZ can develop in several directions. Which possibilities of the region will be exploited, strongly depends on the interests and aspirations of those who influence the development process at the regional level and on exogenous factors such as export markets. Some information on objectives of groups of stakeholders in the NAZ is available, but the number of objectives is often large and clear priority setting per policy view is missing (MIRENEM 1990;

MIDEPLAN 1991; Anonymous 1992a; Kruseman *et al.* 1994). Based on the available information on objectives of groups of stakeholders in the NAZ and objectives of similar groups in other countries (Spharim *et al.* 1992; WRR 1992), five *tentative* policy views for future regional land use in the NAZ were formulated:

- Free Enterprise (EP)
  This policy view mainly represents the multinationals and owners of recently established plantations with palmheart, pineapple, ornamentals, etc. This group of stakeholders is interested, in the first place, in maximizing the economic surplus from their properties in the region. Restrictions (social, economic or environmental), which strongly interfere with their objective, are not appreciated. Maintenance of the current market position for export of agricultural products is considered important;
- National Development (ND)
  At the national level the foreign debt problem and employment are important. This influences policy making at the regional level. In Costa Rica the NAZ is the region with the largest potential for expansion of agricultural production. Increased export of agricultural products, and increased economic surplus, can contribute to reducing the foreign debt problem. Maintenance of the current market position for export of agricultural products is considered important. Increase of employment is a means of providing reasonable living conditions for the population in the region. The extension of agricultural activities in the NAZ could also alleviate population pressure and pressure on the environment in other parts of the country. This, however, should not threaten the currently protected area in the NAZ (Kruseman *et al.* 1994);
- Regional Development (RD)
  In this policy view the local population is put centrally. A wide variation in groups and objectives can be observed among the population in the NAZ. However, the majority of the local population consists of small farmers and (agricultural) labourers. Their main objectives are increase of income, increase of employment, and safe living and working conditions (low exposure to biocides). In their view, the protected areas should be maintained, because they provide a source of income by means of the tourism industry;
- Environmental Protection (EP)
  The "environmentalists" put more emphasis on maintenance of the potential of the land for future generations than on protection of flora and fauna in some currently protected areas. They assume that all the land should be used in a responsible way, avoiding damage to ecosystems. This is translated into reducing the amount of alien substances (i.e. biocides) applied per unit area. According to them, agricultural land use does not necessarily have to be separated from land used for nature;
- Nature Conservation (NC)

About 28 % of the NAZ belongs to protected areas, of which 82 % is reserved for the protection of flora and fauna. Nature conservation groups want to enlarge habitats for animals and plants to preserve the biodiversity in the NAZ. At the same time, they want to diminish the negative side-effects of agriculture on nature (biocide leaching and N-loss) by separating agricultural land use from nature (Anonymous 1992a).

In the MGLP-models these tentative policy views were operationalised with a number of objective functions and bounds on value-driven constraints. Policy views can have objectives in common, but each policy view prioritizes its objectives in different ways. Table 2.2 gives an overview of the relevance of the selected objective functions in the five policy views used in the present study.

Table 2.2. Five tentative policy views for future land use in the NAZ, and the relevance of the objectives in each policy view.

Objective function	Code[a]	Free Enterprise (FE)	National Develop-ment (ND)	Regional Develop-ment (RD)	Environ-mental Protection (EP)	Nature Conser-vation (NC)
Environmental						
Area for agriculture	*ARM*	-[b]	-	-	-	min
Total biocide leaching risk	*BLM*	-	-	-	-	min
Total biocide use	*BUM*	-	-	min	-	-
Biocide use per unit area	*BUHA*	-	-	-	min	-
Total N-loss	*NLM*	-	-	-	-	min
Social						
Total employment	*EMP*	-	max	max	-	-
Economic						
Total economic surplus	*ESP*	max	max	-	-	-
Income per person	*INP*	-	-	max	-	-

[a] codes used in the single-period MGLP-model for the NAZ (Chapter 4);
[b] max=maximization; min= minimization; - = not considered very relevant in this policy view.

When objective functions are not optimized in a particular run of the MGLP-model, they are used as value-driven constraints. Bounds on value-driven constraints can differ per policy view. Table 2.3 presents an overview of the value-driven bounds per policy view, which were used in the present study. These bounds are of course rather arbitrary, because they could not be based on policy documents. Desires for the future are often derived from the current situation. Therefore, the current situation (Section 2.1) was used as point of departure to set upper and lower bounds to these value-driven constraints. These values are tentative, and in additional runs the consequences of changes in these bounds should be made explicit, which is relatively easy with this methodology.

- *The national parks are of international interest, and have the highest degree* of protection. These parks are protected in all policy views. Currently, also the forest reserves and buffer zone receive some degree of protection. Most policy views will consider the currently protected area in the NAZ as the minimum area for nature, because the buffer zone is considered essential for the protection of flora and fauna in the national parks;

- Employment in agriculture can diminish enormously owing to ongoing mechanization and reduction of area for agriculture. For instance, in 1995 in The Netherlands only about 4 % of the economically active population was still working in agriculture (CBS 1997). At present, in the NAZ 50 % of the economically active population is working in agriculture. The minimum employment in agriculture in the NAZ was arbitrarily set at 10 % of the current employment (= 5 % of the economically active population) for policy views NC, EP and FE, and at 100 % for policy views ND and RD;
- In policy views FE and ND the minimum economic surplus was set at the current level. In the other policy views a minimum income per person is considered more important;
- In policy views ND and RD the required income from agriculture was set at the current level (on average 35 % of income from agriculture). For the other policy views an arbitrary reduction of 50 % is accepted, assuming that the relative income from other economic sectors can increase.

Table 2.3 Bounds on value-driven constraints per policy view for the NAZ.

Constraints[a]	Free Enterprise (FE)	National Development (ND)	Regional Development (RD)	Environmental Protection (EP)	Nature Conservation (NC)
Minimum area for nature	national parks	national parks, reserves, buffer zone	national parks, reserves, buffer zone	national parks	national parks, reserves, buffer zone
Minimum employment in agriculture (man years.y^{-1})	2,528	25,280	25,280	2,528	2,528
Minimum economic surplus (10^9 col.y^{-1})[b,c]	7.5	7.5	-	-	-
Minimum income from agriculture (10^4 col.$person^{-1}$.y^{-1})	4.5	8.9	8.9	4.5	4.5
Minimum export level	current[d] export	current export	-	-	-

[a] bounds on objectives used as value-driven constraints, except export level;

[b] the colon (col.) is the currency of Costa Rica, in 1990 US$1=130 colon (Schipper 1996);

[c] estimated as GDP in 1992 (World Bank 1994) minus costs of labour;

[d] estimated current export from the NAZ per year: 1,780 10^3 tonne bananas; 17,000 tonne cassava, 2,246 tonne palmheart, 1,250 tonne beef.

No reference values were available on the current situation regarding biocide leaching risk, biocide use and N-loss. For the following value-driven constraints (i.e. minimum population, dietary pattern, maximum area per crop) no discrimination was made between policy views:

- The minimum population was set at being equal to the estimated population in 2020, assuming that the current population will grow with 2 % per year (about the growth rate for Costa Rica as a whole);
- Only the current dietary pattern (Appendix 7) was taken into account. Consumption of livestock products is high in Costa Rica and is not expected to increase much;
- A maximum of 60,000 ha was used for the total area per crop to promote some diversification in land use. This maximum is slightly higher than the maximum area currently cultivated with one crop in the NAZ.

2.2.3 Selected production activities

Forms of land use

A number of forms of land use has been selected: banana, cassava, maize, palmheart, grass pasture, grass-legume pasture and tree plantations. With these forms of land use the three main agricultural systems are represented (arable cropping, livestock systems, forestry), and annual as well as perennial crops are included. These forms of land use represent differences in labour need, fertilizer need, export of nutrients, biocide use and possibilities for mechanization. Nature is not explicitly included as a form of land use; it was considered the complement of agricultural land use.

Production orientations

From an environmental point of view deforestation, biocide use and nutrient cycling are important for future development of agriculture in the NAZ. At present, deforestation and biocide use are given a good deal of attention (Sader & Joyce 1988; Roldan *et al.* 1991; Veldkamp *et al.* 1992). Two production orientations, representing different perceptions of sustainability, were considered relevant to the present study:

- Yield-oriented agricultural production: with a high production per unit area more land remains available for nature. This orientation has no input restrictions and aims at potential production[1] if a drainage system is present, or at the water-

[1] potential production = production determined by plant characteristics (related to physiology and phenology of the plant), temperature and radiation level as determined by latitude, season and time of production only, no growth limitation owing to shortage or surplus of water and nutrients and no growth reduction caused by pests and diseases occurs (Van Ittersum & Rabbinge 1997).

limited production[2] if no drainage system is constructed;

- Environment-oriented agricultural production: in this orientation lower local pressure on the environment is aimed for. Some yield reduction as compared to the yield-oriented production is accepted if more environment-friendly production is possible. Within this orientation two specifications are used: lower biocide use and reduced N-loss.

Extensive land use (e.g. extensive pastures) was not considered relevant for future land use in the NAZ, as it does not contribute to preservation of flora and fauna, nor does it show efficient input use. At present, much land is used for extensive pasture with a view to obtaining titles to the land, or because farmers lack the knowledge of money to use the land more intensively.

Table 2.4 Feasible combinations of forms of land use and production techniques in the MGLP-model for the NAZ.

	Production technique						
	Mechanization	yes	yes	yes	no	no	no
	Chemical pest and disease control	yes	no	yes	yes	no	yes
	Reduced N-loss	no	no	yes	no	no	yes
Form of land use		*MBN*[a]	*MbN*	*MBn*	*mBN*	*mbN*	*mBn*
Banana[c]		+[b]	+	+	-	-	-
Cassava		+	+	+	+	+	+
Maize		+	+	+	+	+	+
Palmheart[c]		+	-	+	+	-	+
Grass pasture		-	-	-	+	-	+
Grass-legume pasture		-	-	-	+	-	+
Tree plantation		+	-	+	-	-	-

[a] explanation of codes for production techniques: M = cultivation practices mechanized; m = no mechanized cultivation practices; B = chemical control of pests and diseases; b = alternatives for biocide use if possible; N = not aiming at reduced N-loss; n = 40 % lower N-loss compared with yield-oriented production;
[b] + = included; - = not included;
[c] construction of drainage systems in activities with techniques *MBN*, *MbN* and *Mbn* only.

Production techniques

For some crops both manual and mechanized production could be an option within the same production orientation. Animal traction as an alternative to manual or mechanized production is not included, because it is not practised currently, and it is not expected to be practised in the future. In bananas only a few practices can be mechanized, and these are mechanized at present. Return to manual field preparation, manual drainage system construction and manual

[2] water-limited production = water shortage or surplus cause the growth rate of plants to decline from their potential (Van Ittersum & Rabbinge 1997).

transport of bunches to the processing plant was not considered feasible. The same is true for tree plantations: manual felling of trees was not considered an option for the future. Pasture is relatively labour extensive, most practices cannot be mechanized, which is why only manual production is included. For maize, cassava and palmheart mechanized and manual production are taken into account. In palmheart only field preparation and construction of drainage systems can be mechanized. It was assumed that elaborate drainage systems are only constructed in high input systems. Drainage systems lower the ground water level and cause an increase in water-limited productions. Table 2.4 shows the crop activities considered relevant to this study. Production techniques *MBN* and *mBN* represent yield-oriented production, *MbN* and *mbN* aim at reduced biocide use, and *MBn* and *mBn* aim at reduced N-loss per unit area. For livestock different feeding patterns are included, consisting of pasture supplemented with different amounts of crop products. These feeding patterns can be considered as different production techniques for livestock production. The production orientation of the pasture activity determines the production orientation of the related livestock activity. In Chapter 3 the production activities will be further specified.

2.3 Methodological approach for studying uncertainty and temporal aspects

2.3.1 Uncertainties

In the present study uncertainties in biophysical coefficients and their effect on land use scenarios are studied. Special attention is given to uncertainties in coefficients related to nutrients and biocides. These coefficients (i.e. N-loss, biocide leaching risk, biocide use) are included in the environmental objective functions and, therefore, can directly influence land use allocation and objective function values. Uncertainties were quantified by estimating uncertainty in individual parameters influencing these coefficients. For instance, uncertainties in N-recovery and N-concentrations in crops were combined to calculate the uncertainty in fertilizer N-need. Uncertainty in these coefficients is caused, in the first place, by lack of knowledge or by lack of data for quantification of these coefficients. Therefore, no probability distributions can be given for these coefficients. Instead, "optimistic" and "pessimistic" estimates were generated, beside the "average" estimate normally used in deterministic MGLP-models. The "optimistic" estimates represent the lowest fertilizer needs and N-loss and the lowest biocide leaching risk; the "pessimistic" values represent the highest possible values for these coefficients under the assumption of production with "best technical means". Differences between "optimistic", "average" and "pessimistic" values are based on different perceptions of the influence of rainfall on leaching, the influence of soil conditions on retention of nutrients and biocides, etc. Production activities can be ranked from low to high values for each of the input-output coefficients. Uncertainties may also affect the ranking of production activities. Therefore, the relative effect of uncertainties on values of coefficients will be compared with the relative effect of soil type, production technique, and form of land use on values of coefficients.

A single-period MGLP-model for the NAZ was constructed. Sensitivity analysis was used to analyse the effect of uncertainties on land use scenarios. During sensitivity analyses, simultaneously all coefficients relating to nutrients and biocides were changed from "average" coefficients to either "optimistic" or "pessimistic" coefficients. This was possible, because in long-term explorative studies values of agro-ecological coefficients are strongly correlated:

- Production is assumed to take place with "best technical means", i.e. uncertainty due to variation in management of farmers is excluded. This means that efficient fertilizer use at one site and inefficient use at another site at the same time is excluded. In all production activities inputs are used in the technically most efficient way. The maximum technical efficiency is determined by the physical environment, the crop characteristics and the production technique. Besides, a "target-oriented" approach is used to quantify inputs. Therefore, agro-ecological coefficients, such as fertilizer need, N-loss and water use, are closely related to the production level;
- Agro-ecological coefficients are often influenced by the same processes. For instance, leaching of nutrients as well as leaching of biocides is strongly affected by the absorption capacity of organic matter and the groundwater recharge. If apparent nutrient recoveries are higher, less mineral fertilizer will be needed, and less will be lost through leaching or other processes.

In this study uncertainties in coefficients concerning nutrients and biocides are mainly caused by lack of knowledge of underlying biophysical processes or by lack of data for quantification.

The model sensitivity to uncertainties in agro-ecological coefficients was, to some extent, also compared with model sensitivity to changes in economic coefficients, i.e. prices of agricultural products. Uncertainty in prices of agricultural products was considered, because in the past these prices varied more than prices for inputs such as labour, biocides and fertilizers.

2.3.2 *Temporal aspects*

In Section 1.4 four types of temporal aspects were mentioned. Several examples for three of these temporal aspects of land use were quantified with the help of knowledge of biophysical processes underlying agricultural production: growth stages of perennials (type b), fluctuations between periods in input-output coefficients owing to variation in weather conditions (type c), and temporal interactions between production activities such as residual P (type d). Developments in time (type a) were not treated. In long-term explorative studies production with "best technical means" is assumed. This means that the technically most efficient production techniques are used, according to present-day knowledge. Inclusion of further developments in production techniques would be very speculative. Other (irreversible) developments than development of further new production techniques, are not relevant or beyond the scope of these types of studies. The effect of different policy views on land use scenarios can be examined within long-term explorations. The prediction of the transition from one policy view to another policy view or from the actual to the desired situation is no objective of long-term explorations. Developments in prices are topics for economic studies.

Many biophysical processes have strong temporal and spatial aspects and biophysical processes are often not linear. This may complicate the description of temporal aspects in MGLP-models. With the help of a literature review methods and limitations for the description of temporal aspects in multi-period MGLP-models were examined. Next, the single-period MGLP-model for the NAZ was transformed into a multi-period MGLP-model to examine the possibilities and difficulties to include temporal aspects of land use in models for long-term explorations. Results of the single-period and multi-period model were compared to evaluate if the use of multi-period models results in added value to long-term explorations.

Since long-term explorations do not consider developments in time, a cyclic structure as presented in Figure 2.3 could be used for the multi-period model: the first period is preceded by the last period, and the constraints describing the relation between the last period and the first period are similar to the constraints describing the relation between, e.g. periods 1 and 2 (see also Chapter 6, Constraint 6.1). This means that tree plantations can be felled in period 1 if trees were planted in period 2 (20 years earlier). The assumption that the cropping sequences can be repeated several times is explicitly included in this cyclic structure. The maximum length of the growing period of the crops in the present study was assumed to be 20 years. A fixed growing period of 20 years was used for tree plantations. The length of the total growing period of banana, pasture and palmheart was not fixed. A strong increase in model size owing to the introduction of periods is often mentioned as one of the main problems of multi-period MGLP-models (Csaki 1977; Ayyad & Van Keulen 1987; Lohmander 1989). To avoid problems with model size when each year is considered as one period, periods of five years were used in the present study.

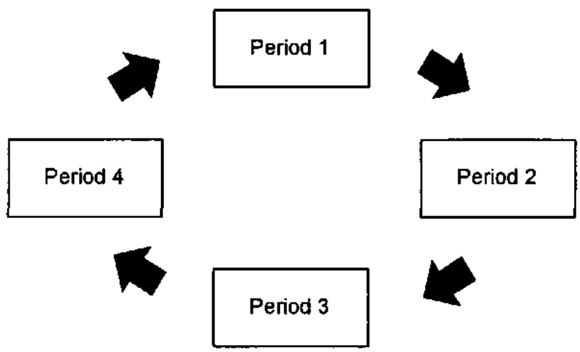

Figure 2.3. The cyclic structure of the multi-period MGLP-model for the NAZ.

3 INPUT-OUTPUT COEFFICIENTS FOR AGRICULTURAL PRODUCTION POSSIBILITIES

Production activities, i.e. crop activities or livestock activities, are described with input-output coefficients. The methods used for deriving these coefficients are described in this chapter, as far as yields, labour, investments, implements, nutrients, biocides, etc. are concerned. Inputs and outputs differ per form of land use, physical production environment and production orientation (Chapter 1). The different physical production environments and the matching production potentials for each form of land use are identified in the land evaluation (Section 3.1). The production level of each production activity is determined with the help of the production orientation. Subsequently, the input-output coefficients are quantified for each production activity, using a "target-oriented" approach and assuming production with "best technical means" (Section 3.2). Coefficients in the single-period MGLP-model for the NAZ represent average yearly values for the entire growing period. For the multi-period MGLP-model input-output coefficients of perennial crops are determined per growth stage. The same data sources and methods are used to determine the coefficients for the single-period as well as for the multi-period model. Special attention is given to temporal aspects and uncertainties in coefficients concerning nutrients and biocides (Sections 3.3 and 3.4, respectively). Abbreviations in italics refer to coefficients and indices used in the MGLP-models as described in Chapters 4 and 6, or to parameters of equations presented in this chapter. Details on methodologies, coefficients and values used in the LP-models are given in the appendices.

3.1 Land evaluation

A qualitative land evaluation was conducted to discriminate between unsuitable physical production environments and potentially suitable physical production environments. In the quantitative land evaluation production potentials in the suitable production environments were estimated (Van Diepen *et al.* 1991).

3.1.1 Qualitative land evaluation

Data on slope, soil drainage, stoniness, effective depth, texture, and pH were used in the qualitative land evaluation. These soil and terrain characteristics were used because of availability and reliability of data in the *Sistema de Informaciôn para la Evaluaciôn de los Suelos y Tierras de la zona Atlántica* (SIESTA; Wielemaker & Vogel 1993).

The selected crops can be grown under all occurring climatic conditions in the region. Radiation is the main factor influencing the potential and water-limited production levels in the NAZ, but radiation was not measured throughout the zone. The relation between radiation and sunshine hours or rainfall is not clear, since errors were made while measuring radiation at some weather stations (Appendix 2), and the available maps on rainfall distribution (Nuhn 1978; Tosi 1985) were contradictory. Crop growth simulations were performed with the partly reliable weather data. The differences in production levels between subregions were not significant (Section 3.1.2). Therefore, no climate zones were distinguished.

Data on minimum crop and management requirements were extracted from literature (Purseglove 1974, 1975; FAO 1983, 1984; Sys 1985; ASBANA 1990; Overbeek 1990; Chaves & Fonseca 1991) and from discussions with experts from several institutes in Costa Rica (CATIE, CCT, CORBANA, EARTH, MAG, MIRENEM, SENACSA). Mechanization puts demands on soil and terrain properties. Therefore, a distinction was made between suitability for mechanized production and manual production.

Table 3.1 Suitability of terrain types for the different forms of land use and area (ha) per terrain type in the NAZ.

	Terrain type						
Form of land use	*s1*	*s2*[a]	*s3*[a]	*s4*	*s5*	*s6*	*s7*
Banana	-[b]	+	+	+	-	-	-
Mechanized cassava	-	+	+	-	-	-	-
Manual cassava	-	+	+	-	+	+	-
Mechanized maize	-	+	+	-	-	-	-
Manual maize	-	+	+	-	+	-	-
Mechanized palmheart	-	+	+	+	-	-	-
Manual palmheart	-	+	+	-	+	-	-
Grass pasture	-	+	+	-	+	+	+
Grass-legume pasture	-	+	+	-	+	+	+
Tree plantations	-	+	+	-	+	+	-
Area outside national parks	263,892	63,257	82,799	45,245	46,808	17,873	2,009
Area outside national parks and buffer zone	311,572	59,333	72,071	35,545	27,503	15,799	60

[a] *terrain types s2 and s3 are suitable for the same forms of land use, but differ in texture and water holding capacity;*
[b] - = unsuitable, + = suitable.

After matching the land characteristics with crop requirements, seven groups of terrain types (i.e. physical production environments) were distinguished, each with different suitability for crops and production techniques (Tables 3.1 and 3.2, and Appendix 1). The terrain types mostly occur in associations of two or more terrain types, and are scattered throughout the region. A large area is qualified as unsuitable for intensive agricultural land use (terrain type *s1*). This terrain type is mainly confined to the poorly drained areas along the coast and to the South-West of the region in the areas classified as natural vegetation or colonization areas in Figure 2.1.

Table 3.2 Characterization of terrain types (average for top 20 cm).

Terrain type	pH (H_2O)	Clay %	Sand %	OM %	Depth cm	Slope %	Stoniness %	Drainage
s1[a]	-	-	-	-	-	-	-	-
s2	5.8	28	33	5.8	90	2	0.1	moderate-well
s3	5.6	13	46	8.1	70	1	0	moderate-well
s4	5.6	30	20	5.3	90	1	0	poor-imperfect
s5	4.9	38	32	5.9	>160	16	1.5	well
s6	4.4	57	17	5.5	160	20	0	well
s7	6.4	7	65	4.6	10	2	7	well-excessive

[a] unsuitable for any intensive agricultural land use, wide variation in characteristics.

3.1.2 Quantitative land evaluation and estimation of livestock production

Crop growth simulation models calculate the potential and water-limited production, using knowledge of underlying biophysical processes. These simulation models were used in the quantitative land evaluation. Climate, soil and crop data are basic inputs for such models. As indicated in Section 3.1.1, no climate zones were distinguished. The available radiation data for the six weather stations are not very reliable and do not completely cover the NAZ (Appendix 2). Besides, no significant differences (analysis of variance; $P > 0.10$) in potential production or water-limited production were found among the six weather stations. Planting or sowing is possible throughout the year, because rainfall is sufficient and well distributed throughout the year. For the *single-period* model, average potential and water-limited production levels were calculated for each terrain type. These averages were based on data of all years with daily weather data and after separately simulating growth for the six weather stations and for twelve planting dates per year. The differences between potential and water-limited production were in most cases caused by water surplus. Differences in simulated water-limited production between terrain types with different ground water levels were never significant (analysis of variance; $P > 0.10$). However, they were maintained for use in the MGLP-model. Differences between ground water levels are plausible, because all included crops are susceptible to oxygen shortage in the rooting zone, and fluctuations in drainage depths occur during the year.

In the *multi-period* model, fluctuations in production, caused by variation in weather conditions, were taken into account. Based on the available weather data, the average potential and water-limited productions were calculated for four groups of five years. The differences in production levels between these four periods were mainly caused by differences in radiation.

Table 3.3 shows an overview of results of the quantitative land evaluation. More information on the estimation of dry matter (DM) production of individual crops is presented below and in Appendix 2. Since animal production is closely linked to pasture production, it is also treated in this section (Table 3.4).

Table 3.3 Estimated average potential production (ground water level 1.6 m) and average water-limited production (ground water levels 0.9 and 0.7 m[a]) in the Northern Atlantic Zone (tonne DM.ha^{-1}.y^{-1}).

	Ground water level[b]		
Form of land use	1.6 m	0.9 m	0.7 m
Maize[c]	19.0	18.3	17.8
Cassava[d]	15.7	15.3	14.9
Tree plantations[e]	28.7	27.2	25.8
Banana[f]	33.2	not relevant	not relevant
Palmheart[f]	3.6	3.4	3.2
Grass pasture[f]	47.0	47.0	47.0
Grass-legume pasture[f]	39.0	39.0	39.0

[a] *differences between potential and water-limited production are caused mainly by water surplus;*
[b] terrain types *s2*, *s3*, and *s4* have a ground water level of 0.9 m, 0.7 m and 0.1 m, respectively; terrain types *s5* to *s7* have a ground water level of 1.6 m; the ground water level of terrain types *s2* to *s4* can be lowered to 1.6 m if a drainage system is constructed;
[c] 2.5 growing cycles per year, DM concentration 86 %;
[d] growing period 10 months, DM concentration 35 %;
[e] average yearly DM stem production in a growing period of 20 years, 75 % timber and 25 % pulpwood;
[f] under continued production, DM concentration banana 23 %, DM concentration palmheart 11 %, utilization efficiency pasture 50 %.

Maize

WOFOST 6.0 was used to estimate the potential and water-limited production (Van Diepen *et al.* 1988; Hijmans *et al.* 1994). Plant parameters for a tropical maize variety were taken (Van Diepen *et al.* 1988). However, the temperature sum for the vegetative phase was adjusted (Van Keulen & Wolf 1986) to avoid unrealistically high harvest indices (> 0.5) under the conditions in the NAZ. It was assumed that 2.5 crops per year can be grown.

Cassava

WOFOST 6.0 was used to estimate the potential and water-limited production (Van Diepen *et al.* 1988; Hijmans *et al.* 1994); plant parameters for cassava were obtained from Van Diepen *et al.* (1988). A growing season of ten months was used for cassava production in the NAZ. The simulated harvest index was 0.44.

Tree plantations

Poels (1995) simulated the water-limited production of teak plantations in the NAZ of Costa Rica with a modified WOFOST version, developed for Surinam. His results were used as starting point for estimating timber production (growing period of 20 years). A thinning regime of 25 % of the biomass every five years was applied. Reductions of 5 % and 10 % in DM production, caused by water excess, were assumed for soils with ground water levels of 0.9 m and 0.7 m, respectively: trees root deeper, so that they are more affected by high ground water levels than annual crops.

Banana

A simple model called LINTUL (Stol *et al.* 1991) was adapted to estimate banana (*Musa* AAA) production in the first harvesting cycle after planting and under continued production. Data on crop physiological development and leaf growth were estimated with the help of field observations, data from Aubert (1971) and data from Soto (1985) for the Costarican situation. A harvest index of 0.43 (Marchal & Mallesard 1979; Stover & Simmonds 1987; Gowen 1995) and a planting density of 1800 plants.ha^{-1} were assumed. With the crop growth simulation model the first banana yield was obtained after about nine months. Under continued production an average of 1.8 harvests per plant per year could be obtained. Construction of drainage systems was assumed for all production techniques. This reduces drainage depth to 1.6 m below the soil surface.

Palmheart

Adaptation of LINTUL for simulation of palmheart (*Bactris gasipaes*) production is complicated, as hardly anything is known about the DM distribution in the plant and the effect of harvesting and pruning on the growth of new suckers. Therefore, field data from the NAZ were used to estimate the water-limited production of palmheart (Hooren unpublished data). The harvesting interval strongly affected the average production per month. In June and July 1994, months with a relatively low radiation, the highest yields were obtained. Extrapolating these yields to annual yields results in a fresh gross palmheart production of 32.6 tonne.ha^{-1}.y^{-1} (about 29,300 palmhearts) under continued production, or about six palmhearts per plant per year. The first palmhearts can be harvested 18 months after planting. Palmheart is very susceptible to water excess. For the production techniques *MBN* and *MBn* construction of drainage systems was assumed, resulting in a decrease of ground water level to 1.6 m below the soil surface. In production techniques without drainage systems, similar reductions as those assumed for trees were applied.

Grass pasture

Production in intensive grass systems was estimated with LINTUL. The main assumptions for the model input were: C4-species (for instance *Brachiaria brizantha, Cynodon nlemfluensis*), rotation scheme of 25 days (five days grazing-20 days regrowth), 25 % light interception directly after grazing (Versteeg 1985), 90 % light interception after 18 days of regrowth. Grazing can start four months after planting (Ibrahim 1994). Grasses root relatively superficially and are less affected by high ground water levels. The same water-limited production was used for all suitable terrain types, except for terrain type *s7*, which is relatively stony and excessively drained. Yield reductions of about 20 % caused by water shortage were assumed for this terrain type.

Grass-legume pasture

For grass-legume pastures no simulation models were available. Therefore, the production of grass-legume pasture was estimated with the help of the production level of intensive grass pasture, some field data and information from literature. Ibrahim (1994) conducted various studies with grass-legume pastures in the NAZ. In the best producing combination (*Brachiaria brizantha* and *Arachis pintoi*) the legume percentage was 23 % of the total DM. Further, it was assumed that the total energy cost of symbiotic N-fixation and transport is 33 % of the plant photosynthates (maximum mentioned by Giller & Wilson 1991), and that legume growth is 20 % lower as compared with grass, owing to more severe defoliation of the legume during grazing. For terrain type *s7* (relatively stony and excessively drained) again a reduction of 20 % of the DM production was assumed.

Table 3.4 Estimated net production of animal products by different animal units[a] with a feeding pattern of pasture DM with "average" nutrient concentrations[b].

Animal unit	Milk kg.year^{-1}	Grown animals (500 kg) number.year^{-1}	Calves number.year^{-1}
Milking cow unit[c]	1,115	0.15	0.59
Beef cattle unit 1[d]	-	0.67	-
Beef cattle unit 2[e]	-	0.78	-

[a] animal units are described in Appendix 2;
[b] lower or higher nutrient concentrations in pasture affect the feeding value, consequently livestock production changes;
[c] calf for replacement included, net production is production minus milk used for the calf;
[d] milk for feeding calves is bought;
[e] milk production for feeding calves is included.

Livestock production

Livestock production (Table 3.4) is related to pasture production. Information on nutritional needs of tropical cattle breeds, and effects of temperature and humidity on livestock production is scarce. Ketelaars (in: Breman & De Ridder 1991) uses the following equations for calculating the energy need for growth of cattle under tropical conditions:

$$DM_{dig} = 3.33 \times N + 9.40 \tag{3.1}$$

$$G = ((DM_{dig} - MN) \times LW^{0.75} \times DED \times EEC) \,/\, (DEW \times 1000) \tag{3.2}$$

In which: DM_{dig} = digestible dry matter intake (g.kg$^{-0.75}$ animal weight)
N = nitrogen concentration (g.kg^{-1})
G = growth (kg.d^{-1})
MN = digestible dry matter needed for maintenance (g.kg$^{-0.75}$)
LW = live weight of the animal (kg)
DED = digestible energy in the DM_{dig} (MJ.kg^{-1})
DEW = digestible energy need for 1 kg weight increase (MJ.kg^{-1})
EEC = efficiency of energy conversion for growth (-)

The parameters for Equations 3.1 and 3.2 were adjusted to the situation in the NAZ. NRC (1988, 1996) mentions maintenance digestible energy requirements of 649 KJ.kg$^{-.75}$.d^{-1}. This resulted in a digestible DM requirement for maintenance (*MN*) of 42 g.kg$^{-0.75}$ for the pastures in this study. Based on data from Benavides (1983) for cattle weighing 45 to 500 kg, an average protein concentration of 180 g per kg live weight and a fat concentration of 150 g per kg live weight were assumed. The digestible energy requirements for protein and fat are 23.6 MJ.kg^{-1} and 39.3 MJ.kg^{-1}, respectively (Breman & De Ridder 1991), resulting in a digestible energy requirement for weight increase (*DEW*) of 10.14 MJ.kg^{-1}. An efficiency of energy conversion for growth (*EEC*) of 0.5 was used (Breman & De Ridder 1991) and a 30 % increase in energy requirements for the last six weeks of pregnancy (NRC 1988, 1996). The digestible energy requirement for milk with a fat percentage of 4.0 % was estimated at 6.0 MJ.kg^{-1} (NRC 1988; Breman & De Ridder 1991). Livestock production can be limited by energy availability, but also by protein availability. A maintenance protein requirement of 0.5 g.kg$^{-0.75}$ was used (Breman & De Ridder 1991). The average efficiency of conversion of digestible protein to body protein is 73 %. For milk production the total crude protein requirement per kg milk with 4 % fat is 90 g (NRC 1988). With the above equation extremely high live weight gains per day were obtained. Therefore, the daily DM intake was adjusted for live weight as described by Brouwer (1994; Equation 3.1 was replaced by Equations 3.3 and 3.4). This still resulted in high daily growth rates. The highest reported live weight gain in the NAZ was 0.96

kg.animal^{-1}.d^{-1} (Ibrahim 1994). It was assumed that this is close to the potential under the conditions in the NAZ. Therefore, the daily weight increase was limited to 1.1 kg.animal^{-1}.d^{-1}.

$$DOMI = M \times W^{b-0.75} \times A^{0.75-b} \times W^{0.75} \tag{3.3}$$

$$b = \ln(M - 2) + 0.75 - \ln(DOMI / W^{0.75} - 2) \tag{3.4}$$

In which: *DOMI* = digestible organic matter intake (kg; digestible organic matter = 0.9 * digestible dry matter)
M = maintenance requirements (0.9 * *MN*; g digestible organic matter per kg metabolic weight)
W = live weight (kg)
A = adult weight (kg)

Assumptions on mortality, calving rate, lactation period, mature weight and weaning per animal unit are presented in Appendix 2.

3.1.3 Reliability of production estimates

Some uncertainty exists about the level of the simulated potential and water-limited productions in Table 3.3: the radiation data of some weather stations are not very reliable; a simple water balance was used in the crop growth simulation models ("tipping-bucket"); in soils of volcanic origin wilting point and field capacity may not be achieved at *pF* = 2.0 and *pF* = 4.2; only a few *pF*-curves and hydraulic conductivity curves were available. The simulated potential and water-limited productions are much higher than the average productions currently obtained in the NAZ (Table 3.5). Few sources are available to verify whether these simulated productions can indeed be reached. Only for maize some experimental data from the NAZ are available (Foster-Russell 1982), which corresponded with the simulated productions. The measured radiation levels are relatively low, so that the potential simulated maize production is not very high compared with other regions. For the other crops experts were consulted or simulated productions were compared with current production figures. The experts considered the production levels for palmheart, pasture and tree plantations high, but attainable under proper water supply and good drainage conditions (personal communications Janssen, 't Mannetje, Lantinga, De Graaff). For pasture and tree plantations higher productions have been obtained in other regions (Dayan *et al.* 1981; Iturbide 1983; Versteeg 1985; Philips *et al.* 1994).

Palmheart is a new crop for which hardly any reliable production data are available. However, if one assumes a DM concentration of 11 % and a harvest index of 8.3 % (gross palmheart production), a total DM production of 43 tonne.$ha^{-1}.y^{-1}$ (119 kg DM.$ha^{-1}.d^{-1}$) is obtained under continued production of palmheart. This is not exceptionally high for a perennial crop. The simulated potential production in banana plantations was about 210 kg DM.$ha^{-1}.d^{-1}$. For all banana plantations in Costa Rica export figures are available (Paez-Castro & Barrientos-Angulo 1994). The simulated production level was compared with these export figures, assuming that the DM concentration of bananas is 23 % and that 22.5 % of the banana production is rejected for export. The average simulated banana production is 39 % higher than the highest average exportable production obtained in the NAZ. However, in practice the percentage of rejected bananas can be much higher (up to 40 %; Rivera 1986) and plant spacing is often far from optimal, resulting in lower exportable productions.

Table 3.5 Current production levels and average inputs for some crops in the Atlantic Zone of Costa Rica. Source: Kruseman *et al.* (1994).

Crop	Fresh produce tonne.$ha^{-1}.y^{-1}$	Fertilizer-N kg N.$ha^{-1}.y^{-1}$	Fertilizer-P kg P.$ha^{-1}.y^{-1}$	Fertilizer-K kg K.$ha^{-1}.y^{-1}$	Biocides[a] kg a.i.$ha^{-1}.y^{-1}$
Maize	2.86	40	8	4	1.40
Cassava	6.73	0	0	0	0.89
Banana	52.37	297	105	521	30.72
Palmheart	5.16	117	9	4	1.25

[a] a.i. = active ingredient.

Simulated pasture production is high and, consequently, high stocking rates were obtained. The simulated live weight exceeds 3,000 kg.$ha^{-1}.y^{-1}$. This is considerably more than the live weight increase of 937 kg.$ha^{-1}.y^{-1}$ obtained by Ibrahim (1994). This difference in production is mainly caused by the difference in stocking rate. The simulated daily DM intake of the beef cattle units is relatively low (1.9 % of live weight). Chamberlain (1989) mentions a DM intake of 2 to 2.5% on tropical pastures. This may indicate that higher DM intake and higher live weight gains are possible under the conditions in the NAZ.

The simulated milk production per cow is in the same order as the production levels obtained by Rodriguez (1976) and Murillo & Navarro (1986) and the average currently obtained in the NAZ (Urgyles 1996). Chamberlain (1989) mentions higher potentials for tropical regions. This indicates that the simulated milk productions per cow are conservative. Using data on milk production per cow from other regions was considered speculative, because the high temperatures and humidity in the NAZ are very likely to affect milk production negatively:

according to Castro (1988) at a humidity of 60 % or more and a temperature above 24°C DM intake and milk production will get affected. Simulated DM intake was relatively low (1.9 % of live weight). Simulated gross milk production per hectare ranged from 7,000 kg milk.$ha^{-1}.y^{-1}$ for cows fed with grass-legume only to > 11,000 kg milk.$ha^{-1}.y^{-1}$ for cows with a feeding pattern of 80 % grass-legume and 20 % maize. This is considerably more than the milk production of dual purpose cows in the NAZ of 500 to 1,500 kg milk.$ha^{-1}.y^{-1}$ (Ibrahim 1994), but it is in the same order as the maximum of 7,000 to 10,000 kg milk.$ha^{-1}.y^{-1}$ for grass-legume pastures mentioned by Urgyles (1996).

3.2 Calculation of inputs and outputs for production activities

For the quantification of inputs and outputs in this study production with "best technical means" was assumed, i.e. available knowledge and available means of production are optimally applied, which precludes any waste or inefficient use of resources (De Koning *et al.* 1995). Further, the inputs were quantified using a "target-oriented" approach, which means that the inputs to realize a particular output level were quantified using knowledge on the processes involved (De Wit *et al.* 1988; De Koning *et al.* 1992). The production orientation relates directly or indirectly to a certain physical production level (Figure 3.1). In the production orientation aiming at high soil productivity, the highest possible yields per unit area in each production situation are aimed for. Inputs such as fertilizers, biocides, and labour, and outputs such as nutrient loss are derived from this production level. If reduction of biocide use is the aim, this can have consequences for the production level (Van Ittersum & Rabbinge 1997). E.g. at present no real alternatives for fungicide use in bananas are available. Therefore, strongly reduced use of fungicides will result in reduced production levels. In that case, the inputs and outputs are derived from the lower production level.

Non-substitutable inputs, i.e. water and nutrients, fulfill a specific and essential role in the plant and cannot be replaced by other inputs. Knowledge on nutrient behaviour in the soil, plant uptake, decomposition of plant material, transformation processes in the plant, etc. was used to determine nutrient requirements of crops and uptake efficiency. For calculation of the total amounts needed of these non-substitutable inputs production with "best technical means" was assumed. Differences between production activities in levels of these non-substitutable inputs only reflect differences in production level and in physical production environments, but are not caused by variation in management. Substitutable inputs can be replaced by other inputs, up to a certain degree. E.g. herbicide use can be replaced by mechanized or manual weeding; machines can be replaced by manual labour. The amounts needed of these inputs are also calculated assuming production with "best technical means". The differences between activities in input levels of these inputs reflect the differences in production level, physical production environment and production technique (Van Ittersum & Rabbinge 1996).

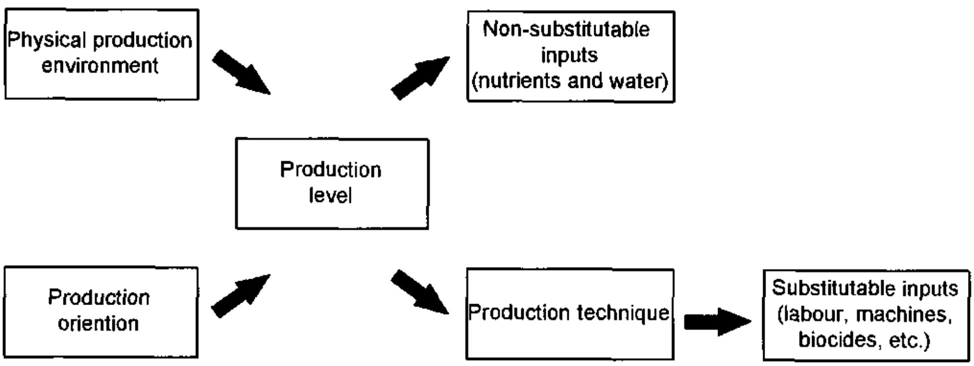

Figure 3.1 The target-oriented approach for calculating inputs and outputs of production activities.

3.2.1 Production levels

In the yield-oriented production activities (production techniques *MBN* and *mBN*) the highest productions per unit area, as estimated in Section 3.1, were used as target (Table 3.1). No differences in production levels between mechanized (*MBN*) and manual (*mBN*) production activities were taken into account. There is only one exception: the construction of drainage systems in palmheart with production technique *MBN* caused yields to be up to 10 % higher than in production technique *mBN*, because the crop suffered less from water surplus. Production levels for the other orientations were derived from these production levels. For quantification of environment-oriented production, aiming at reduced biocide use (production techniques *MbN* and *mbN*), the following criteria were used:

- If alternatives for biocides are available, these are used to avoid yield reduction;
- If no alternatives are available, a maximum yield reduction of 25 % is accepted.

Manual or mechanized weeding is a good alternative for herbicide use, without causing yield reductions. A promising alternative biological nematicide (pyrrolidine alkaloid DMDP) is being developed for use in bananas (personal communication Torres). Exclusion of nematicide use in maize and cassava will cause some yield reduction. At present, no alternatives are available for fungicide sprayings. Thus, strongly reducing the number of sprayings in banana will reduce yield levels. Maize production without fungicide use in the NAZ could result in complete crop failure, therefore, fungicide use was not reduced in *MbN* and *mbN*. In all production techniques the insecticide use is low, and if possible *Bacillus thuringiensis*, a biological insecticide, is used.

Production levels in environment-oriented production aiming at reduced N-loss (production techniques *MBn* and *mBn*) were estimated with the help of nutrient balances (Section 3.3). The aim of the production orientation was set at 40 % reduction of N-loss compared with the N-loss in yield-oriented production. With the help of the N-concentrations, the apparent nitrogen recovery and the fraction loss, the matching yields were calculated. Production levels of all production activities are presented in Appendix 2.

For livestock the production levels presented in Section 3.1.2 and Appendix 2 were used. For these production levels a specified amount of pasture DM and crop products is needed per animal unit (Appendix 2). This means that the livestock production per unit area is determined by the production level of the pastures and the use of crop products.

3.2.2 Labour requirements

The labour requirements in this study comprise the labour needed for manual and mechanized activities in the field. Only for banana, selection and packing was also included. The labour needs for processing of products, maintenance of small equipment and machines, management, etc. were not included.

Labour estimates in this study were based on literature from Costa Rica (Lopez 1985; Gomez 1988; Castro 1989; CATIE/DGF 1989; Reiche *et al.* 1991; BNC 1992; Clement 1993), data collected by the Atlantic Zone Programme (Arze & Gomez 1992; Jongschaap 1992; Ramirez & Aragon 1994), data from other countries (Van Heemst *et al.* 1981; PAGV 1992), and own estimates. When available, crop specific estimates were used. For banana and palmheart several plantation managers were interviewed. Average labour requirements per cropping practice were used, leaving out extremely high and low values. It was assumed that these average labour requirements represent efficient working. In the case of steep slopes increased labour requirements were used for all practices (for a 16-20% slope 10% increase in labour requirements). Labour requirements for felling of trees is stronger affected by steep slopes. Soil preparation and harvesting of cassava on very clayey soil (> 50 % clay) was assumed to take 25% more time than on less clayey soil. The construction of drainage systems on poorly drained soils was assumed to require twice as much time compared with well-drained soils. Details on labour requirements are presented in Appendix 5.

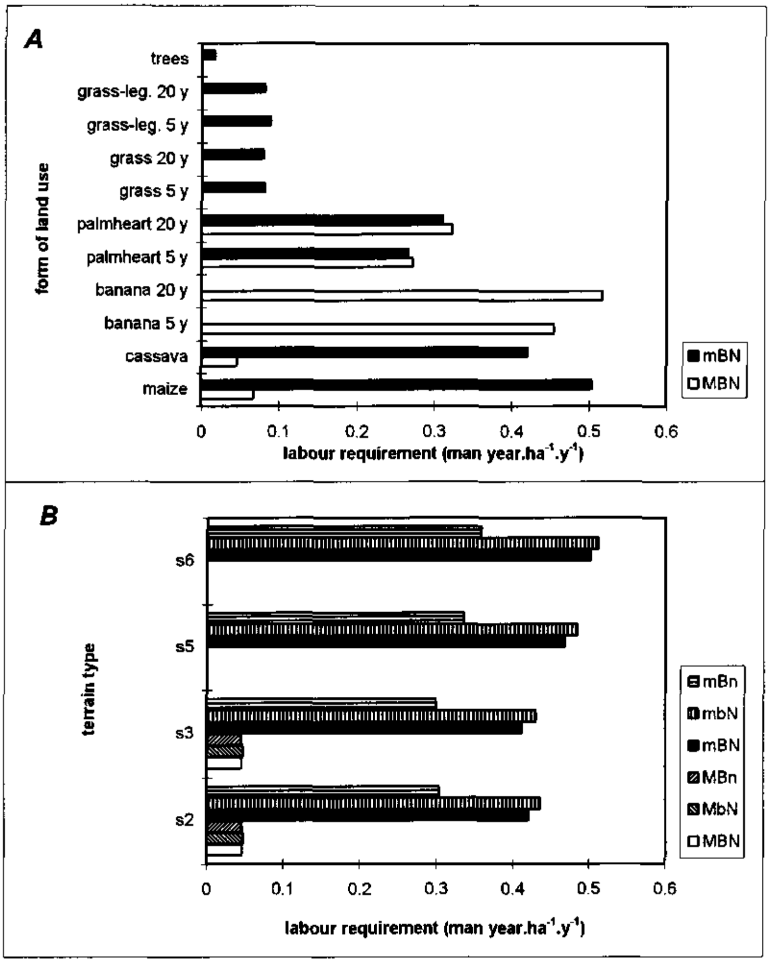

Figure 3.2 Average labour requirements for various production activities in the single-period MGLP-model. A: for yield-oriented production on terrain type *s2*; B: for cassava production on various terrain types and with various production techniques.

In Figure 3.2 labour requirements of different forms of land use, production techniques and terrain types are compared. Differences in labour requirements between forms of land use are large (Figure 3.2A): on terrain type *s2* banana with a growing period of 20 years is most labour intensive and tree plantations have the lowest labour requirements. Changes in the length of growing period (20 years instead of five years) only have a clear effect in banana. Mechanized production of maize and cassava requires far less labour than manual production (Figures 3.2A and 3.2B). For palmheart the differences between production techniques *MBN* and *mBN* are very small, because only land preparation can be mechanized. Figure 3.2B shows that the differences in labour need between terrain types is small for cassava. From the above, it can be concluded that the largest differences in labour requirements are observed between forms of land use, followed by differences between production techniques. The differences between terrain types are smallest.

3.2.3 Production costs and prices

For the calculation of production costs and profits the prices of 1991 were used. The physical amounts needed of fertilizers, biocides, labour, and input of crop products and animal products were multiplied by a unit price. Most of the current labour in agriculture is unskilled labour. The wages at banana plantations in the NAZ were used for all labour in my study. For biocides and fertilizers the average price per kg active ingredient was calculated with data from Schipper (personal communication). No distinction was made between different formulations. The use of machinery, small equipment, seeds or planting materials, construction materials, vaccinations, artificial insemination, etc. was estimated separately with the help of data from Costa Rica or similar regions. It was assumed that these inputs are efficiently used. The aggregate costs of these inputs (plus depreciation costs) were included in the MGLP-models. The costs per unit or the costs per unit time of these inputs were based on data from Schipper (personal communications) and BNC (1992). Administrative costs and management costs were not included in the description of the production activities. For agricultural products "region" gate prices of 1991 were used. In the NAZ prices of agricultural products vary far more than prices of inputs. Therefore, in my study the sensitivity of the *single-period model* to changes in prices of agricultural products was analysed. Data on variation in local market prices or export prices were used in this analysis. The effects of demand and supply on price levels were not analysed. It was assumed that the observed variation was random. Details on prices and production costs are presented in Appendix 6.

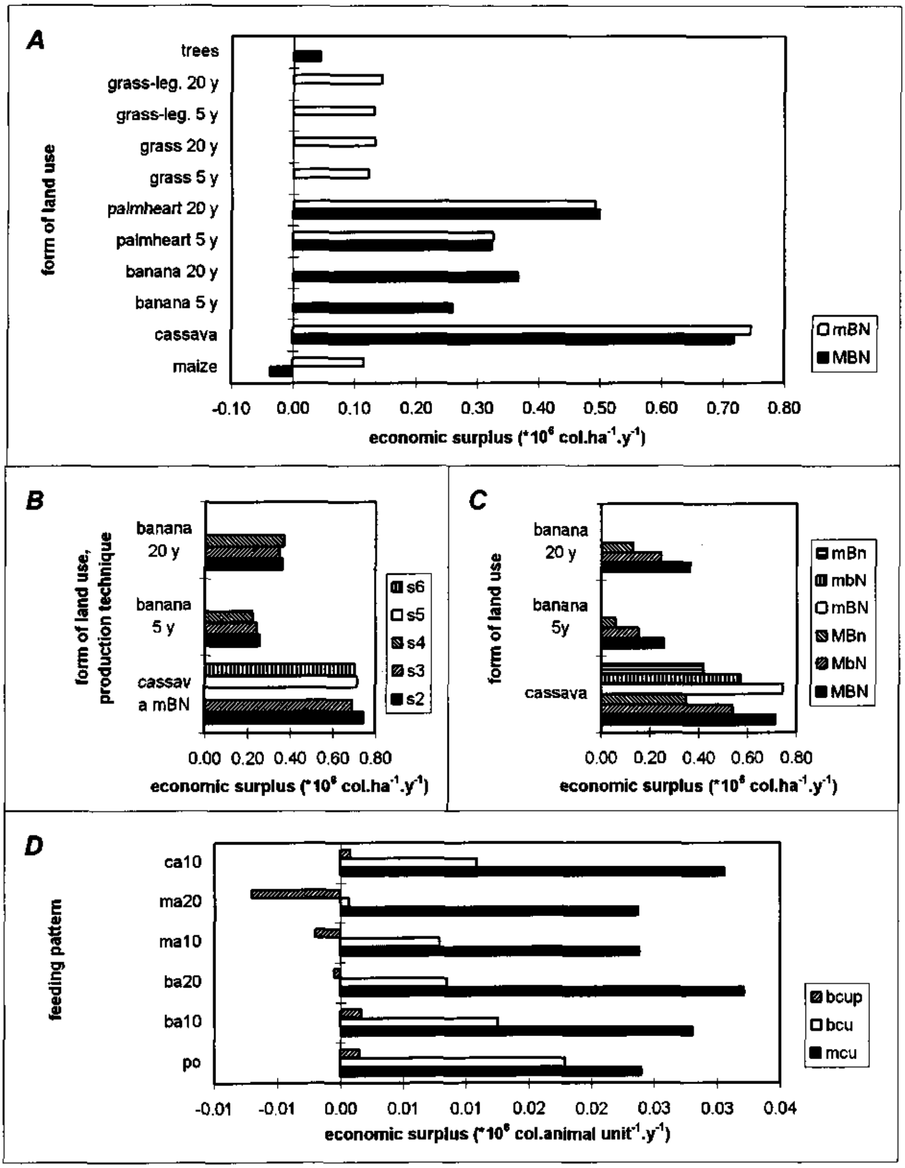

Figure 3.3 Average economic surplus for various production activities in the single-period MGLP-model, calculated with "average" coefficients. A: for yield-oriented production (*MBN,* but *mBN* for pastures) on terrain type *s2*; B: on various terrain types; C: for various production techniques; D: for various livestock activities on pasture with a growing period of 20 years on terrain type *s2*. For codes see Tables 2.4 and 4.1.

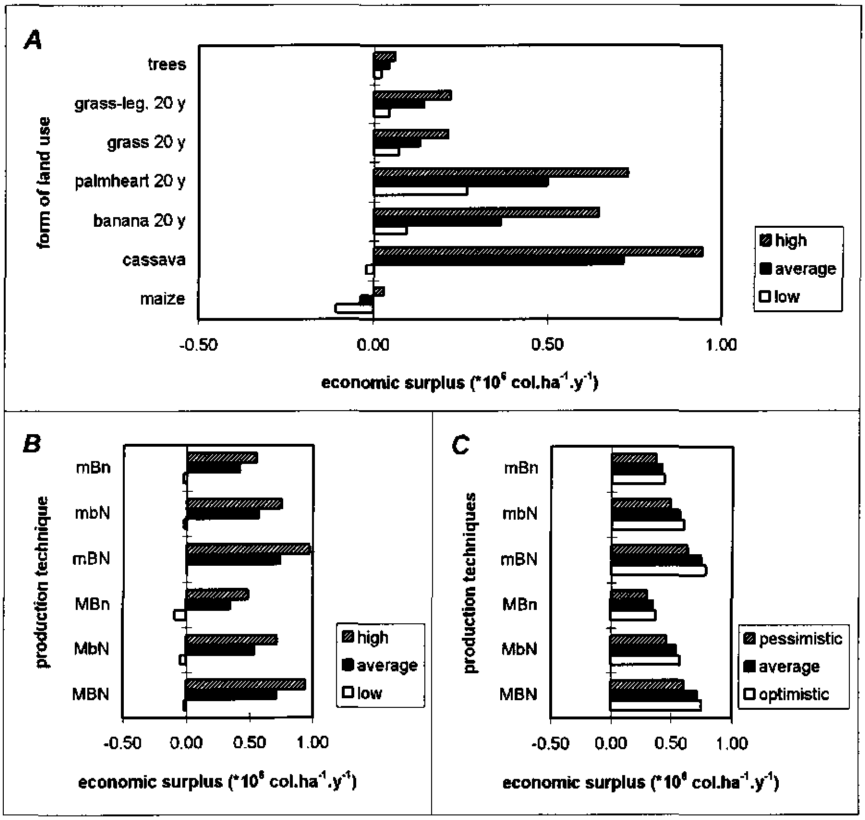

Figure 3.4 Economic surplus for production activities on terrain type *s2* in the single-period model: A: for yield-oriented activities, calculated with "average" coefficients (feeding pattern *po* on pasture); B: for cassava, calculated with "average" agro-ecological coefficients and "high", "average" and "low" prices; C: for cassava, calculated with "average" prices and "optimistic", "average" and "pessimistic" agro-ecological coefficients.

With the help of the product prices and the production costs the economic surplus (revenue - production costs) of the production activities could be calculated. In Figure 3.3 the economic surplus of various forms of land use, production techniques and terrain types is compared.

Average economic surplus differs considerably between forms of land use (Figure 3.3A): cassava is most profitable, followed by palmheart and banana. Changes in the length of the growing period of perennials (20 years instead of five years) only have a clear effect in banana, because the costs for the establishment of infrastructure in the banana plantation are high. Differences between mechanized and manual production are small, except for maize. Economic surplus in yield-oriented production (i.e. *MBN* and *mBN*) is clearly higher than in environment-oriented production (*MbN, Mbn, mbN* and *mBn*; Figure 3.3C). This is mainly caused by the difference in production level. Differences between terrain types are small (Figure 3.3B). Figure 3.3D presents the economic surplus of livestock activities. The type of animal unit clearly affects the economic surplus; feeding pattern is less important. As for labour requirements, the largest differences in average economic surplus are found between forms of land use, and the smallest differences between terrain types.

Figures 3.4A and 3.4 B present some examples of the consequences of different price levels on economic surplus. For instance, the "low" price of cassava is only 25 % of the "average" price. Consequently, economic surplus is negative if "low" prices are used. In Figure 3.4C the consequences of uncertainty in agro-ecological coefficients are shown. Owing to the higher or lower fertilizer requirements if "pessimistic" or "optimistic" agro-ecological coefficients are used, economic surplus slightly changes. The consequences of uncertainties in agro-ecological coefficients on economic surplus are less pronounced than the consequences of changes in prices. The consequences of changes in prices on economic surplus are of the same order as the effects of form of land use on economic surplus.

3.3 Nutrient inputs and outputs

3.3.1 General methodology

The methodology used to calculate fertilizer requirement and N-loss per crop activity is presented below (Figure 3.5). The method is basically the same for nitrogen (N) and potassium (K). Phosphorus (P) shows residual effects for much longer periods than nitrogen and potassium. This could easily be included in the single-period model, since the single-period model implicitly assumes that continuous cultivation of the same crop takes place. Thus, long-term effects of P can be incorporated by considering equilibrium situations. In a multi-period model cropping sequences are not known a priori. Therefore, a different approach has to be used for P, which will be presented in Chapter 6.

Step 1 Calculating the nutrient uptake

$$UN = HI \times DM \times NCP + (1 - HI) \times DM \times NCR \tag{3.5}$$

Step 2 Calculating the total nutrient requirement

$$NI = \frac{UN}{ANR} \tag{3.6}$$

Step 3 Calculating the temporary immobilization

$$IMM = (1 - FL) \times (1 - ANR) \times NI \tag{3.7}$$

Step 4 Calculating the nutrient loss caused by leaching, gaseous loss or fixation

$$NL = FL \times (1 - ANR) \times NI \tag{3.8}$$

Step 5 Calculating the nutrient input from mineral fertilizer

$$MF = NI - DE - IMM - AD - NBF + ER \tag{3.9}$$

In which:

- *AD* = amount added through atmospheric deposition ($kg.ha^{-1}.y^{-1}$)
- *ANR* = apparent nutrient recovery (-), defined as (uptake by fertilized crop in period of application - uptake by unfertilized crop) / application rate
- *DE* = amount released through decomposition of crop residues, i.e. (1 - *HI*) * *DM* * *NCR* ($kg.ha^{-1}.y^{-1}$)
- *DM* = total dry matter production ($kg.ha^{-1}.y^{-1}$)
- *ER* = amount lost through erosion ($kg.ha^{-1}.y^{-1}$)
- *FL* = fraction lost through leaching, gaseous loss or fixation (-)
- *HI* = harvest index (-)
- *IMM* = amount temporary immobilized ($kg.ha^{-1}.y^{-1}$)
- *MF* = fertilizer requirement ($kg.ha^{-1}.y^{-1}$)
- *NBF* = amount added through non-symbiotic biological fixation ($kg.ha^{-1}.y^{-1}$)
- *NCP* = nutrient concentration in crop product ($kg.kg^{-1}.y^{-1}$)
- *NCR* = nutrient concentration in crop residue ($kg.kg^{-1}.y^{-1}$)
- *NI* = nutrient requirement ($kg.ha^{-1}.y^{-1}$)
- *NL* = amount lost ($kg.ha^{-1}.y^{-1}$)
- *UN* = nutrient uptake ($kg.ha^{-1}.y^{-1}$)

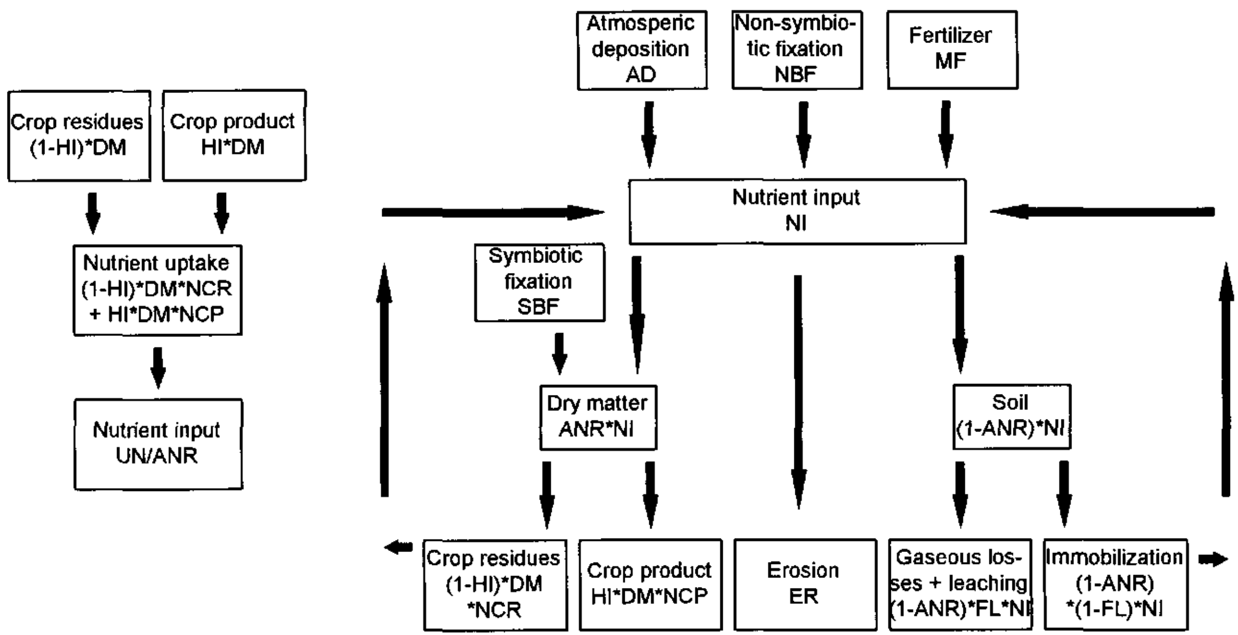

Figure 3.5 Basic methodology for calculating fertilizer requirement and nutrient loss, based on De Koning *et al.* (1992).

The method described above assumes a steady-state situation. The crop is preceded and followed by the same crop, because nutrient inputs from decomposition (*DE*) and remobilisation (*IMM*) are based on the same crop with the same production level.

For pastures, the calculation method is more complicated. Most of the nutrients consumed by livestock are returned to the soil with urine and dung (defined as fraction of the amount of nutrients consumed). N and K from urine and dung are taken up with a lower apparent nutrient recovery (*ANR*) than from mineral fertilizer. A weighted *ANR* based on the *ANR* of mineral fertilizer and the *ANR* of manure was calculated. Besides, in grass-legume pastures N can be added through symbiotic biological fixation. This N is not prone to leaching or gaseous loss until decomposition of the legume. For these grass-legume pastures nutrient requirement (*NI*) was replaced by *NI* - (*SBF* / *ANR*), in which *SBF* is the symbiotic biological fixation ($kg.ha^{-1}.y^{-1}$).

For the quantification of nutrient inputs for environment-oriented production aiming at reduced N-loss (production techniques *MBn* and *mBn*), the order of steps was reversed. First, the allowed N-loss was determined (40 % of N-loss under yield-oriented production). Subsequently, the matching production level and mineral fertilizer need were calculated. In the optimization runs with "optimistic" (lowest N-loss and mineral fertilizer need) and "pessimistic" (highest N-loss and mineral fertilizer need) estimates of agro-ecological coefficients the same production level as for the "average" estimate was used (Chapter 5). In the case of "pessimistic" estimates, increasing nutrient concentrations with increasing production level were used. Consequently, the proportional reduction in N-loss in production techniques aiming at reduced N-loss was more than the reduction of production, as compared with yield-oriented production.

For P steps 3, 4, and 5 were modified. No leaching of P is expected, as the soils have a high P-retention. Instead of *IMM* a residual P effect (*REP*) was calculated. In the single-period MGLP-model a "steady-state" situation was assumed. Therefore, it can be assumed that the crop can profit from the residual effect of P applied in preceding years.

Step 3 Calculating the residual effect of P

$$REP = FREP \times (1 - ANR) \times NI \qquad 3.10$$

The fraction (1- *FREP*) becomes available only over a much longer period (>15 years), or is fixed irreversibly by the soil. This fraction was assumed to be unavailable to the crop.

Step 4 Calculating the unavailable P

$$FIX = (1 - FREP) \times (1 - ANR) \times NI \tag{3.11}$$

Step 5 Calculating the fertilizer-P requirement

$$MF(P) = NI - DE - AD - REP + ER \tag{3.12}$$

In which:
- *AD* = amount added through atmospheric deposition ($kg.ha^{-1}.y^{-1}$)
- *ANR* = apparent nutrient recovery (-)
- *DE* = amount released through decomposition of crop residues ($kg.ha^{-1}.y^{-1}$)
- *ER* = amount lost through erosion ($kg.ha^{-1}.y^{-1}$)
- *FIX* = unavailable amount ($kg.ha^{-1}.y^{-1}$)
- *FREP* = fraction residual effect (-)
- *REP* = amount residual P ($kg.ha^{-1}.y^{-1}$)
- *MF(P)* = fertilizer-P need ($kg.ha^{-1}.y^{-1}$)
- *NI* = nutrient requirement ($kg.ha^{-1}.y^{-1}$)

In the multi-period model, periods of five years are used. Therefore, residual effects of P in the period of application and in the periods after application are discriminated. Separate residual effects (*REPs*) were calculated for these periods. The fertilizer-P requirements depend on the cropping sequences selected by the multi-period MGLP-model. Consequently, the final fertilizer-P requirements have to be calculated in the multi-period MGLP-model (Section 6.3).

3.3.2 Quantifying parameters for nutrient inputs and outputs

Only few data from the NAZ or from similar regions are available on nutrient recovery, leaching, gaseous loss, immobilization, etc. under production with "best technical means". As a result, the coefficients used in this study are uncertain. "Average", "optimistic", and "pessimistic" values for all coefficients were calculated. These estimates were based on different perceptions of the influence of climatic and soil conditions on leaching, retention, etc. Below some details are presented for the different input parameters. More details can be found in Appendix 3.

Nutrient concentrations in crop products and residues (NCP and NCR)

Two different assumptions can be adopted for estimating nutrient concentrations: 1. nutrient concentrations are independent of production levels, or 2. nutrient concentrations increase with increasing production levels (Bessembinder 1995). In addition, uncertainty owing to lack of data for quantification of nutrient concentrations exists. For the "optimistic" estimates in the present study, i.e. low fertilizer requirements and N-loss, constant and low nutrient concentrations were used. For the "pessimistic" estimates high nutrient concentrations were used, and higher nutrient concentrations were used for the yield-oriented activities than for environment-oriented activities with lower production levels (Appendix 3). Low nutrient concentrations in pasture do not result in efficient livestock production: at least 1.6 % N (i.e. 10 % crude protein) in pasture DM is needed for meat production and 1.92 % is the minimum N-concentration for milk production (Chamberlain 1989; 't Mannetje 1992). "Average", "optimistic" and "pessimistic" nutrient concentrations for pastures were based on observations in the NAZ by Vargas & Fonseca (1989) and Ibrahim (1994). The low nutrient concentrations used in the "optimistic" estimates, resulted in low fertilizer needs and low N-loss, but also in lower livestock production.

Apparent nutrient recoveries (ANR)

Only for maize two data sets from the NAZ were available with sufficient information to calculate apparent nutrient recoveries. Table 3.6 shows these recoveries and some recoveries mentioned in literature. A wide variation in *ANRs* was found, owing to differences in weather, soil, plant and management characteristics. In this study, differences caused by variation in management were excluded, because production with "best technical means" was assumed. *ANRs* for each crop activity were estimated with the help of rankings for crop, soil and management characteristics (Grimme & Juo 1985; Haynes *et al.* 1986; Martinez *et al.* 1987; Groffman *et al.* 1988; White 1988; De Willigen & Van Noordwijk 1989; Masayoshi Koshino 1990; Seyfried & Rao 1991; Babbar & Zak 1994). These characteristics were ranked from positive (high value: 3) to negative (low value: 1) effects on *ANRs*. For N-recovery, the characteristics rooting distribution and depth, frequency of application, water holding capacity of the soil, organic matter concentration of the soil, and soil depth were used. The highest sum of rankings for these five characteristics was obtained for banana and palmheart on terrain type *s4*. This sum of rankings was set equal to an "average" N-recovery of 0.70. Lower sums of rankings resulted in lower "average" N-recoveries (see Appendix 3). For P-recovery, the rooting distribution and depth, frequency of application, pH and P-retention were considered relevant, and for K-recovery, rooting distribution and depth, frequency of application, water holding capacity of the soil, organic matter concentration of the soil, soil depth, and base saturation were taken into account. In production techniques aiming at low biocide use, 5 % lower recoveries were used, because crops infested by pests or diseases, are less efficient in nutrient uptake. Under intensive grazing much N from urine and dung is lost by a combination of leaching, denitrification and volatilization (Van der Meer & Van Lohuyzen 1986; Floate 1987; Steele 1987; White 1987). Therefore, a recovery of 0.30 was used for N from urine and dung. There is no reason to assume a lower P-recovery for organic P. Cattle excrete K mainly through dung. In dung patches K is prone to leaching: a recovery that was 0.10 lower than the recovery for mineral fertilizer was assumed.

Table 3.6 Apparent fertilizer recovery fractions of N, P and K in maize from different information sources.

	N	P	K
Average Atlantic Zone[a]	0.44	0.10	-
Maximum Atlantic Zone[a]	0.66	0.26	-
Ranges found in literature			
Baligar & Bennett (1986)	0.20-0.80	0.10-0.30	0.20-0.40
Janssen & Wienk (1990)	0.30-0.50	0.15-0.25	0.35-0.60
Van Duivenbooden (1992)	0.00-0.90	0.00-0.70	0.11-0.60
Van Keulen & Van Heemst (1982)	0.10-0.80	<0.30	0.50-0.80
Averages or standard values from literature			
Sanchez (1976)	0.3-0.5	-	-
Baligar & Bennett (1986)	0.50	0.10	0.40
Janssen & Wienk (1990)	0.40	0.20	0.50
Van Duivenbooden (1992)	0.36	0.18	0.34
Values used in other explorative studies			
Van Duivenbooden *et al.* (1991)	0.20-0.50	0.15-0.30	0.50-0.65
De Koning *et al.* (1992; potential)	0.75	-	-
De Koning *et al.* (1992; water-limited)	0.36-0.60	-	-
Expert estimates for the Atlantic Zone			
Janssen (pers. comm.)	0.50	0.20	0.50
Schröder (pers. comm.)	0.40	-	-

[a] based on data from Erenstein (1989) and Chin-Fo-Sieeuw (1994).

To take into account the uncertainty in *ANRs*, *ANRs* that were 0.10 higher were used for N and K in the "optimistic" estimates. For P, *ANRs* that were 0.05 higher were used. In the "pessimistic" approach, for N and K *ANRs* that were 0.10 lower than the "average" were used, however for maize and cassava 0.15 lower *ANRs* were used (see under decomposition). For P, *ANRs* that were 0.05 lower were used for the "pessimistic" estimates. These ranges were estimated on the basis of Table 3.6. "Average" recoveries are presented in Appendix 3.

Immobilization (IMM)

Part of the nutrients released from mineral fertilizer, organic matter or other sources will be temporarily immobilized. These nutrients become available for the next crops. Data on N-immobilization in literature range from 3 to 30 % of the input (Grimme & Juo 1985; Matson *et al.* 1987; Masayoshi Koshino 1990; Haggar *et al.* 1993), however there are no data from the NAZ. N-immobilization is influenced by the C/N ratio. N can be temporarily immobilized if organic matter with a high C/N ratio is added. The estimated nutrient concentrations in plant material in this study are relatively low. Therefore, the C/N ratio of the DM is high. DM production is also high in all crop activities defined in the present study, and plant residues from the perennial crops are continuously added to the soil. As a result, N can be continuously incorporated in soil organic matter. Immobilization was defined as a fraction of the nutrients that are not taken up by the crop. The remainder of the nutrients not taken up by the crop, is lost through leaching or gaseous loss (Martinez *et al.* 1987). In annual crops the nutrient input through decomposition of plant material is more concentrated in certain periods of the year, therefore the risk of nutrient leaching is higher in annuals than in perennials. In this study a N-immobilization fraction of 0.40 was used for perennial crops and 0.30 for annual crops (De Koning *et al.* 1992). Most K that is not taken up by the crop will leach because of the high precipitation rate and the low base saturation. It was assumed that 15-25 % is temporary immobilized by the soil (personal communication Guiking), depending on CEC and base saturation. For "optimistic" estimates of the immobilized fraction 0.10 higher values were used; for "pessimistic" estimates of the immobilized fraction 0.10 lower values were used. For P *IMM* was replaced by *REP*, which is treated below.

Residual effect of phosphorus (FREP and REP)

To calculate the residual effect of phosphorus in the years after application, the following equation used: $Rt = (0.8 - R1)^{t-1} * R1$, in which *Rt* and *R1* are the recovery fractions in year *t* and year 1, respectively. The equation can be applied for calculating the residual effect for up to five years after application of P. Long-term (> five years) residual effects are slightly underestimated with this equation (Janssen & Wolf 1988). In spite of this restriction the simple equation was used for calculating longer-term residual effects, because:

- The uncertainty in the P-recovery estimates in this study is much higher than the underestimation of residual P by using this equation for longer periods;
- P-retention by allophanes in the soils in the NAZ may reduce the residual effects of mineral P application (Sanchez 1976; Landon 1991);
- Data for a more comprehensive model are lacking (Wolf *et al.* 1987).

The cumulative residual effect calculated with the equation did not increase much after about ten years (< 0.1% of the applied mineral P per year). Therefore, only residual effects of P up to 10 years after application were taken into account in the present study.

Decomposition (DE)

Most organic materials decompose in three to four months (Sauerbeck & Gonzalez 1977), only branches and trunks decompose much slower (Poels 1995). Flores & Vargas (1992a; 1992b) found that 70-80 % of banana leaves had decomposed within 21 weeks. Data on recoveries of the released nutrients are almost absent. In the NAZ plant growth and dying take place all the year round, therefore plant residues are gradually added to the soil in perennial crops. There is a well-developed root system all the year round, so that released nutrients can be taken up directly from decomposing plant material. It was assumed that the apparent nutrient recovery from nutrients released by decomposition can be the same as the recovery from mineral fertilizer. In annual crops good management is required to obtain the same *ANR* for nutrients from decomposed material as from mineral fertilizer. Part of the year no active root system is present for uptake of nutrients. However, in this study it is assumed that the period between subsequent crops is short and that plant residues are worked into the soil only shortly before the next crop is planted or sown. Since in annuals the risk of leaching of N and K from decomposing plant material is higher than for perennials, the "pessimistic" *ANRs* were assumed to be 0.15 lower than the "average" value, instead of the 0.10 lower values used for perennials. The "average" and "optimistic" *ANRs* for organic sources of nutrients were assumed to be the same as for mineral sources.

Atmospheric deposition (AD)

In humid regions wet deposition is far more important than dry deposition. Only one reference on wet deposition in the NAZ is available (Parker 1985) and two references from Turrialba, just outside the region (Imbach *et al.* 1989; Forti & Neal 1992). These data were combined for estimating "average", "optimistic" and "pessimistic" deposition rates. The deposition rates were adjusted for the NAZ, assuming a linear relation between deposition and rainfall.

Symbiotic biological N-fixation (SBF)

In grass-legume pastures N is fixed symbiotically by the legume. After decomposition of the legume the fixed N becomes available to the grass. Estimates for percentages of N in leguminous crops fixed by *Rhizobium* differ considerably (Tisdale *et al.* 1985; Stoorvogel & Smaling 1991; Smaling & Fresco 1993). Giller & Wilson (1991) mention a range of 15-98 %, with an average of

68 %. For tropical legume-pastures they mention percentages with an average of 83 %. In this study it was assumed that under good management on a soil with pH=5.5, 80 % of N in legumes can be obtained by symbiotic N fixation. As "optimistic" and "pessimistic" estimates 90 % and 65 % were used respectively. A maximum of 65 % fixation is rather low, but fixation may be reduced under the N-rich conditions occurring in the soils of the NAZ. For terrain types *s5* and *s6* lower symbiotic fixation rates were used, because these soils have a lower pH. If the N-requirement of the grass-legume cannot be met with symbiotic fixation, it was assumed to be supplemented with mineral fertilizer.

Non-symbiotic N-fixation (NBF)

Non-symbiotic fixation was taken into account only for grass-legume pastures. Generally, contributions of N by non-symbiotic fixation are low (Sanchez 1976; Haynes *et al.* 1986; Gibson *et al.* 1988). An average non-symbiotic fixation of 5 $kg.ha^{-1}.y^{-1}$ for grass-legume was used in this study. For the "optimistic" and "pessimistic" estimates 10 and 0 $kg.ha^{-1}.y^{-1}$ were used respectively.

Water erosion (ER)

Erosion was estimated with the Universal Soil Loss Equation (USLE). The rainfall-erosivity (*R*) calculated by Vahrson (1991) for the Atlantic Zone ranges from 500 to >800. Based on Vahrson's map a weighted value of about 650 for the whole NAZ was calculated. Soil erodibility factors (*K*) were determined with the nomograph of Wischmeier *et al.* (1971). *K*-values for high organic matter concentrations were obtained by extrapolation. In this study 50 % lower values were used for factor *K* as aggregation of clay and organic matter particles causes soils with volcanic material to be more stable (Ahn 1977). The nomograph of Wischmeier & Smith (1978) was used to estimate the effect of slope and slope length (*LS*) on erosion, assuming a slope length of 100 m. With the help of the figures for mulch cover and canopy cover given by Wischmeier & Smith (1978), the *C*-values for the different production activities were estimated. The *C*-values in this study are lower than those found in literature (Solorzano *et al.* 1991; Stoorvogel 1995). However, fast canopy closure and high amounts of mulch can be expected under production with "best technical means". Contouring on slopes was assumed (Wischmeier & Smith 1978). Nutrient concentrations in the eroded soil material were derived from the organic matter concentration, the total P and the total K figures from the topsoil, and using an enrichment factor of two. The USLE-equation has not been validated for the NAZ. Taking into account uncertainty for all factors, a 50 % higher erosion than the "average" erosion could easily be obtained. As "optimistic" estimates 25 % lower values than the "average" erosion were used.

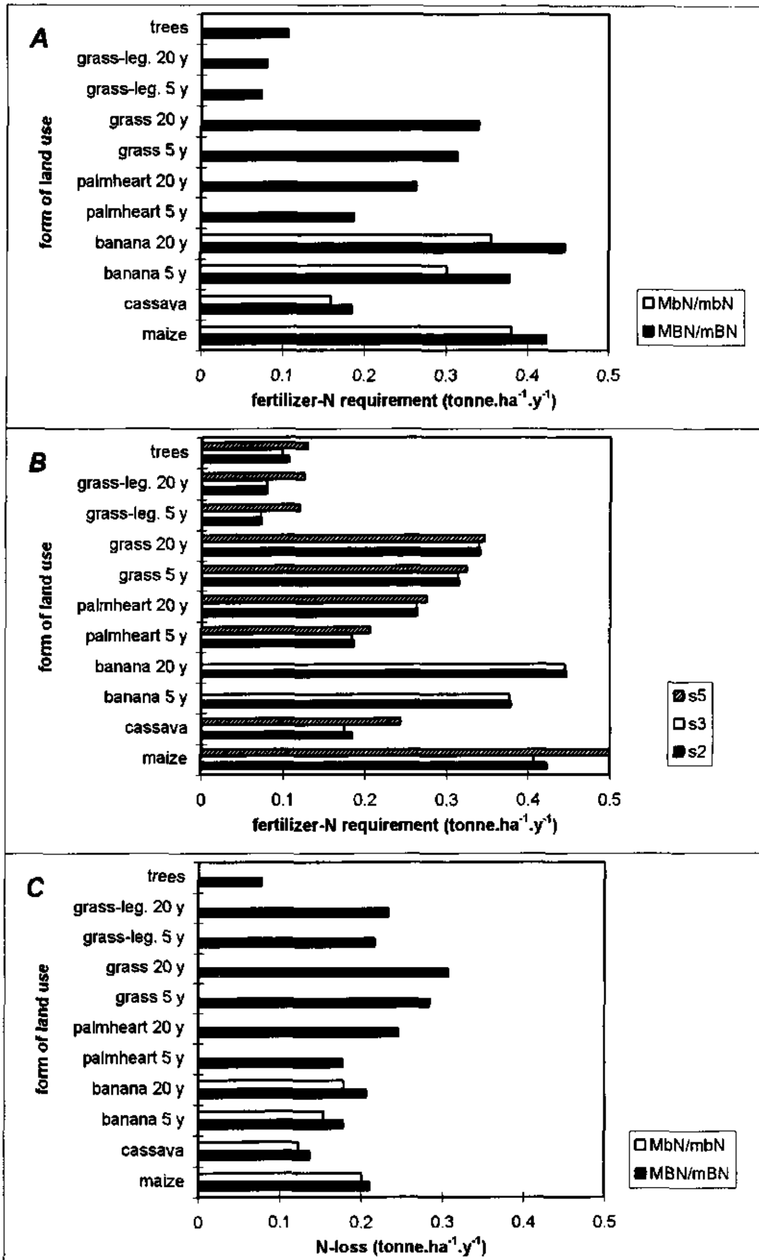

Figure 3.6 Average yearly fertilizer-N requirements (*MF*) and N-loss (*NL*) for various crop activities in the single-period MGLP-model, calculated with "average" coefficients. A: N requirement on terrain type *s2*; B: N requirement for yield-oriented production on various terrain types; C: N-loss on terrain type *s2*.

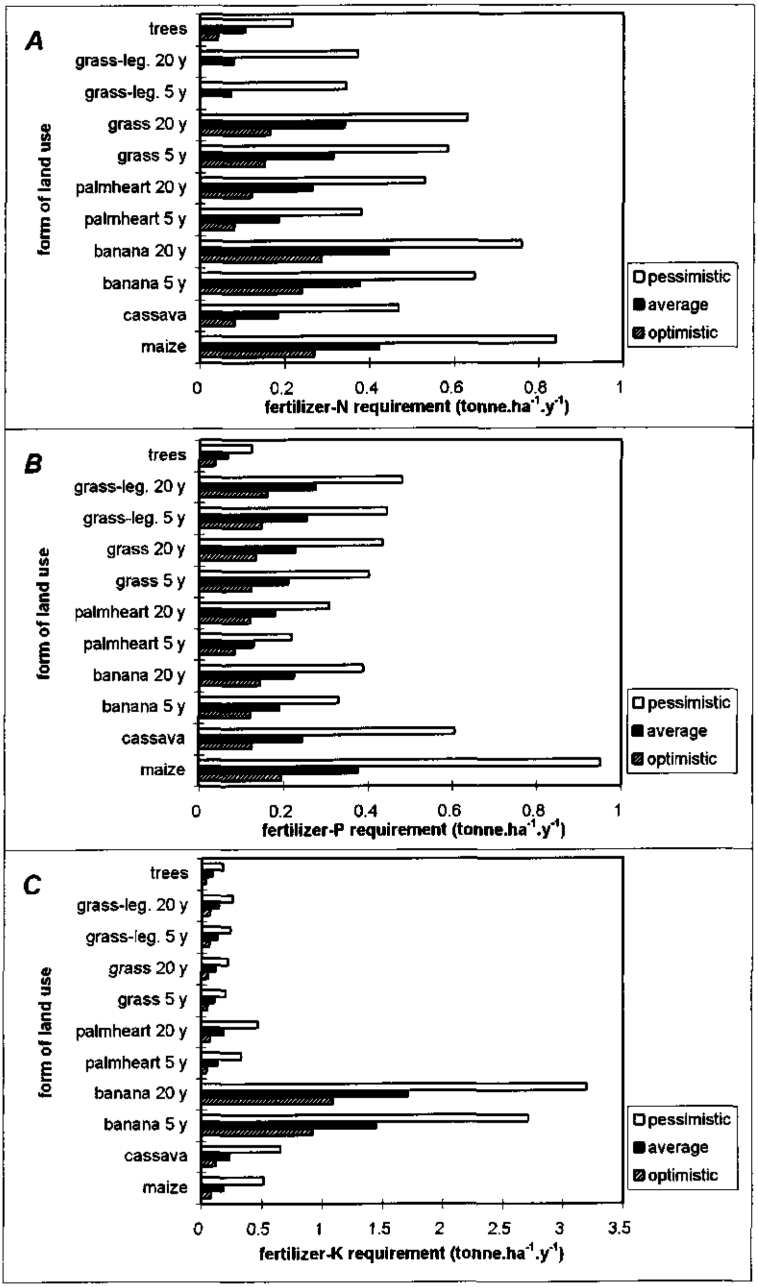

Figure 3.7 Yearly fertilizer requirements for yield-oriented production on terrain type *s2* in the single-period MGLP-model, calculated with "average", "optimistic" and "pessimistic" parameters. A: nitrogen; B: phosphorus; C: potassium.

Figure 3.6 shows examples of calculated fertilizer-N requirements and N-loss. Generally, differences between terrain types are smaller (Figure 3.6B) than differences between forms of land use and production techniques (Figures 3.6A and 3.6C), because fertilizer requirements are strongly related to production levels. Maize and banana have the highest fertilizer-N requirement (Figures 3.6A and 3.6B). N-loss is highest in palmheart and pasture (Figure 3.6C). The calculated mineral fertilizer inputs are clearly higher than the mineral fertilizer inputs currently used in the NAZ (Table 3.5). For instance, at present fertilizers are hardly ever used in cassava production and consequently the soils are depleted. The currently used amounts of fertilizer in banana production are close to the amounts in Figure 3.6, but current production levels are much lower than those used in this study. The calculated fertilizer-P requirements are extremely high, because a large amount of the applied P is fixed by the soil. Figure 3.7 compares "average", "optimistic" (i.e. low) and "pessimistic" (i.e. high) estimates for calculated mineral fertilizer requirements. The proportional differences between "average", "optimistic" and "pessimistic" estimates are not identical for all production activities. For instance, "optimistic" fertilizer-N requirements are 35 % to 100 % lower than "average" N requirements, and "pessimistic" N requirements are 55 % to 441 % higher. This is caused by differences in relative uncertainties in nutrient concentrations, *ANRs*, symbiotic fixation and fraction immobilized. From Figures 3.6 and 3.7 it can be concluded that to estimate absolute values of fertilizer requirements and N-loss, the uncertainties in agro-ecological parameters and the forms of land use are more important than production techniques or terrain types.

Table 3.7 Some examples of "average" coefficients (kg $P.ha^{-1}.5\ y^{-1}$) used in the multi-period MGLP-model (coefficients for terrain type *s2* and period 1[a]).

Coefficient	Code in MGLP-model[b]	Yield-oriented production: Establishment banana *l=ba1*	Yield-oriented production: Continued banana *l=bac*	Environment-oriented production, reduced biocide use: Establishment banana *l=ba1*	Environment-oriented production, reduced biocide use: Continued banana *l=bac*
Preliminary P requirement	*pmf*	1175	1455	803	892
Residual P 1 period after application	*mfr1*	149	185	102	113
Residual P 2 periods after application	*mfr2*	13	16	9	10

[a] in the multi-period model fluctuation in inputs and outputs caused by variation in weather conditions was included, see Chapter 6;
[b] the codes for the multi-period MGLP-model are explained in Tables 6.1 and 6.3.

Table 3.7 lists some coefficients for the multi-period MGLP-model. These coefficients were calculated per period of five years, and for perennial crops different growth stages were distinguished. Differences in fertilizer requirements per growth stage are largest for tree plantations, followed by banana and palmheart. The differences in fertilizer requirements between growth stages for pasture are relatively small.

Mineral fertilizer requirement and N-loss were most sensitive to uncertainties in the parameter *ANR*. In almost all crops an increase or decrease of the *ANR* by 10 % resulted in a change of more than 10 % in fertilizer requirement and N-loss. Nutrient inputs and outputs were slightly less sensitive to changes in nutrient concentrations, fraction immobilized, and production level.

3.4 Biocide use and risk of biocide leaching

The coefficients biocide use and risk of biocide leaching were included in the environmental objective functions. Information was available on currently used and advised application rates, but information on processes influencing biocide leaching was insufficient for estimating the quantities of leached biocides in the NAZ. With the help of models that simulate biocide behaviour in the soil, the production activities can be ranked for biocide leaching risk. Below, the methods used for estimating biocide use and biocide leaching risk in the present study, are described. In Appendix 4 more detailed information is given.

3.4.1 Amounts of biocides used

For the various forms of land use that require biocides, a selection was made of currently applied and promising biocides. Since Himel *et al.* (1990) state that most current biocide spraying methods are inefficient and that more efficient use is possible, the estimates of biocide use in each crop activity were based on the incidence of pests and diseases and the *minimum* advised and used amounts of the biocides (Bonilla 1983; Montaldo 1985; Soto 1985; INA 1987; Anonymous 1989; Castro 1989; Geilfus 1989; IICA 1989; Monge 1989; Pardo Tassies 1989; SEPSA 1989; CATIE 1990; Canton *et al.* 1991; CATIE 1991; Chaves & Fonseca 1991; MAG 1991; MAG/UNED 1991; De Haan & Waaijenberg 1992; Tomlin 1994). When a herbicide is used as a soil herbicide, higher rates are required on clayey soils than on sandy soils. In these cases the adjustment factors mentioned by Luyten (1995) were applied (Appendix 4). High crop densities offer a more favourable microclimate for fungal diseases. Lower yield levels are often related to lower crop densities. Therefore, in the environment-friendly production with reduced N-loss and reduced yield level, a 20% lower fungicide requirement was assumed. Effects of soil type on nematicide requirements were not included. Organic matter is probably the main factor influencing nematicide requirement (personal communication Van Bezooyen), but organic matter concentration is high in all soils in the NAZ. It was assumed that the application of the various herbicides is alternated, to avoid development of resistance. The same was assumed for insecticides, fungicides, and nematicides. Figure 3.8 shows some examples of estimated biocide use. Biocide use is highest in banana, followed by maize and cassava. Although in production techniques *MbN* and *mbN* use of biocides is considerably reduced, it remains higher than the biocide use in yield-oriented production of palmheart, pasture and tree plantations. The average yearly biocide use in palmheart and tree plantations is very low: biocides are only applied to control weeds during establishment of the plantations. Details on biocide use in crop activities are presented in Appendix 4. In livestock activities only very small amounts of biocides are used in the form of medicaments, therefore biocide use was assumed to be zero.

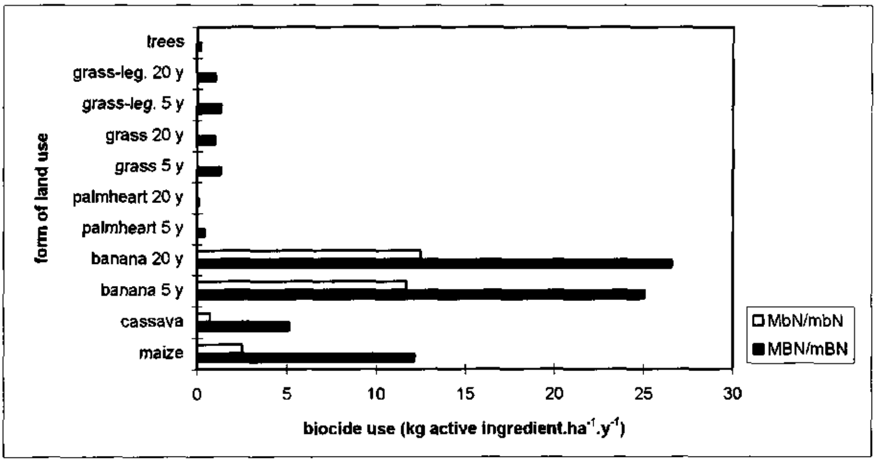

Figure 3.8 Average yearly biocide use for crop activities on terrain type *s2* in the single-period MGLP-model.

3.4.2 Risk of biocide leaching

Research on the behaviour of biocides in the tropics is scarce, and only a few quantitative studies on biocide behaviour in Costa Rica are available (Gonzalez & Carazo 1986; Behm *et al.* 1992; Rosales *et al.* 1992). Current data on the amounts of used biocides are often available, but data on volatilization, half-lives, adsorption to organic matter and clay minerals have almost exclusively been collected in temperate regions or in laboratory conditions. Kleveno *et al.* (1992) have shown that the absolute amount of biocides leached into the ground water in volcanic soils are difficult to predict with simulation models. They also showed that in Hawaii the same rankings for biocide leaching risks were obtained with the help of a simple index (*AF*) as with a more comprehensive dynamic simulation model (*PRZM*). The *AF*-index, ranging from 0 to 1, was proposed by Rao *et al.* (1985; Equations 3.13 and 3.14). It is a means of ranking the likelihood of potential leaching for various chemicals. The larger the value of *AF*, the more likely it is that the chemical will leach (in: Kleveno *et al.* 1992).

$$AF = \exp \frac{-0.693 \times d \times RF \times \theta_{FC}}{q \times t_{½}} \qquad 3.13$$

$$RF = 1 + \frac{\phi_b \times f_{oc} \times K_{oc}}{\theta_{fc}} + \frac{n_a \times K_H}{\theta_{fc}} \qquad 3.14$$

In which:
- d = distance from the soil surface to the water table (m)
- RF = retardation factor (-)
- θ_{FC} = soil-water content at field capacity (volume fraction)
- q = the net ground water recharge ($m.d^{-1}$)
- $t_{1/2}$ = biocide half-life (d)
- ϕ_b = soil bulk density ($kg.dm^{-3}$)
- f_{oc} = soil organic carbon (mass fraction)
- K_{oc} = biocide sorption coefficient to organic carbon (-)
- K_H = Henry's constant (-)
- n_a = soil air-filled porosity (volume fraction)

The parameters in Equations 3.13 and 3.14 on biocide properties were compiled from literature (Felsot *et al.* 1982; IARC 1983; ADB 1987; Anonymous 1989; Schoubroeck *et al.* 1989; Anonymous 1991; Canton *et al.* 1991; Behm *et al.* 1992; Kleveno *et al.* 1992; Oshiro *et al.* 1993; Tomlin 1994) and from several data bases (DGSV, EPA, IRPTC, UNA, UNED). In a few cases missing data were estimated with the help of other properties and regression analysis (Rao & Davidson 1980; Green & Karickhoff 1990). For instance, missing values for K_{oc} were estimated with the help of the octanol/water distribution coefficient (K_{ow}) and a regression equation found by Rao & Davidson (1980). For all biocide properties low, average and high values are listed in Appendix 4.

Low, high and average values for biocide properties were used to calculate "average", "optimistic" and "pessimistic" *AF*-values. For instance, lowest values for half-lives and precipitation were combined with the highest values for sorption coefficients to organic carbon, organic carbon contents in the soil and Henry's constants, resulting in the lowest ("optimistic") estimate for biocide leaching risk. The "average", "optimistic" and "pessimistic" *AF*-values showed considerably different rankings of biocides for leaching risk. Generally, low *AF*-values were obtained, except for terrain type *s4*, which has a very shallow ground water level if no drainage system is constructed. For the other terrain types the "average" *AF* was always lower than 0.1, the "pessimistic" *AF* lower than 0.5, and the "optimistic" *AF* lower than 0.0001. The only exception is the *AF*-value for carbofuran, which has a low K_{oc} combined with a relatively long half-life.

The risk of biocide leaching to ground water level was calculated by multiplying the *AF*-indices of all biocides with the amount of active ingredient (a.i.) used per crop activity:

$$lb_{l,c,s} = \sum_{b} AF_{b,s} \times amount\ a.i._{b,l,c,s} \tag{3.15}$$

In which: $AF_{b,s}$ = *AF*-index (kg^{-1})
b = biocide
c = production technique
l = form of land use
$lb_{l,c,s}$ = biocide leaching risk (-)
s = terrain type

Figure 3.9 shows examples of the biocide leaching risk. The differences between "average", "optimistic" and "pessimistic" estimates are extremely large owing to the uncertainty in biocide properties (Figure 3.9A). Differences in leaching risks between terrain types are mainly caused by differences in ground water level (Figure 3.9B). The differences in risk of biocide leaching between production techniques correspond more or less with the differences in biocide use (Figure 3.9C). The proportional differences between "average", "optimistic" and "pessimistic" estimates are not identical for all production activities. For instance, "pessimistic" estimates of biocide leaching risk are five to 1800 times higher than the "average" biocide leaching risk. This is mainly caused by the nonlinear structure of the *AF*-index and differences in relative uncertainties in half-lives and sorption coefficients to organic carbon. As for nutrient needs and loss, it can be concluded that to estimate absolute values of biocide leaching risk the uncertainties in agro-ecological parameters and the forms of land use are more important than the production techniques. The effect of terrain type is in the same order as the effect of forms of land use, because ground water level strongly affects the risk of biocide leaching.

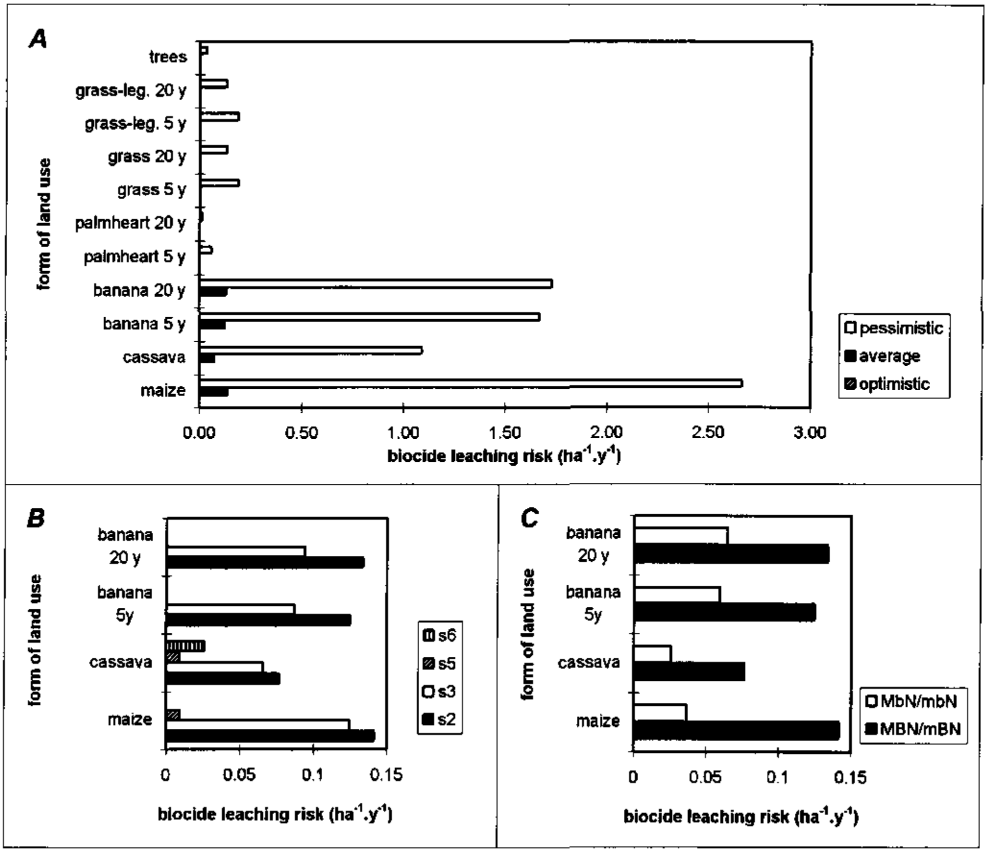

Figure 3.9 Risk of biocide leaching of several crop activities in the single-period MGLP-model. A: for yield-oriented production on terrain type *s2*, calculated with "average", "optimistic" and "pessimistic" coefficients; B: "average" biocide leaching risk for yield-oriented production on various terrain types; C: "average" biocide leaching risk for various production techniques on terrain type *s2*.

Uncertainty about biocide properties arises partly from the methods used to determine them (Taylor & Spencer 1990). Laboratory and field measurements of half-lives can differ considerably, while spatial variability in the field is probably also very important for the degradation of biocides (Chee Chow Lee 1987; Jaquess 1991). Besides, for some biocides properties were not measured, but approximated with regression analysis. Small changes in values of half-lives and sorption coefficients to organic carbon change the *AF*-index dramatically, because relations between parameters are not linear. A 10 % change in the average sorption coefficient resulted in more than 1000 % change in the "average" *AF*-value, whereas a 10 % change in the lowest sorption coefficients resulted in up to 300 % change in the "pessimistic" *AF*-value. The consequences of changes in the depth to ground water, organic carbon content, bulk density, and net ground water recharge are in the same order of magnitude. Uncertainties in Henry's coefficients and soil air-filled porosity hardly influence the *AF*-index, unless the soil organic carbon content and sorption coefficient are extremely low.

Several aspects, important to biocide leaching risk, cannot be taken into account with the *AF*-index, such as transport by run-off and by-pass flow, volatilization, uptake by plants, adsorption to clay minerals (only adsorption to organic carbon is considered in *AF*-index), heterogeneity of soils and daily variation in weather conditions, the formulation of the biocide and application method, interaction between biocides (Oudejans 1991) and leaching of biocide residues. With the help of dynamic models that simulate the behaviour of biocides in the soil, these aspects could be included. However, knowledge of most of these processes is either scarce or insufficient data are available for quantification of the processes. The *AF*-index is a simple method with only few data requirements. Kleveno *et al.* (1992) showed that the *AF*-index allows a first comparison of the relative leaching risk of biocides in various conditions.

4 DESCRIPTION OF THE SINGLE-PERIOD MGLP-MODEL FOR EXPLORATION OF SUSTAINABLE LAND USE OPTIONS

In this chapter the mathematical description of the single-period MGLP-model is presented and assumptions underlying this model are specified. First, the various production activities are defined (Section 4.1). Section 4.2 presents all objective functions, and technical and value-driven constraints. Explanations of the codes for indices (subscript type), coefficients (small type) and variables (capitals) are presented in Tables 4.1, 4.2 and 4.3, respectively, at the end of the chapter.

4.1 Definition of production activities

A MGLP-model helps to find an optimum combination of production activities, under a number of constraints and objective functions. Two main groups of production activities can be distinguished in this study: crop activities and livestock activities. A crop activity ($CLA_{l,c,s}$) uses exactly one hectare and is characterized by a form of land use ($_l$), production technique ($_c$) and terrain type ($_s$). Several perennial crops are included in this study. For all but tree plantations, the length of the growing period can vary. For instance, banana plantations may be abandoned or replanted after a few years, but also complete replanting may take place only after 20 years or more of continued cultivation. In the single-period model the different lengths of growing periods (5, 10, 15, or 20 years) are included as different forms of land use (e.g. for banana $_{l=ba5}$, $_{l=ba10}$, $_{l=ba15}$ and $_{l=ba20}$). A livestock activity ($AN_{au,d}$) is a combination of an animal unit ($_{au}$) and a feeding pattern ($_d$). All production activities are described with coefficients, representing average yearly inputs and outputs.

4.2 Mathematical description of objective functions and constraints

In Chapter 2, Table 2.2, the objective functions and their relevance in the five policy views were shown. Below, the mathematical description of these objective functions is presented. The objective functions are subject to various constraints. These constraints are presented in thematic groups. Several constraints in the MGLP-model are balances, and most constraints are of a technical nature. If a constraint is value-driven, it is indicated that the bound may differ per policy view (see also Table 2.3). The objective functions serve as value-driven constraints if they are not optimized.

Objective functions

Minimization of total area under agriculture (*ARM*; Equation 4.1): the area available for nature is maximized if the cropped area summed over all crop activities ($CLA_{l,c,s}$) is minimized.

$$ARM = \sum_{l}\sum_{c}\sum_{s} CLA_{l,c,s} \tag{4.1}$$

Minimization of total biocide leaching risk (*BLM*; Equation 4.2): leached biocides can be transported to other areas with ground water, drainage water or river water. This may pose threads to human beings, animals and plants. The total biocide leaching risk is calculated as the biocide leaching risk per hectare ($lb_{l,c,s}$) multiplied by the cultivated area, summed over all crop activities. The use of biocides in livestock activities is very low and very small amounts will reach the soil, therefore biocide use and biocide leaching in livestock activities were assumed to be zero. During sensitivity analyses (Section 5.3) "optimistic", "average" or "pessimistic" estimates were used for biocide leaching risk per hectare.

$$BLM = \sum_{l}\sum_{c}\sum_{s} CLA_{l,c,s} \times lb_{l,c,s} \tag{4.2}$$

Minimization of total biocide use (*BUM*; Equation 4.3): a considerable number of poisonings occur each year. Many of these accidents can be avoided by more careful handling, although contact with biocides will always imply some risk. The total amount of applied biocides is used as a measure of the safety of working and living conditions and of environmental impact. The total biocide use is calculated as the biocide use per hectare ($ub_{l,c,s}$) multiplied by the cultivated area, summed over all crop activities.

$$BUM = \sum_{l}\sum_{c}\sum_{s} CLA_{l,c,s} \times ub_{l,c,s} \tag{4.3}$$

Minimization of average biocide use per hectare (*BUHA*; Equation 4.4): application of large amounts of biocides per unit area may be more harmful, than spreading the same amount over a larger area. Minimization of average biocide use per hectare is a nonlinear function, since both biocide use and agricultural area are variables in the MGLP-model. However, it can be approximated with Equation 4.4, in which *buref* represents the minimum biocide use per hectare in all crop activities (0.12 kg active ingredient.$ha^{-1}.y^{-1}$ in the present study).

$$BUHA = BUM - buref \times ARM \qquad 4.4$$

Minimization of total N-loss (*NLM*; Equation 4.5): nutrients lost through erosion, leaching, volatilization, etc. can be transported to other areas. This may affect, e.g. plant species composition in protected areas. Total N-loss is calculated as the N-loss per hectare ($ln_{l,c,s}$) multiplied by the cultivated area, summed over all crop activities. The production of manure and the subsequent loss of nitrogen from manure is included in the $ln_{l,c,s}$ of the pasture activities. During sensitivity analyses "optimistic", "average" or "pessimistic" estimates were used for N-loss per hectare.

$$NLM = \sum_{l}\sum_{c}\sum_{s} CLA_{l,c,s} \times ln_{l,c,s} \qquad 4.5$$

Maximization of total employment (*EMP*; Equation 4.6): employment can be seen as a measure of the distribution of income over the population. Total employment, measured in man years of 225 working days of eight hours, is calculated as the labour requirement per hectare ($lab_{l,c,s}$) multiplied by the cultivated area, summed over all crop activities plus the labour requirement per animal unit ($lab_{au,d}$) multiplied by the number of animal units, summed over all livestock activities ($AN_{au,d}$).

$$EMP = \sum_{l}\sum_{c}\sum_{s} CLA_{l,c,s} \times lab_{l,c,s} + \sum_{au}\sum_{d} AN_{au,d} \times lab_{au,d} \qquad 4.6$$

Maximization of total economic surplus from agriculture (*ESP*; Equation 4.7): the economic surplus is used as a measure of the profit obtained from agricultural production. Total economic surplus (*ESP*) is calculated as the revenue from export minus the production costs and minus imports. Revenue from export is calculated as the exported physical amount of products (EX_{cp} and EX_{ap}) multiplied by a unit price ($price_{cp}$ and $price_{ap}$), summed over all crop products ($_{cp}$) and animal products ($_{ap}$). In the case of negative values for EX_{cp} and Ex_{ap}, products are imported. Production costs comprise the total costs of labour input (*LABCOST*), mineral fertilizer input (*MFCOST*), biocide input (*BCOST*), input of crop and animal products in livestock activities (*INLCOST*), and other inputs (*RCOST*). During sensitivity analyses "high", "average" or "low" prices were used (Section 5.4).

$$ESP = \sum_{cp} EX_{cp} \times price_{cp} + \sum_{ap} EX_{ap} \times price_{ap} - MFCOST - BCOST - INLCOST - LABCOST - RCOST \quad 4.7$$

Maximization of average income per person is not a linear function. It can be approximated by the minimization of *INP* (Equation 4.8), in which *inref* represents the highest income per person as obtained in the zero-round (0.655 10^6 colon.person^{-1}.y^{-1} in case of runs with "average" coefficients; Section 5.2). *Inref* x *POP*, therefore, represents the highest *GDP* that can be obtained for a certain population size.

$$INP = inref \times POP - GDP \quad 4.8$$

Area constraints

Crops are only cultivated on suitable terrain types. The cultivated area per terrain type summed over all crop activities ($CLA_{l,c,s}$) cannot be more than the available area per terrain type ($area_s$).

$$\sum_{l} \sum_{c} CLA_{l,c,s} \leq area_s \quad 4.9$$

A maximum was set to the cultivated area per crop (Equation 4.10). Some diversification is preferred to reduce financial risks and the risk of severe pest and disease development. Although this maximum is a value-driven, it was kept equal for all policy views.
For cassava ($_{l=ca}$), maize ($_{l=ma}$) and tree plantations ($_{l=wt}$):

$$\sum_{c} \sum_{s} CLA_{l,c,s} \leq maxar \quad 4.10a$$

For the quantification of a maximum area for banana ($_{l=ba5,\ ba10,\ ba15,\ ba20}$), palmheart ($_{l=pa5,\ pa10,\ pa15,\ pa20}$), grass pasture ($_{l=gi5,\ gi10,\ gi15,\ gi20}$) and grass-legume pasture ($_{l=gl5,\ gl10,\ gl15,\ gl20}$) no distinction is made between different lengths of growing periods. For banana (similar constraints used for palmheart, grass pasture and grass-legume pasture):

$$\sum_{l=ba5}^{ba20} \sum_{c} \sum_{s} CLA_{l,c,s} \leq maxar \quad 4.10b$$

Physical inputs and outputs of crop activities

Totals for inputs and outputs are calculated as the input or output per hectare multiplied by the cultivated area, summed over all activities. For inputs such as plant material, implements, vaccinations, machinery for construction of drainage systems, only aggregate costs are included (Appendix 6). A limited number of inputs (nutrients, biocides) are included in physical units in the single-period MGLP-model. The total input of biocides is calculated with Equation 4.3. The physical input of nutrients (UF_n) is calculated as the requirement per hectare ($uf_{n,l,c,s}$) multiplied by the cultivated area summed over all crop activities (Equation 4.11). During sensitivity analysis the "average" values of $uf_{n,l,c,s}$ were replaced by "optimistic" or "pessimistic" values.

$$UF_n = \sum_l \sum_c \sum_s CLA_{l,c,s} \times uf_{n,l,c,s} \qquad 4.11$$

The total physical production ($TPROD$) of crop products ($_{cp}$) is calculated as the average yearly production per hectare of a crop product ($yield_{cp,l,c,s}$) multiplied by the cultivated area, summed over all crop activities (Equation 4.12).

$$TPROD_{cp} = \sum_l \sum_c \sum_s CLA_{l,c,s} \times yield_{cp,l,c,s} \qquad 4.12$$

Physical inputs and outputs of livestock activities

Livestock feeds on grass pasture ($_{cp=gig}$) or grass-legume pasture ($_{cp=glg}$), possibly supplemented with maize ($_{cp=mai}$), banana residues ($_{cp=banr}$) or cassava residues ($_{cp=casr}$). It was assumed that the regional grass pasture production ($TPROD_{cp=gig}$) and the regional grass-legume production ($TPROD_{cp=glg}$) are in equilibrium with the consumption by livestock ($lneed_{cp,au,d}$; Equation 4.13). This implies that pasture production is only selected if livestock activities ($AN_{au,d}$) are selected as well. The amount needed of pasture DM depends, among others, on the protein concentration. For the "optimistic" and "pessimistic" estimates of fertilizer requirements different nutrient concentrations were used. Consequently, the feeding value of crop products changed, as well as the required input of crop products in livestock activities ($lneed_{cp,au,d}$). This meant that, during sensitivity analysis, $lneed_{cp,au,d}$ changed simultaneously with the values for fertilizer requirement (Section 5.3).
For grass pasture ($_{cp=gig}$) and grass-legume pasture ($_{cp=glg}$):

$$TPROD_{cp} = \sum_{au}\sum_{d} AN_{au,d} \times Ineed_{cp,au,d} \qquad 4.13$$

The total amounts of maize, banana residues and cassava residues consumed by livestock ($INL_{cp=mai}$, $INL_{cp=banr}$, and $INL_{cp=casr}$, respectively) are calculated by multiplying the input requirement per animal unit ($Ineed_{cp,au,d}$) by the number of animal units, summed over all livestock activities (Equation 4.14). In some livestock activities also animal products ($_{ap}$) are needed as input: for fattening, calves ($_{ap=clvi}$) are bought and in the first months milk ($_{ap=mlk}$) is needed to feed them. The total inputs of animal products are calculated in a similar way as for crop products.

For $_{cp=mai}$, $_{cp=banr}$ and $_{cp=casr}$ (similar constraints for $_{ap=clvi}$ and $_{ap=mlk}$):

$$INL_{cp} = \sum_{au}\sum_{d} AN_{au,d} \times Ineed_{cp,au,d} \qquad 4.14$$

It was assumed that banana and cassava residues are not imported into the NAZ for livestock production, because they are very bulky, and consequently transport is expensive (Equation 4.15).

For $_{cp=banr}$ and $_{cp=casr}$:

$$TPROD_{cp} \geq \sum_{au}\sum_{d} AN_{au,d} \times Ineed_{cp,au,d} \qquad 4.15$$

The total physical production of animal products ($TPROD_{ap}$) is calculated as the average yearly physical production per animal unit ($yield_{ap,au,d}$) multiplied by the number of animal units, summed over all livestock activities (Equation 4.16).

$$TPROD_{ap} = \sum_{au}\sum_{d} AN_{au,d} \times yield_{ap,au,d} \qquad 4.16$$

Employment and population constraints

A minimum employment in agriculture (minemp) is included (Equation 4.17). The required level differs per policy view.

$$EMP \geq minemp \qquad 4.17$$

It was assumed that the population size (*POP*) in the NAZ is determined by the local population (*popl*) and immigration. The local population (*popl*) was assumed to be the population in 2020 with a growth rate of 2 % between 1990 and 2020 (275,418 persons). When labour requirement is high, immigration can take place and, consequently, the population increases. At present, one out of each 5.7 (= *cemppop*) persons in the NAZ is working in the agricultural sector (Chapter 2). It was assumed that this percentage of persons working in the agricultural sector (17.5 %) will not increase in the future (Equation 4.18). No maximum was set to immigration.

$$POP \geq popl \qquad 4.18a$$

$$POP \geq EMP \times cemppop \qquad 4.18b$$

Consumption constraints

The amounts of crop products and animal products consumed per person ($cons_{cp}$ and $cons_{ap}$) were based on the consumption pattern in 1991 (Jansen *et al.* 1996), and the energy and protein requirements given by Passmore *et al.* (1978). Details are presented in Appendix 7. During sensitivity analyses $cons_{cp}$ and $cons_{ap}$ changed simultaneously with the fertilizer-N requirement, because different N-concentrations (and thus different protein concentrations) were used for the "optimistic" and "pessimistic" estimates of fertilizer requirement. The total consumption of crop and animal products ($CONS_{cp}$ and $CONS_{ap}$) is calculated by multiplying the consumption per person by the population size (Equation 4.19; similar constraints for animal products ($_{ap}$)):

$$CONS_{cp} = POP \times cons_{cp} \qquad 4.19$$

Export and import constraints

The total export and import of crop and animal products (EX_{cp} and EX_{ap}) of the region are calculated as the difference between production in the region and use of products for human consumption ($CONS_{cp}$ and $CONS_{ap}$). For some crop products and animal products also the use by livestock activities (INL_{cp} and INL_{ap}) in the region has to be taken into account. In other words, it was assumed that all products produced in the region are exported, except those products consumed by the population or used for livestock production. The use of products can be higher than the production in the region (Equation 4.20). In that case, products are imported. No self-sufficiency in agricultural products was required.

For banana ($_{cp=ban}$), cassava ($_{cp=cas}$), palmheart ($_{cp=pal}$), pulpwood ($_{cp=wop}$) and timber ($_{cp=wot}$), and similar constraints for beef ($_{ap=bf}$) and calves ($_{ap=clv}$):

$$EX_{cp} = TPROD_{cp} - CONS_{cp} \qquad 4.20a$$

For maize ($_{cp=mai}$), and a similar constraint for milk ($_{ap=mlk}$):

$$EX_{cp} = TPROD_{cp} - CONS_{cp} - INL_{cp} \qquad 4.20b$$

It was assumed that pasture DM is not imported or exported, nor are crop residues ($maxex_{cp}$ = 0). In some policy views a minimum export of products (*$minex_{cp}$* and *$minex_{ap}$*) is required (Equation 4.21; similar constraints for animal products ($_{ap}$)):

$$minex_{cp} \leq EX_{cp} \leq maxex_{cp} \qquad 4.21$$

Economic constraints

The total costs of labour input (*LABCOST*), fertilizer input (*MFCOST*), biocide input (*BCOST*), input of crop and animal products in livestock activities (*INLCOST*), and other inputs (*RCOST*) are calculated separately (Equations 4.22 to 4.26). For the labour costs an average wage per man year (*pricelab*) was assumed. For mineral N, P and K an average price per kg active ingredient (*$pricef_n$*) was used (Appendix 6). For biocides an estimate of total costs per hectare was made by multiplying the amounts of biocides applied per hectare with their average price per kg active ingredient (*$bcost_{l,c,s}$*; Appendix 6). *BCOST* represents the costs of biocides summed over all crop activities. *INLCOST* represents the total costs of transport of crop residues (*pricetr* per tonne) and the import of calves (*priceclv* per calf). Transportation costs of other inputs than banana and cassava residues were assumed to be negligible. The costs of maize and milk for livestock activities are included through the production costs or through the costs of import of these products. The costs of other inputs (*RCOST*) comprise two components: i. *$rcost_{l,c,s}$* represents the aggregate costs per crop activity for inputs such as machinery, planting material, implements, fencing; ii. *$rcost_{au,d}$* represents the aggregate costs per livestock activity of inputs such as implements, vaccinations, milking machine.

$$LABCOST = EMP \times pricelab \qquad 4.22$$

$$MFCOST = \sum_{n} UF_{n} \times pricef_{n} \quad 4.23$$

$$BCOST = \sum_{l}\sum_{c}\sum_{s} CLA_{l,c,s} \times bcost_{l,c,s} \quad 4.24$$

$$INLCOST = INL_{cp(banr)} \times pricetr + INL_{cp(casr)} \times pricetr + INL_{ap(clvl)} \times price_{ap(clv)} \quad 4.25$$

$$RCOST = \sum_{l}\sum_{c}\sum_{s} CLA_{l,c,s} \times rcost_{l,c,s} + \sum_{au}\sum_{d} AN_{au,d} \times rcost_{au,d} \quad 4.26$$

The minimum required economic surplus (*mines*) differs per policy view (Equation 4.27).

$$ESP \geq mines \quad 4.27$$

The average income per person from agricultural activities is obtained by dividing the gross domestic product from agriculture (*GDP*) by the population. *GDP* is estimated as the economic surplus plus the labour costs plus the value of consumed agricultural products (Equation 4.28). A minimum average income per person (*mininc*) is included in all policy views. However, this minimum differs per policy view (Equation 4.29).

$$GDP = ESP + LABCOST + \sum_{cp} CONS_{cp} \times price_{cp} + \sum_{ap} CONS_{ap} \times price_{ap} \quad 4.28$$

$$GDP \geq POP \times mininc \quad 4.29$$

Table 4.1 List of indices used in the single-period MGLP-model.

Index	Description	Elements
ap	animal product	milk ($_{ap=mlk}$); calves (output: $_{ap=clv}$; input: $_{ap=clvi}$); beef ($_{ap=bf}$)
au	animal unit	milking cow unit with calf for replacement ($_{au=mcu}$); beef cattle unit 1 ($_{au=bcu}$); beef cattle unit 2, with milk production for calves included ($_{au=bcup}$)
c	production technique	mechanized yield-oriented production ($_{c=MBN}$); manual yield-oriented production ($_{c=mBN}$); mechanized environment-oriented production, reduced biocide use ($_{c=MbN}$); manual environment-oriented production, reduced biocide use ($_{c=mbN}$); mechanized environment-oriented production, reduced N-loss ($_{c=MBn}$); manual environment-oriented production, reduced N-loss ($_{c=mBn}$)
cp	crop product	bananas ($_{cp=ban}$); banana residues ($_{cp=banr}$); cassava ($_{cp=cas}$); cassava residues ($_{cp=casr}$); DM from grass pasture ($_{cp=gig}$); DM from grass-legume pasture ($_{cp=glg}$); maize ($_{cp=mai}$); palmhearts ($_{cp=pal}$); pulpwood ($_{cp=wop}$); timber ($_{cp=wot}$)
d	feeding pattern	100 % pasture ($_{d=po}$); 90 % pasture + 10% banana ($_{d=ba10}$); 80 % pasture + 20 % banana ($_{d=b20}$); 90 % pasture + 10 % maize ($_{d=m10}$); 80 % pasture + 20% maize ($_{d=m20}$); 90 % pasture + 10 % cassava ($_{d=c10}$)
l	form of land use	banana ($_{l=ba5,\ l=ba10,\ l=ba15,\ l=ba20}$); cassava ($_{l=ca}$); maize ($_{l=ma}$); palmheart ($_{l=pa5,\ l=pa10,\ l=pa15,\ l=pa20}$); grass pasture ($_{l=gi5,\ l=gi10,\ l=gi15,\ l=gi20}$); grass-legume pasture ($_{l=gl5,\ l=gl10,\ l=gl15,\ l=gl20}$); tree plantations ($_{l=wt}$)
n	nutrient	nitrogen ($_{n=N}$), phosphorus ($_{n=P}$), potassium ($_{n=K}$)
s	terrain type	$_{s=s1}$ to $_{s=s7}$

Table 4.2 List of coefficients used in the single-period MGLP-model for the NAZ. All coefficients are expressed per year.

Coefficient	Description	Unit of measurement
$area_s$	available area per terrain type	ha
$bcost_{l,c,s}$[d]	costs of biocide use per crop activity	colon.ha^{-1}
buref	reference value for biocide use	kg active ingredient.ha^{-1}
cemppop	coefficient for conversion of employment to population	man year.person^{-1}
$cons_{cp}$[a]	human consumption of crop products	tonne fresh product.person^{-1}, tonne DM.person^{-1},
$cons_{ap}$[a]	human consumption of animal products	tonne fresh product.person^{-1}, number of animals.person^{-1}
inref	reference value for income	colon.person^{-1}
$lab_{l,c,s}$	labour requirement per crop activity	man year.ha^{-1}
$lab_{au,d}$	labour requirement per livestock activity	man year.animal unit^{-1}
$lb_{l,c,s}$[a]	biocide leaching risk per crop activity	ha^{-1}

Table 4.2 Continued.

Coefficient	Description	Unit of measurement
$ln_{l,c,s}$ [a]	N-losses per crop activity	$kg.ha^{-1}$
$lneed_{cp,au,d}$ [a]	crop product need per livestock activity	tonne fresh product.animal $unit^{-1}$, tonne DM.animal $unit^{-1}$
$lneed_{ap,au,d}$ [a]	animal product need per livestock activity	tonne fresh product.animal $unit^{-1}$, number of calves.animal $unit^{-1}$
maxar	maximum area per crop	ha
$maxex_{cp}$	maximum export of crop products from the NAZ	tonne fresh product, tonne DM
$maxex_{ap}$	maximum export of animal products from the NAZ	number of animals, tonne fresh product
minemp	minimum required employment in agriculture	man year
mines	minimum required economic surplus from agriculture	colon[d]
$minex_{cp}$	minimum required export of crop products from the NAZ	tonne fresh product, tonne DM
$minex_{ap}$	minimum required export of animal products from the NAZ	number of animals, tonne fresh product
mininc	minimum required income per person	$colon.person^{-1}$
popl	minimum population in the NAZ	number of persons
$price_{cp}$ [b]	price of crop products	colon.tonne fresh $product^{-1}$, colon.tonne DM^{-1}
$price_{ap}$ [b]	price of animal products	$colon.animal^{-1}$, colon.tonne fresh $product^{-1}$
$pricef_{n}$	price of mineral fertilizer	colon.kg N^{-1}, colon.kg P^{-1}, colon.kg K^{-1}
pricelab	price of labour input	colon.man $year^{-1}$
pricetr	price of transport	colon.tonne fresh $product^{-1}$
$rcost_{l,c,s}$	costs of machinery, implements, seeds, etc. per crop activity	$colon.ha^{-1}$
$rcost_{au,d}$	costs of machinery, implements, vaccinations, etc. per livestock activity	colon.animal $unit^{-1}$
$ub_{l,c,s}$	biocide use per crop activity	kg active $ingredient.ha^{-1}$
$uf_{n,l,c,s}$ [a]	mineral fertilizer use per crop activity	kg $N.ha^{-1}$, kg $P.ha^{-1}$, kg $K.ha^{-1}$
$yield_{cp,l,c,s}$	physical yield per crop activity	tonne fresh $product.ha^{-1}$, tonne $DM.ha^{-1}$,
$yield_{ap,au,d}$ [c]	physical yield per livestock activity	tonne fresh product.animal $unit^{-1}$, number of animals.animal $unit^{-1}$

[a] "optimistic", "average", and "pessimistic" estimates available;
[b] "high", "average" and "low" prices available;
[c] livestock production affected by "optimistic", "average" and "pessimistic" nutrient concentrations in crop products;
[d] US$1 = 130 colon in 1990 (Schipper, 1996).

Table 4.3 List of variables used in the single-period MGLP-model for the NAZ. All variables are expressed per year.

Variable	Description	Unit of measurement
$AN_{au,d}$	livestock activity	animal unit[a]
ARM	total area under agriculture	ha
$BCOST$	total costs of biocide use	colon[b]
BLM	total biocide leaching risk	-
$BUHA$	auxiliary variable for calculating average biocide use per unit area	kg active ingredient
BUM	total biocide use	kg active ingredient
$CLA_{l,c,s}$	crop activity	ha
$CONS_{cp}$	total human consumption per crop product	tonne fresh product, tonne DM[c]
$CONS_{ap}$	total human consumption per animal product	tonne fresh product, number of animals[c]
EMP	total employment in agriculture	man year
ESP	total economic surplus from agriculture	colon
Ex_{cp}	total export from or import in the NAZ per crop product	tonne fresh product, tonne DM
Ex_{ap}	total export from or import in the NAZ per animal product	tonne fresh product, number of animals
GDP	total gross domestic product from agriculture	colon
INL_{cp}	total input per crop product in livestock activities	tonne fresh product
INL_{ap}	total input per animal product in livestock activities	tonne fresh product, number of calves
$INLCOST$	total costs of input of crop and animal products in livestock activities	colon
INP	auxiliary variable for calculating average per capita income	colon.person^{-1}
$LABCOST$	total costs of labour input	colon
$MFCOST$	total costs of mineral fertilizer use	colon
NLM	total N-loss	kg
POP	population size	persons
$RCOST$	total costs of plant material, machinery, vaccinations, etc.	colon
$TPROD_{cp}$	total physical production per crop product	tonne fresh product, tonne DM
$TPROD_{ap}$	total physical production per animal product	tonne fresh product, number of animals
UF_n	total mineral fertilizer use per nutrient	kg N, kg P, kg K

[a] animal unit = one average animal, with or without calf for replacement (Appendix 2);
[b] US$1 = 130 colon in 1990 (Schipper, 1996);
[c] production of bananas, cassava, maize, palmhearts and milk is described in tonnes fresh product; production of pasture and wood in tonne DM; production of beef and calves is described in number of animals.

5 RESULTS OF LAND USE OPTIMIZATION AND SENSITIVITY ANALYSIS WITH THE SINGLE-PERIOD MODEL

In this chapter the results of the optimization runs with the single-period MGLP-model for the NAZ, described in Chapter 4, are presented and discussed. To start with, in Section 5.1 the outer boundaries of the "playing field" are determined in the first round of optimization runs (the zero-round). In Section 5.2 the results of the single-period MGLP-model with "average" coefficients are presented per policy view. The results for each policy view are characterized by a specific combination of objective function values and selected production activities, i.e. a land use scenario. Details of the steps after the zero-round and details of the land use scenarios per policy view are presented in Appendix 8.

Sensitivity analyses are performed to study the effect of uncertainties on land use scenarios. In Section 5.3 the sensitivity of these scenarios to uncertainties in agro-ecological coefficients concerning nutrients and biocides is presented. As LP models were originally developed for economic analysis (Hazell & Norton 1986), mainly the model sensitivity to economic aspects was analysed. Section 5.4 presents an example of the sensitivity of the single-period MGLP-model to changes in prices. In Sections 5.3 and 5.4, the consequences for land use scenarios of uncertainties in agro-ecological coefficients and prices are also compared with the consequences of differences between forms of land use, production techniques and terrain types. In Section 5.5 the sensitivity of the single-period model to uncertainties in agro-ecological coefficients and prices are compared. Further, long-term options for land use in the NAZ are discussed. Abbreviations in italics refer to the indices, coefficients and variables as presented in Chapter 4.

5.1 Extreme values of objective functions

In the first step of optimization (the zero-round) the extreme values of the objective function values are determined by optimizing each of the objective functions in separate runs, putting no or only light bounds on value-driven constraints. This zero-round indicates the optimum and worst values that can be obtained for each objective function. In other words, the initial freedom of choice for the stakeholders or the outer boundaries of the "playing field" are determined.

In the zero-round of the single-period MGLP-model for the NAZ no bounds were put on value-driven constraints. This meant that no maximum area per crop, minimum income, minimum employment, etc. were used. The technical restrictions on economic surplus and income per person (≥ 0 colon.y^{-1}) and the consumption of agricultural products by the local population resulted in the selection of at least some agricultural activities in all optimization runs. Table 5.1 presents the optimum and worst values for all objective functions obtained with the single-period MGLP-model with "average" coefficients. The optimum and worst values of all objective functions differ considerably, indicating that there is ample room for policy. The total biocide use, biocide leaching risk, and economic surplus show the widest ranges. Of course, the optimum values of the objective functions cannot be obtained simultaneously. During the subsequent rounds of optimization per policy view the trade-offs between the different objective functions are calculated (Section 5.2 and following).

Table 5.1 Extreme values of the objective functions for the single-period MGLP-model with "average" agro-ecological coefficients and "average" prices.

Objective function	*Optimum value*	*Worst value*	*Dimension*
Area under agriculture	7,876	257,991	ha
Total biocide use[a]	1.4	1,682	tonne a.i. y^{-1}
Biocide use per unit area	0.12	6.52	kg a.i. $ha^{-1}.y^{-1}$
Total biocide leaching risk	0	11,220	y^{-1}
Total N-loss	1,086	52,028	tonne.y^{-1}
Total employment	151,330	3,314	man year.y^{-1}
Total economic surplus[b]	163,368	0	10^6 colon.y^{-1}
Per capita income	0.655	0.025	10^6colon.$person^{-1}.y^{-1}$

[a] biocide use measured in kg active ingredient (a.i.);

[b] the colon is the currency of Costa Rica, in 1990 US$1=130 colon (Schipper 1996).

To put the results of the zero-round in perspective, they are compared with actual figures on agricultural production. In most cases, the current situation in the NAZ is far from the extreme values presented in Table 5.1. An exception is the maximum area used for agriculture, which is not far from the worst value. According to Stoorvogel & Eppink (1995) about 175,000 ha were used for agriculture and pasture in 1984. An additional 207,000 ha were classified as extensive agriculture (mainly pasture). At present, most suitable land outside the buffer zone and protected areas in the NAZ is utilized. However, the potential of the land is not fully utilized, as has been indicated already in the quantitative land evaluation (Section 3.1.2): the calculated potential and water-limited yields are much higher than the yields obtained at present.

Biocide use has increased rapidly in Costa Rica. According to data from B. Valverde (personal communication, CATIE), in 1993 the total biocide use in Costa Rica was 7,860 tonnes active ingredient (import -export). In 1982-1984 the total biocide use was only 3,667 tonnes per year (WRI 1992). Data for individual regions within Costa Rica are not available. However, when we assume an average biocide use of 6 kg active ingredient per year per hectare arable land (Wesseling *et al.* 1993), the total annual biocide use in the NAZ would be about 1,050 tonnes active ingredient. At present, the largest amounts of biocides are used in banana plantations. More efficient use of biocides is possible and part of the biocides can be replaced by alternatives (Section 3.4).

In 1989, the average biocide use in Costa Rica was about 6 kg active ingredient per year and per hectare of arable land, being twice the amount used in intensive agricultural regions in industrialized countries (Wesseling *et al.* 1993). This high value in Costa Rica is caused, among others, by the high biocide use in banana plantations, of which more than 95 % are situated in the Atlantic Zone of Costa Rica. The optimum value in the zero-round shows that biocide use per hectare can be strongly reduced by selecting other types of land use. In palmheart, pasture and tree plantations small amounts of biocide are used. In banana, cassava, and maize production considerably more is used. Also the production technique affects the average biocide use per hectare.

No data on current total biocide leaching in the NAZ are available. Vega (1991) reported several cases of mortality of fauna caused by biocides. It is, however, not clear whether these were caused by leaching of biocides. Most likely, these were caused by improper handling (run off, poorly directed application by aeroplanes, cleaning of equipment in rivers, etc.). Although biocides are applied year round, a survey of river water in the NAZ in 1987-1988 resulted in only a few samples with identifiable residues of organochlorine and organophosporus compounds. Generally, concentrations were lower than expected for the heavy spraying (Von Dueseln 1993). Dilution because of heavy rainfall is mentioned as a cause for the low concentrations of biocides in the river water, but also rapid degradation under the influence of the high temperatures in the NAZ may contribute. The range between the extreme values in Table 5.1 shows that the risk of biocide leaching can be reduced dramatically by selecting other types of land use.

No data on total N-loss in the NAZ are available. Precipitation in the NAZ is very high and in some crops large amounts of N are applied, therefore the total N-loss is probably considerable. The estimated current N-loss in the subregion Neguev is 25.8 kg $N.ha^{-1}.y^{-1}$ (Stoorvogel 1995). This is an average of intensively and extensively used land. The "average" N-loss in my study ranges from 45 to 485 kg $N.ha^{-1}.y^{-1}$.

In 1990, the estimated employment in agriculture in the NAZ was 25,280 man year.y^{-1}. This employment was obtained by assuming that 35 % of the population is economically active and 50 % is working in agriculture, using a 5.7 % unemployment rate (Chapter 2). The values in Table 5.1 are far from this current employment. The lowest figure is achieved when the area for agriculture is minimized; the highest employment is obtained when mainly manual production techniques are selected.

The estimated economic surplus of agriculture in 1992 in the NAZ was about 5.0 10^9 colon (Gross Domestic Product - labour costs). The optimum value is 32 times higher. This optimum value was obtained under the assumption of constant prices. Large production volumes in the NAZ may influence prices negatively. However, the economic surplus from agriculture can clearly increase.

In 1992, the income per person in Costa Rica was US$1960 (World Bank 1994). The estimated income per person from agriculture in 1992 in the NAZ is 89.10^3 colon (US$686; 35 % of GDP from agriculture). For Costa Rica as a whole the average income from agriculture is 38.10^3 colon per year (US$294; 15 % of income; World Bank 1994). The maximum value obtained in the zero-round (655 10^3 colon.$person^{-1}$.y^{-1}) is clearly higher.

The extreme values presented in Table 5.1 were obtained using "average" agro-ecological coefficients and "average" prices. To get some idea of the influence of input data on the outer boundaries, the zero-round optimization runs were also carried out with "low" and "high" product prices, and "optimistic" and "pessimistic" coefficients for nutrients and biocides (Chapter 3). All three price levels were combined with "optimistic", "average" and "pessimistic" estimates for nutrients and biocides. Table 5.2 presents the ranges that were found for the extreme values. The optimum and worst values for the biocide leaching risk, N-loss, economic surplus, and per capita income were affected most by the uncertainty in coefficients. Remarkable is that the lowest worst value for biocide leaching risk is much lower than the highest optimum value. This indicates that the uncertainty on biocide leaching risk is great, as has been observed already in Section 3.4. For the other objective functions, the differences between the optimum and worst values remain large when taking into account uncertainty.

Table 5.2 Observed ranges for optimum and worst values of objective functions during sensitivity analysis[a] in the zero-round of the single-period MGLP-model.

Objective function	Optimum value Lowest	Optimum value Highest	Worst value Lowest	Worst value Highest	Dimension
Area under agriculture	7,338	18,134	257,991	257,991	ha
Total biocide use[b]	1.2	2.1	1,367	5,021	tonne a.i. y^{-1}
Biocide use per unit area	0.12	0.12	5.30	19.5	kg a.i. $ha^{-1}.y^{-1}$
Total biocide leaching risk	0	175	7	215,937	y^{-1}
Total N-loss	389	7,251	23,265	121,219	tonne.y^{-1}
Total employment	114,135	151,346	3,088	5,729	man year.y^{-1}
Total economic surplus[c]	38,447	231,842	0	0	10^6 colon.y^{-1}
Per capita income	0.173	0.903	0.022	0.032	10^6colon.$person^{-1}.y^{-1}$

[a] sensitivity to changes in product prices ("low", "average" and "high") and to uncertainties in coefficients for nutrients and biocides ("optimistic", "average" and "pessimistic");
[b] biocide use measured in kg active ingredient (a.i.);
[c] the colon is the currency of Costa Rica, in 1990 US$1=130 colon (Schipper 1996).

5.2 Land use scenarios obtained with the single-period model and "average" coefficients

For generating land use scenarios for the five policy views, bounds were put on the value-driven constraints as presented in Table 2.3, and the relevant objective functions presented in Table 2.2 were optimized. As clear information on priorities for objectives per policy view was lacking, in the present study arbitrarily the same weights were attached to all relevant objective functions per policy view. Below, the steps followed during optimization are briefly described. In Appendix 8 the methodology is illustrated for policy view National Development (ND).

First, again the optimum and worst values of the relevant objectives per policy view are determined, but now using the bounds as presented in Table 2.3. The relative difference between these optimum and worst values is used to find an optimal compromise between the various objective functions of a policy view. For this purpose, an additional objective function is used, which simultaneously minimizes the relative deviation between a compromise and the optimum values (in % of difference between optimum and worst value). The relative deviation is defined in the following way:

$$\frac{optimum - compromise}{optimum - worst} \times 100 \qquad 5.1$$

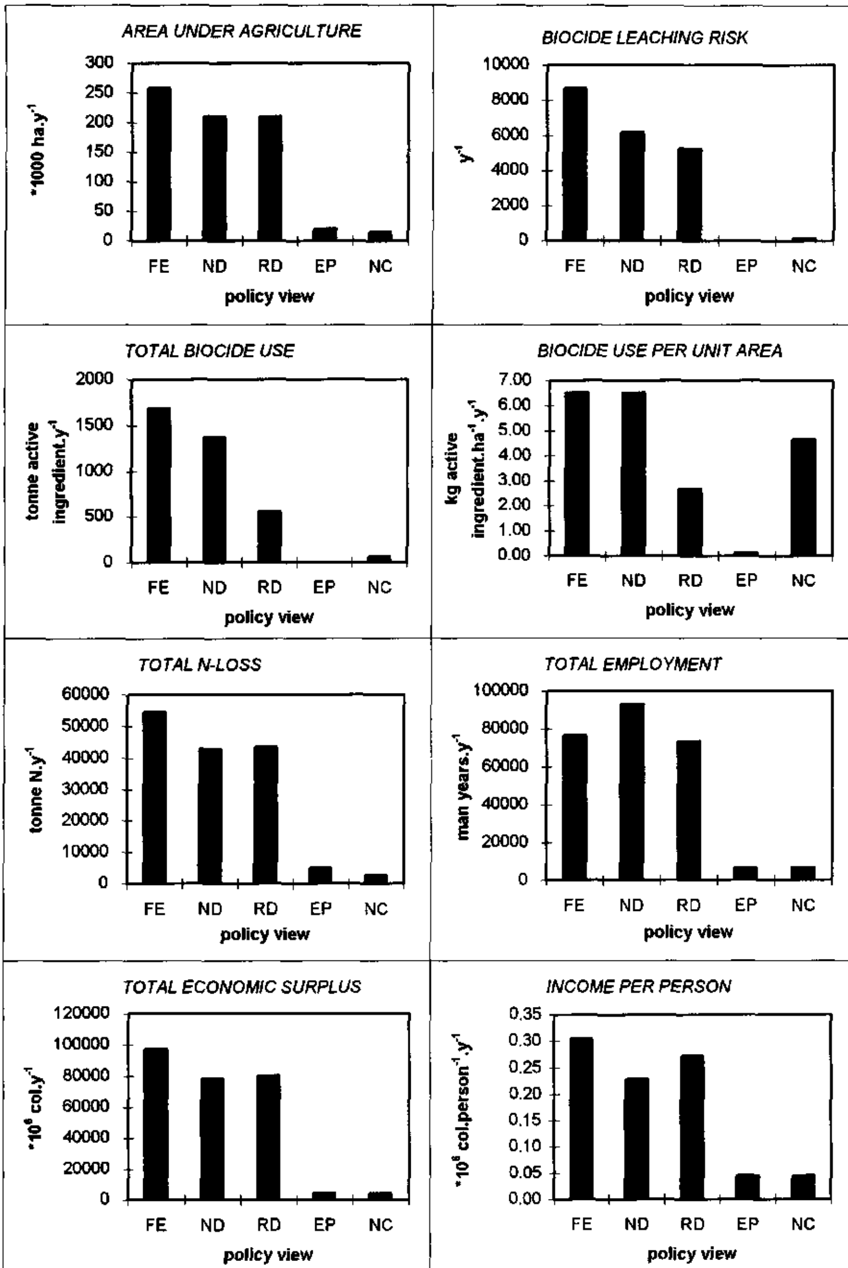

Figure 5.1 Single-period MGLP-model with "average" coefficients: objective function values for each policy view. For codes see Table 2.2.

The optimum land use scenario for a policy view is obtained when the lowest relative deviation from the optimum values is found, which is valid for all relevant objective functions. For instance, in policy view ND economic surplus and employment are maximized. If the economic surplus is 20 % lower than the optimum economic surplus, the employment in agriculture also has to be within 20 % of its optimum value (Appendix 8).

In Figure 5.1 the objective function values of the five policy views are compared. Figure 5.2 gives information about the selected forms of land use and production techniques for the five policy views.

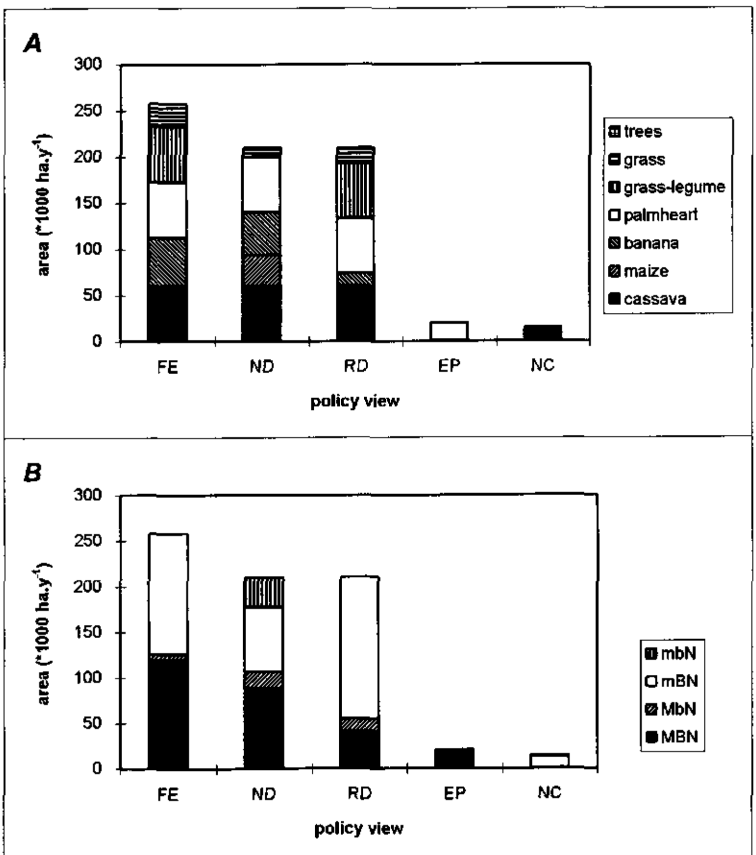

Figure 5.2 Single-period MGLP-model with "average" coefficients: selected forms of land use (A) and selected production techniques (B) for each policy view. For codes see Tables 2.2 and 2.4.

Below, the most evident results for the five scenarios are described:

- High values for one objective function value are associated with high values for other objective functions. Policy views Free Enterprise (FE) and National Development (ND) show high values for all objective functions. Policy views Environmental Protection (EP) and Nature Conservation (NC) have low values for all objective functions, except for biocide use per unit area in policy view NC. Policy view Regional Development (RD) has high values for most objective functions, but biocide use is at an intermediate level. The environmental burden per unit economic surplus showed a different pattern: the objective concerning N-loss and the economic objectives seem less conflicting when the environmental impact per unit economic surplus is considered (Figure 5.3);
- The differences in objective function values and land use allocation between policy views FE and ND on the one hand, and policy views EP and NC on the other are extremely large. This is mainly caused by the differences in area under agriculture;
- Yield-oriented production techniques are selected most often. In general, these production techniques are most profitable (Figure 3.3C), and the differences between forms of land use regarding labour need, economic surplus, biocide use, N-loss, etc. are much larger than the differences between production techniques (Chapter 3);
- The optimum values for total employment, total economic surplus and income per person for the various policy views are clearly lower than the optimum values in the zero-round. This is caused by the value-driven constraint on maximum area per crop (60,000 ha) in the optimization runs per policy view;
- The economic surplus in policy views EP and NC is closest to the estimated current economic surplus, but in these policy views only a fraction of the current land under agriculture is used.

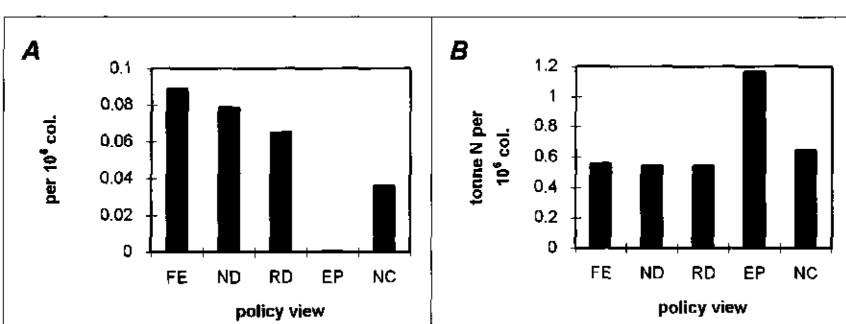

Figure 5.3 Biocide leaching risk (A) and N-loss (B) per unit economic surplus in the five policy views. For codes see Table 2.2.

Some information per policy view is presented below. Information for comparing the coefficients of production activities can be found in Chapter 3 and in the Appendices.

In policy view FE the main objective is maximization of economic surplus. Therefore, the MGLP-model selected on profitability of production activities. Mainly yield-oriented production ($_{c=MBN}$ and $_{c=mBN}$), which has the highest yield per unit area, is selected. The most profitable form of land use is cassava, followed by palmheart (Figure 3.3A). Every available and suitable hectare outside the national parks is used for agricultural production and, consequently, the total biocide use, N-loss, biocide leaching risk, and employment are high. The income per person is high, because the economic surplus and employment are high.

Policy view ND focuses on maximization of employment and maximization of economic surplus. No agricultural activities are allowed in the buffer zone in this policy view. This caused a 18.5 % reduction in available area and a 19.7 % reduction in economic surplus, compared with policy view FE. However, only 10.4% reduction in economic surplus is caused by the reduction of available area. The remaining 9.3 % reduction is caused by the simultaneous maximization of employment. To increase employment, maize ($_{l=ma}$) with production technique ($_{c=mbN}$) is preferred to pasture and banana ($_{l=gl20,\ l=gl20}$ and $_{l=ba20}$) (Appendix 5). Compared with FE, a larger area is cultivated with production techniques aiming at reduced biocide use ($_{c=MbN}$ and $_{c=mbN}$). These production techniques have a higher labour demand than yield-oriented production (Figure 3.2.B).

In policy view RD income per person and employment are both maximized and the total biocide use is minimized. The total biocide use is reduced by 59 %, income per person is increased by 20 %, and employment is reduced by 21 %, as compared with policy view ND. Compared with ND, shifts take place in production techniques and forms of land use: only yield-oriented production techniques, $_{c=MBN}$ and $_{c=mBN}$, and more manual production techniques are selected; maize and bananas, $_{l=ma}$ and $_{l=ba20}$ (crops with high biocide use, Figure 3.8), are almost completely replaced by grass-legume pasture, $_{l=gl20}$.

In policy view EP minimization of biocide use per unit area is the primary objective. Palmheart ($_{l=pa20}$) has the lowest biocide use per unit area (Figure 3.8), and it is the only selected form of land use in this scenario. The bounds on minimum income per person and minimum population size are binding, and determine the total area for agriculture and the selected terrain type.

In policy view NC the area under agriculture, the total N-loss and the total biocide leaching risk are minimized. The bounds on minimum income per person and minimum population size are binding. The production activities with the highest income per unit area are selected to keep the area available for nature as large as possible. Manual, yield-oriented cassava production on terrain type $_{s=s6}$ gives the highest income (Figures 3.2A and 3.3A). Biocide leaching risk in cassava is also low on terrain type $_{s=s6}$ (the low ground water level results in low biocide leaching risk; Figure 3.9B). Part of the cassava is cultivated on terrain type $_{s=s2}$ with production technique $_{c=mbN}$, with reduced biocide use and lower N-loss. However, this production activity also generates a lower income owing to the lower water-limited production on terrain type $_{s=s2}$.

The differences between the land use scenarios for the five policy views show that there is ample scope for policy: different policy views result in very different optimum land use allocations. Consequently, the objectives for land use should be clear during a land use planning procedure. Before further conclusions can be drawn on land use options and trade-offs between objectives, sensitivity analyses are needed to test the robustness of the land use scenarios presented above.

5.3 Sensitivity to uncertainty in agro-ecological coefficients

Figure 5.4 and Table 5.3 show the results of the sensitivity analyses to uncertainty in agro-ecological coefficients concerning nutrients and biocides. Simultaneously, all agro-ecological coefficients were changed to "optimistic" or "pessimistic" estimates, as explained in Section 2.3.1. "Average" prices were used and, again the same bounds as described in Table 2.3 were used. More information on the sensitivity analyses is presented in Appendix 8.

The most evident result from this sensitivity analysis is that the values of the environmental objective functions are strongly affected by the uncertainty in coefficients related to nutrients and biocides, but that the land use allocation is hardly affected. Below, some details are presented:

- The objective function values for the biocide leaching risk and N-loss are relatively and absolutely affected most by the uncertainty in coefficients concerning nutrients and biocides. The total biocide leaching risk even shows dramatic changes under the influence of uncertainties. This is consistent with the observed large differences between "optimistic", "average" and "pessimistic" estimates for biocide leaching risk as presented in Section 3.4;
- Other objective functions are also affected by the uncertainties in coefficients for biocides and nutrients, as in most production activities the "optimistic" estimates of fertilizer requirement result in lower fertilizer costs and in an

increased added value per unit area. This is illustrated clearly in policy view EP. In all three runs palmheart ($_{l=pa20}$) is selected as the only form of land use, but the area needed to obtain the minimum income per person is different in each run (see Appendix 8). Only for livestock activities "optimistic" estimates are not associated with higher added values. The lower nutritional value of pastures owing to the "optimistic" nutrient concentrations results in lower growth rates and lower added values (Appendix 2). The "pessimistic" estimates of nutrient concentrations in pasture result in higher nutritional values and higher livestock production, although the increase in economic surplus from the higher livestock production does not always compensate for the increase in fertilizer costs;

- Changes in the land use allocation to forms of land use are limited (see Appendix 8), because rankings of production activities hardly change under the influence of uncertainty. Only the ranking for profitability of livestock production on pastures compared with the profitability of other crop activities changes. Therefore, in policy views FE, ND and RD the largest changes in area per form of land use are observed for pasture;
- Differences in objective function values and land use allocation between runs with "pessimistic" estimates and "average" coefficients are larger than differences between runs with "optimistic" and "average" coefficients. Some abrupt changes in objective function values take place between the runs with "average" and "pessimistic" estimates owing to changes in selected production activities. In the run with "pessimistic" coefficients for policy view NC a shift to production techniques with lower biocide leaching risk ($_{c=mbN}$) takes place, and some palmheart ($_{l=pa20}$) is included beside cassava ($_{l=ca}$). This causes the strong decreases in total biocide use (-82 %) and biocide use per unit area (-87 %), and the increase in total N-loss (+137 %). Compared with the run with "average" coefficients, in the run with "pessimistic" coefficients for policy view ND more banana ($_{l=ba20}$) is selected, at the expense of maize ($_{l=ma}$): the relative and absolute increase in fertilizer-N requirement of maize in the "pessimistic" estimate is higher than that for banana (Figure 3.7).

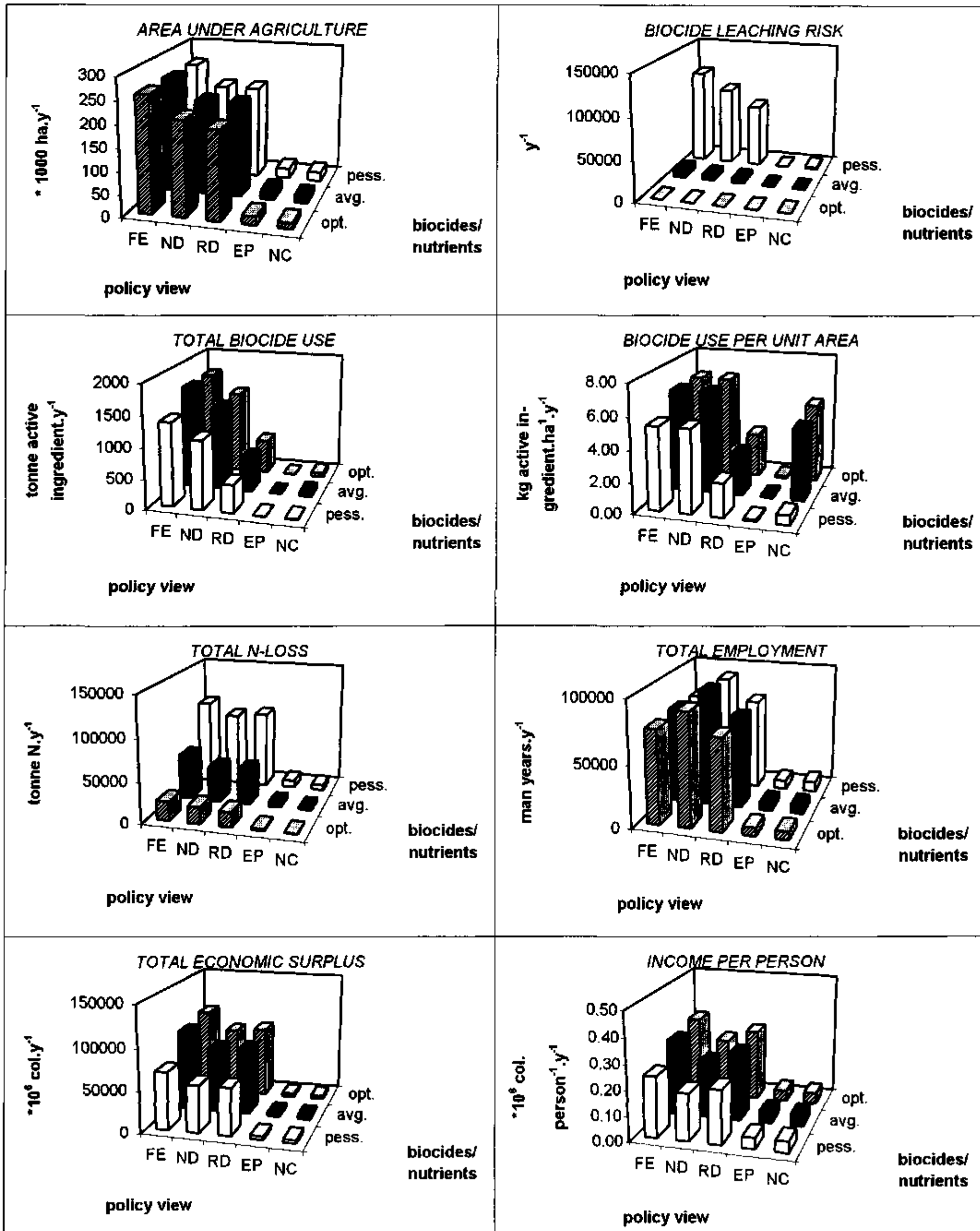

Figure 5.4 Sensitivity of the single-period MGLP-model for the NAZ, with "average" prices, to uncertainties in agro-ecological coefficients: objective function values for each policy view. For codes see Table 2.2.

Table 5.3 Sensitivity of the single-period MGLP-model to changes in agro-ecological coefficients: maximum relative changes[a] in objective function values in the five policy views as compared to the results of the model with "average" prices and "average" agro-ecological coefficients.

Objective function	Maximum decrease (%)	Obtained in policy view	Maximum increase (%)	Obtained in policy view
Area under agriculture	- 8	NC	+ 37	NC
Total biocide leaching risk	- 100	EP/NC	+ 7900	EP
Total biocide use	- 82	NC	+ 10	EP
Biocide use per unit are	- 87	NC	+ 11	NC
Total N loss	- 66	NC	+ 137	NC
Total employment	- 3	ND	+ 21	NC
Total economic surplus	- 29	FE/RD	+ 8	RD
Per capita income	- 21	RD	+ 7	FE

[a] relative changes in all policy views range from 0 % to the maximum relative change presented in this table. Relative changes for all policy views can be calculated with the data in Appendix 8.

5.4 Sensitivity to changes in prices

The effects of uncertainties in agro-ecological coefficients are compared with the sensitivity of the land use scenarios to changes in prices for agricultural products. Simultaneously, prices of all agricultural products were changed to "low" or "high" prices (Section 3.2.3.). For all other coefficients "average" values were used. Bounds on constraints were also kept unchanged. The relative increase or decrease in price is not the same for all products (Appendix 6). Consequently, the ranking of production activities for profitability may change when another set of prices is used. Although in reality prices for various agricultural products are not clearly correlated, they were increased or decreased simultaneously for all products, in a similar way as was done for agro-ecological coefficients. In this way, the extreme consequences of changes in prices for objective function values could be examined, and compared with the effects of uncertainty in agro-ecological coefficients on objective function values. Figure 5.5 and Table 5.4 present some results of this sensitivity analysis to changes in prices of agricultural products. More information on the sensitivity analyses is given in Appendix 8.

The most evident result from the sensitivity analysis with "low", "average" and "high" prices is that the values of the economic objective functions are strongly affected by the changes in prices of agricultural products. The land use allocation only changed when the ranking of production activities for economic coefficients changed, as happened in the optimization runs with "low" prices. Below, some details are listed:

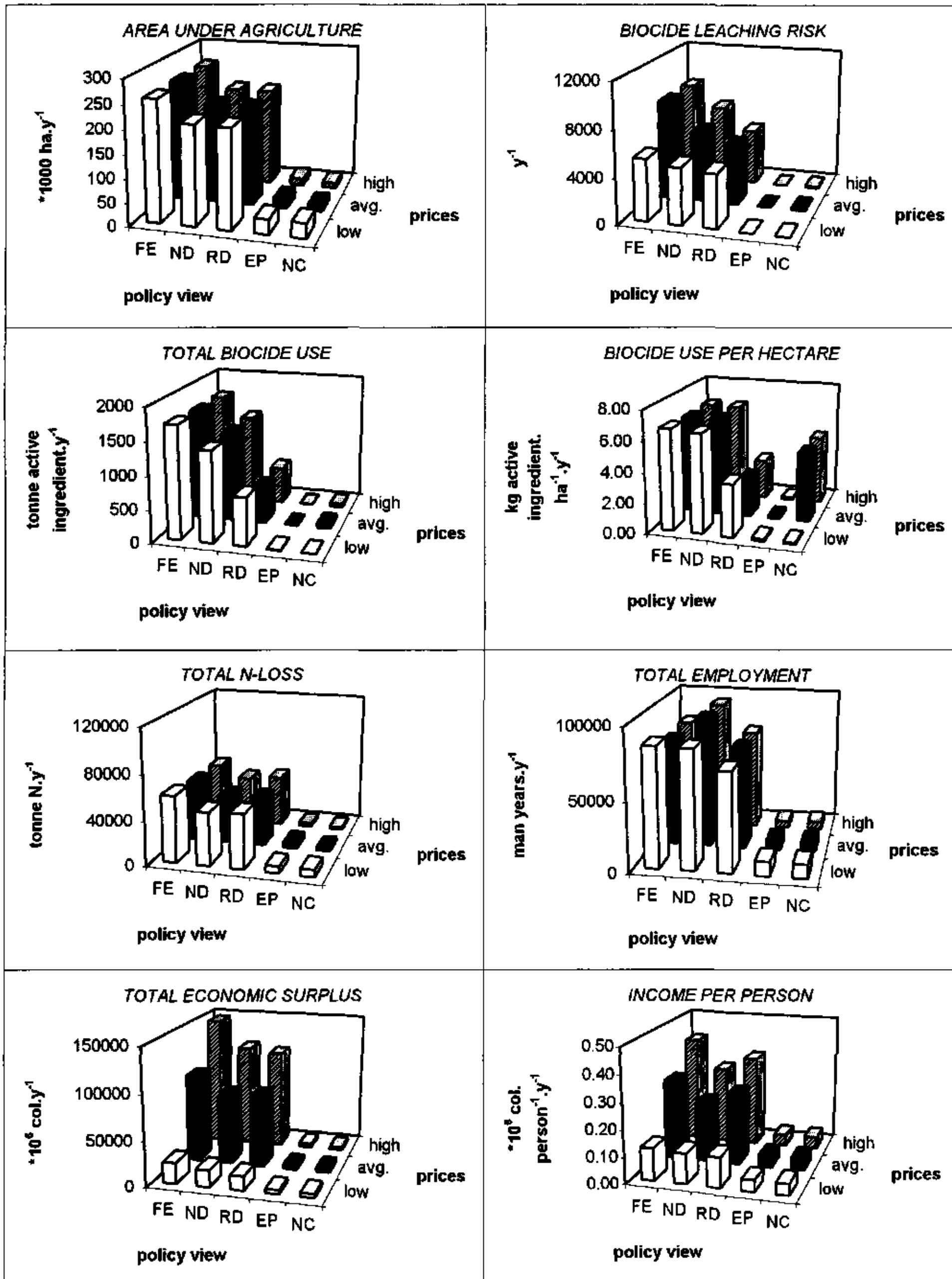

Figure 5.5 Sensitivity of the single-period MGLP-model for the NAZ, with "average" agro-ecological coefficients, to changes in prices: objective function values for each policy view. For codes see Table 2.2.

- The total economic surplus and income per person in policy views FE, ND and RD are affected most (in absolute terms) by the changes in prices. In policy views EP and NC economic surplus and income per person are hardly or not affected, because the minimum income per person and minimum population size are the binding constraints;
- Changes in values of other objective functions are caused by changes in cultivated area or by shifts in selected production activities. In policy view EP, palmheart ($_{l=pa20}$) is the only selected form of land use in all runs. In the case of a 33 % decrease in the price of palmhearts, a 58 % increase in total cultivated area is needed to reach the minimum income per person as compared to the run with "average" prices. Cassava is very profitable when "average" or "high" prices are used. However, when "low" prices are used most other forms of land use become more profitable than cassava (Figure 3.4A). Therefore, the area under cassava is strongly reduced (in policy views FE, ND and RD) or cassava is completely removed from the land use scenario (in policy view NC) in the runs with "low" prices;
- The largest relative changes in objective function values are again obtained for the environmental objective functions in policy views EP and NC (Table 5.4). However, these large relative changes correspond with small absolute changes in objective function values;
- Differences in objective function values and land use allocation between runs with "low" prices and runs with "average" prices are larger than differences between runs with "high" and "average" prices. Some abrupt changes in objective function values take place between the runs with "average" and "low" prices, owing to changes in selected production activities. For instance, in policy view NC: cassava ($_{l=ca}$) is selected in both the run with "average" prices and the run with "high" prices, but in the run with "low" prices cassava is completely replaced by palmheart ($_{l=pa20}$), owing to changes in income per unit area. This change in selected forms of land use also explains the decrease in total biocide leaching risk (-99 %), total biocide use (-94 %) and biocide use per unit area (-97 %), and the increase of total N-loss (+127 %), compared to the run with "average" prices. In policy view EP an increase or decrease of the price of palmhearts results in a decrease of 27 % or increase of 58 %, respectively, in the cultivated area.

Table 5.4 Sensitivity of the single-period MGLP-model with "average" agro-ecological coefficients to changes in prices: maximum relative changes[a] in objective function values in the five policy views as compared with the results of the model with "average" prices and "average" agro-ecological coefficients.

Objective function	Maximum decrease (%)	Obtained in policy view	Maximum increase (%)	Obtained in policy view
Area under agriculture	- 27	EP	+ 122	NC
Total biocide leaching risk	- 99	NC	+ 12	NC
Total biocide use	- 94	NC	+ 58	EP
Biocide use per unit area	- 97	NC	+ 31	RD
Total N-loss	- 27	EP	+ 127	NC
Total employment	- 27	EP	+ 54	EP
Total economic surplus	- 80	RD	+ 50	FE
Per capita income	- 60	FE	+ 35	FE

[a] relative changes in all policy views range from 0 % to the maximum relative change presented in this table. Relative changes for all policy views can be calculated with the data in Appendix 8.

5.5 Discussion and conclusions

5.5.1 Model sensitivity to uncertainties in agro-ecological coefficients and prices

The sensitivity of the *objective function values* to uncertainties in agro-ecological coefficients and prices is determined by the absolute values of these coefficients. In this study uncertainties in coefficients concerning biocides and nutrients were larger than uncertainties in prices (Chapter 3). Therefore, economic objective function values were less affected by changes in prices, than were environmental objectives by uncertainties in biocide leaching risk and N-loss.

Sensitivity of *land use allocation* to changes in prices and agro-ecological coefficients is strongly determined by changes in rankings of production activities with respect to the criterion considered in the objective function, e.g. profitability or biocide leaching risk. When the ranking of production activities does not change under the influence of uncertainty, the solution of the MGLP-model, in terms of selected production activities, will not change. In this study, uncertainty in coefficients related to nutrients and biocides was mainly caused by lack of knowledge of underlying biophysical processes or by lack of data for quantification. Therefore, the "optimistic", "average" and "pessimistic" estimates represent different perceptions of the effect of environmental factors and, consequently, the values of the agro-ecological coefficients are strongly correlated (Chapter 2). This means that hardly any changes in rankings of production activities for environmental objectives take place under de influence of uncertainty in agro-ecological coefficients. High prices for one product do not automatically coincide with high prices for other products, i.e. many combinations of price levels for the various products are possible. Consequently, rankings of production activities for profitability and income per person may change dramatically (Figure 3.4A), and also land use allocation. Therefore, with the type of sensitivity analysis executed in the present study only few conclusions can be drawn on the effects of uncertainties in prices on optimal land use allocation, but the extreme values of economic objective functions can be determined.

Uncertainties in bounds on variables can also affect land use scenarios. For instance, the requirement of a minimum income per person affected the area needed for agriculture and the selected production activities in policy views EP and NC. The total available area for agriculture and the maximum area per form of land use affected the land use scenarios of policy views EP, ND and RD. In none of the policy views restrictions were put on total N-loss or total biocide leaching risk, because no quantitative information was available for the translation of N-loss and biocide leaching risk to damage to the environment. The analysis of effects of uncertainty in value-driven bounds, or the analysis of effects of the absence of bounds on agro-ecological variables on land use scenarios, was beyond the scope of this study. A strong point of the MGLP-procedure is though, that the effects of different values for bounds can easily be analysed, and in that way trade-offs can be revealed.

5.5.2 Options for the Northern Atlantic Zone

Based on the quantification of input-output coefficients (Chapter 3), the following conclusions can be drawn on the options for sustainable land use in the long term in the NAZ, and on further research needs:

- In the NAZ, conflicts about space do not necessarily need to arise between intensive agricultural land use and nature conservation, as more than 50 % of the area outside the national parks is unsuitable for intensive agriculture (crops, pasture and tree plantations; Section 3.1). Spatial distribution of the area is important for nature conservation and to a lesser extent for agriculture. However, LP has only limited possibilities for including spatial distribution of crop activities. Therefore, a detailed post-optimization analysis is needed to find out whether the spatial distribution of intensive agricultural land use and nature does not result in conflicts, e.g. because leached biocides end up in nature conservation areas or because different nature areas are not linked;
- The production potential of the land is not fully exploited. Section 3.1 showed that the current production levels are much lower than the potential and water-

limited productions. This means that a much higher economic surplus can be obtained in the NAZ, or that the current production can be obtained on a much smaller area than presently used. Particularly, replacement of livestock production on extensive pastures by livestock production on intensive pastures can strongly reduce the area needed for agricultural activities;
- The low *AF*-values indicate that the biocide leaching risk in the NAZ is not very high (Section 3.4) when biocides are properly managed. Even "pessimistic" *AF*-values were relatively low (< 0.5). Biocides with low adsorption coefficients and long half-lives, and biocide use on soils with high ground water levels (in banana, cassava and maize production on terrain types $_{s\text{-}s2}$ and $_{s\approx s3}$) caused the highest risk of biocide leaching. The *AF*-indices should be interpreted with some caution, as the *AF*-index does not include all aspects of biocide behaviour in the soil (Section 3.4).

In the present chapter the options for future land use in the NAZ were explored by confronting biophysical possibilities and constraints with the value-driven objectives of five groups of stakeholders. Based on these analyses the following conclusions can be drawn:
- High values for socio-economic objective functions are associated with high values for environmental objective functions (Figures 5.1, 5.4 and 5.5). This means that socio-economic and environmental objectives are clearly conflicting. For instance, a high economic surplus can only be obtained if a large area is used for agriculture. This also results in high total N-loss, total biocide use, total employment, etc.
- The environmental impact per unit economic surplus not necessarily increases with economic surplus (Figure 5.3). Efficiency of input use or damage to the environment can be measured in various ways. In the LP-models in the present study total inputs and outputs, and input and output use per unit area were used. However, input or output per unit economic surplus or per person can also be considered. Which description of environmental impact is used, depends on the policy view;
- In general, adjusting the form of land use resulted in a larger gain for the environmental objective functions, than shifting to another terrain type or production technique. The forms of land use in the NAZ show wide ranges in labour need, economic surplus, biocide use and leaching risk, fertilizer requirement and N-loss (Chapter 3). These differences are wider than the differences between production techniques or terrain types. Since economic surplus per unit area or income per person per unit area are important in all policy views, mainly yield-oriented production techniques were selected and sometimes environment-oriented techniques aiming at lower biocide use;
- The trade-offs observed in this case-study for the NAZ are partly determined

by the forms of land use included. For instance, reduction of biocide use often resulted in increased N-loss, because the forms of land use with low biocide use (palmheart and pasture) also show high N-loss; high economic surplus and low biocide use are combined in palmheart production; high economic surplus and low N-loss are combined in cassava production. Changes in price levels or changes in ratios between prices of products can affect the trade-offs between environmental and socio-economic objective functions. For instance, at higher timber prices tree plantations would be attractive from an economic as well as from an ecological point of view.

In the present chapter also the sensitivity of land use scenarios to uncertainties in agro-ecological coefficients was determined. Based on the sensitivity analyses, the following conclusions can be drawn:

- The effect of uncertainties on absolute values of coefficients is in the same order or greater than the effect of differences between forms of land use on absolute values of coefficients. This means that, if there is main interest in determining the *absolute values of objective functions* under different policy views, than the uncertainties should be more carefully determined. On the other hand, when one is mainly interested in optimal *land use allocation*, uncertainties in agro-ecological coefficients are less important; they hardly affected the ranking of production activities;
- The differences between land use scenarios for the five policy views were large, regardless which agro-ecological coefficients or price levels were used. This means that, the "playing field" of policy makers in the NAZ is determined, in the first place, by the aspired objectives of the groups of stakeholders. Not until the effect of policy views on land use options is known, it becomes relevant to determine the effect of uncertainties on land use options.

6 TEMPORAL ASPECTS IN LONG-TERM EXPLORATIONS OF SUSTAINABLE LAND USE OPTIONS

In this chapter the possibilities of including temporal aspects of land use in long-term explorative studies are examined. In long-term explorative studies production with "best technical means" is assumed, which presumes that the technically most efficient production techniques are applied, according to present-day knowledge. Irreversible developments, such as the introduction of further new production techniques and discontinuities concerning the physical environment, e.g. caused by flooding or volcanic eruptions, would be speculative (Chapter 2). The other three types of temporal aspects as mentioned in Chapter 1 (i. Growth and ageing, ii. Fluctuations, iii. Temporal interactions) are treated in Sections 6.1, 6.2 and 6.3, respectively. Each of these sections starts with a short introduction on methods used in other LP-studies. Next, this information is used to describe these temporal aspects in a multi-period version of the single-period MGLP-model as presented in Chapter 4. The multi-period model consists of four periods of five years and has a cyclic structure (see Figure 2.3). Consequently, the growing period of perennial crops is subdivided in growth stages of five years and the maximum length of the growing period is four periods or 20 years. Possibilities and difficulties of including temporal aspects in this multi-period MGLP-model are demonstrated. Each section ends with a short discussion on advantages and disadvantages of the methods used. In Section 6.4 the results of the multi-period MGLP-model are compared with those of the single-period MGLP-model, to evaluate whether the explicit inclusion of temporal aspects in the MGLP-model results in different objective function values and land use allocation. In Section 6.5 the use of multi-period models in long-term explorative studies is discussed. The codes for indices, variables and coefficients in the multi-period model are explained in Tables 6.1 to 6.3.

Table 6.1 List of indices used in the description of the multi-period MGLP-model[a].

Index	Description	Elements
c	cropping technique	mechanized yield-oriented production ($_{c=MBN}$); manual yield-oriented production ($_{c=mBN}$); mechanized environment-oriented production, reduced biocide use ($_{c=MbN}$); manual environment-oriented production, reduced biocide use ($_{c=mbN}$); mechanized, environment-oriented production, reduced N-loss ($_{c=MBn}$); manual, environment-oriented production, reduced N-loss ($_{c=mBn}$)
cp	crop products	bananas ($_{cp=ban}$); banana residues ($_{cp=banr}$); cassava ($_{cp=cas}$); cassava residues ($_{cp=casr}$); DM[b] from grass pasture ($_{cp=gig}$); DM from grass-legume pasture ($_{cp=glg}$), maize ($_{cp=mai}$); palmheart ($_{cp=pal}$); pulpwood ($_{cp=wop}$); timber ($_{cp=wot}$)
l	form of land use	banana ($_{l=ba1,\ l=bac}$); cassava ($_{l=ca}$); maize ($_{l=ma}$); palmheart ($_{l=pa1,\ l=pac}$); grass pasture ($_{l=gi1,\ l=gic}$); grass-legume pasture ($_{l=gl1,\ l=glc}$); tree plantations ($_{l=wt}$)
p	period	$_{p=p1}$ to $_{p=p4}$
s	terrain type	$_{s=s1}$ to $_{s=s7}$

[a] the indices in the single-period model and the multi-period model only show differences at two points: for forms of land use different elements were used and an index for periods was added;
[b] DM = dry matter.

Table 6.2 List of variables used in the description of the multi-period MGLP-model. All variables are expressed per period of five years.

Variable	Description	Unit of measurement
$CLA_{l,c,s,p}$	crop activity	ha
EMP_p	total employment per period	man years
$D1_{l,c,s,p}$	difference in cultivated area per crop activity between period i and i-1	ha
$D2_{l,c,s,p}$	difference in cultivated area per crop activity between period i and i-2	ha
$R1_{s,p}$	residual effect of P applied in period i-1, which is not available for crops in period i, per terrain type	kg P
$R2_{s,p}$	residual effect of P applied in period i-2, which is not available for crops in period i, per terrain type	kg P
$Up_{s,p}$	fertilizer-P requirement per terrain type	kg P

Table 6.3 List of coefficients used in the description of the multi-period MGLP-model. All coefficients are expressed per period of five years.

Coefficient	Description	Unit of measurement
$area_{s,p}$	available area per terrain type	ha
empmin	minimum employment in agriculture in period i, defined as fraction of employment in period 1	-
empmax	maximum employment in agriculture in period i, defined as fraction of employment in period 1	-
$mfr1_{l,c,s,p}$	residual effect in period i of P applied in period i-1, per crop activity	kg P.ha^{-1}
$mfr2_{l,c,s,p}$	residual effect in period i of P applied in period i-2, per crop activity	kg P.ha^{-1}
$pmf_{l,c,s,p}$	preliminary fertilizer-P requirement per crop activity, without residual P effects	kg P.ha^{-1}
$mf1_{l,c,s,p}$ [a]	fertilizer-P requirement in the first growth stage of tree plantations, taking into account residual P	kg P.ha^{-1}
$mf2_{l,c,s,p}$ [a]	fertilizer-P requirement in the second growth stage of tree plantations, taking into account residual P	kg P.ha^{-1}
$mf3_{l,c,s,p}$ [a]	fertilizer-P requirement in the third growth stage of tree plantations, taking into account residual P	kg P.ha^{-1}
$mf4_{l,c,s,p}$ [a]	fertilizer-P requirement in the fourth growth stage of tree plantations, taking into account residual P	kg P.ha^{-1}
$yield_{cp,l,c,s,p}$	physical yield per crop product per crop activity	tonne fresh product.ha^{-1}, tonne dry matter.ha^{-1}
$yield2_{cp,l,c,s,p}$ [a]	physical yield of timber or pulpwood in the second growth stage of tree plantations	tonne dry matter.ha^{-1}
$yield3_{cp,l,c,s,p}$ [a]	physical yield of timber or pulpwood in the third growth stage of tree plantations	tonne dry matter.ha^{-1}
$yield4_{cp,l,c,s,p}$ [a]	physical yield of timber or pulpwood in the fourth growth stage of tree plantations	tonne dry matter.ha^{-1}

[a] the first growth stage of tree plantations represents the years 1-5, the second growth stage the years 6-10, the third growth stage years 11-15 and the fourth growth stage the years 16-20.

6.1 Growth and ageing of crops and livestock

In single-period deterministic LP-models, occasionally, distinction is made between inputs and outputs in different subperiods of the year, mainly for labour. Differences in inputs and outputs between different growth stages of perennial crops are not taken into account, but average yearly inputs and outputs are used. Multi-period LP-models offer the possibility to take into account differences in inputs and outputs between different growth stages of, e.g. perennial crops. The length of the periods in the multi-period model (mostly between one and ten years) determines the detail in the descriptions of growth stages. The inclusion of multiple periods in a LP-model requires that the description be changed of production activities with growing periods that are longer than one period, as compared with the single-period model. Two methods can be used:

- Description of the growing period with several variables, each representing a different growth stage with its specific inputs and outputs (Method 1);
- Description of the growing period with one variable, and inputs and outputs in different growth stages are described with separate coefficients (Method 2).

Publications on multi-period models often do not specify the method (O'Hara *et al.* 1989; Cox & Sullivan 1995; Weintraub *et al.* 1995). If specified, generally the first method with separate variables for each growth stage is used (Propoi 1977; Dykstra 1984; Hof *et al.* 1993; Nicholson *et al.* 1994).

Multi-period model NAZ

In the multi-period MGLP-model in the present study both above-mentioned methods were applied. For banana, pasture and palmheart two variables are used to represent growth and crop development: one variable for the establishment period of the crop and a second variable for continued production. The length of the growing period of these crops is not fixed: the multi-period model determines the optimum length of the growing period. For instance for banana, an establishment period of five years ($_{l=ba1}$) can be combined with zero to three periods of five years with continued cultivation ($_{l=bac}$)[1]. This results in growing periods of 5, 10, 15 or 20 years (comparable with $_{l=ba5}$, $_{l=ba10}$, $_{l=ba15}$, and $_{l=ba20}$, respectively, in the single-period model). Table 6.4 shows the coefficients used for the description of physical yields in banana plantations in both the single-period and multi-period model. Equation 6.1b shows how total banana production is calculated with these coefficients in the multi-period model.

[1] It was assumed that under continued production of banana, palmheart, grass and grass-legume the inputs and outputs remain about the same for several periods. Only variations in weather conditions cause slight differences in input-output coefficients between periods under continued production.

Table 6.4 Description of physical yield in banana plantations (non-fixed growing period) and tree plantations (fixed growing period), with production technique $_{c=MBN}$ on terrain type $_{s=s2}$, in the single-period MGLP-model and the multi-period MGLP-model (period 1[a]).

Production activity	Explanation		Physical production (*yield*)	
Single-period MGLP-model				
$_{l=ba5}$	banana, growing period 5 years		90	tonne fresh bananas.ha^{-1}.year^{-1}
$_{l=ba10}$	banana, growing period 10 years		101	tonne fresh bananas.ha^{-1}.year^{-1}
$_{l=ba15}$	banana, growing period 15 years		104	tonne fresh bananas.ha^{-1}.year^{-1}
$_{l=ba20}$	banana, growing period 20 years		106	tonne fresh bananas.ha^{-1}.year^{-1}
$_{l=wt}$	tree plantation, growing period 20 years		9.5	tonne timber.ha^{-1}.year^{-1}
Multi-period MGLP-model				
$_{l=ba1}$	banana, establishment period		450	tonne fresh bananas.ha^{-1}.5 years^{-1}
$_{l=bac}$	banana, continued cultivation		558	tonne fresh bananas.ha^{-1}.5 years^{-1}
$_{l=wt}$	tree plantation	age 0-5 years	0	tonne timber.ha^{-1}.5 years^{-1}
		age 6-10 years	23	tonne timber.ha^{-1}.5 years^{-1} (*yield2*[b])
		age 11-15 years	29	tonne timber.ha^{-1}.5 years^{-1} (*yield3*[b])
		age 16-20 years	139	tonne timber.ha^{-1}.5 years^{-1} (*yield4*[b])

[a] in the multi-period MGLP-model fluctuations between periods in yield caused by variation in weather conditions were included, the yield in period 1 was equal to the average yield in the single-period model (see also Section 6.2);
[b] to describe inputs and outputs for this production activity separate coefficients were used for each growth stage.

The length of the growing period for tree plantations was considered fixed (20 years). In tree plantations inputs and outputs of each growth stage are different. Therefore, four variables (4x5 years) are needed when Method 1 is used. In case of a fixed length of the growing period, the area under subsequent growth stages is known when the area established in each period is known. In this situation, Method 2 with one variable for the entire growing period, can be used. Table 6.4 shows the coefficients used for the description of physical yields in tree plantations in both the single-period and multi-period model. In the multi-period model the area under trees is only explicitly mentioned in the period of establishment. Inputs and outputs in the next three periods are described as a function of the area in the establishment period. This means that inputs and outputs in the second, third and fourth growth stage have to be described with additional coefficients. This is illustrated below with Equation 6.1, which describes the total crop production per period ($TPROD_{cp,p}$) in tree plantation activities and other crop activities. The coefficients $yield_{cp,l(wt),c,s,p}$, $yield2_{cp,l(wt),c,s,p-1}$ and $yield3_{cp,l(wt),c,s,p-2}$ refer to the physical yield obtained from thinnings in tree plantations. Coefficient $yield4_{cp,l(wt),c,s,p-3}$ refers to the physical yield obtained during the final cut of all trees (Table 6.4). The multi-period model gets a cyclic structure by assuming that period 1 is preceded by period 4 (example in Equation 6.1a).

For the crop products pulpwood ($_{cp=wop}$) and timber ($_{cp=wot}$):

$$\begin{aligned}
TPROD_{cp,p(1)} &= \sum_c \sum_s CLA_{l(wf),c,s,p(1)} \times yield_{cp,l(wf),c,s,p(1)} \\
&+ \sum_c \sum_s CLA_{l(wf),c,s,p(4)} \times yield2_{cp,l(wf),c,s,p(4)} \\
&+ \sum_c \sum_s CLA_{l(wf),c,s,p(3)} \times yield3_{cp,l(wf),c,s,p(3)} \\
&+ \sum_c \sum_s CLA_{l(wf),c,s,p(2)} \times yield4_{cp,l(wf),c,s,p(2)} \\
TPROD_{cp,p(2)} &= \sum_c \sum_s CLA_{l(wf),c,s,p(2)} \times yield_{cp,l(wf),c,s,p(2)} \\
&+ \sum_c \sum_s CLA_{l(wf),c,s,p(1)} \times yield2_{cp,l(wf),c,s,p(1)} \\
&+ \sum_c \sum_s CLA_{l(wf),c,s,p(4)} \times yield3_{cp,l(wf),c,s,p(4)} \\
&+ \sum_c \sum_s CLA_{l(wf),c,s,p(3)} \times yield4_{cp,l(wf),c,s,p(3)}
\end{aligned} \tag{6.1a}$$

For other crop products:

$$TPROD_{cp,p} = \sum_l \sum_c \sum_s CLA_{l,c,s,p} \times yield_{cp,l,c,s,p} \tag{6.1b}$$

For crops with non-fixed lengths of growing periods constraints have to be formulated that ensure that the multi-period model selects continued production only after the crop has been established: Equation 6.2 restricts the area under continued banana production to the area under continued banana production in the former period ($_{p-1}$) plus the area established with bananas in the former period. To avoid infinite length of growing periods, caused by the cyclic structure, a maximum is included for the number of periods with continued banana production. With Equation 6.3 the length of the growing period is restricted to four periods of five years: the area per terrain type under continued banana production can never be more than the area established in the three previous periods. Similar constraints are used for palmheart ($_{l=pa1,\ pac}$), grass pasture ($_{l=gi1,\ gic}$) and grass-legume pasture ($_{l=gl1,\ glc}$).

$$CLA_{l(bac),c,s,p} \le CLA_{l(bac),c,s,p-1} + CLA_{l(ba1),c,s,p-1} \tag{6.2}$$

$$CLA_{l(bac),c,s,p} \le CLA_{l(ba1),c,s,p-1} + CLA_{l(ba1),c,s,p-2} + CLA_{l(ba1),c,s,p-3} \tag{6.3}$$

Discussion

In general, Method 1 (separate variables for each growth stage) has more advantages than Method 2 (one variable for the entire growing period):

- Method 1 can be used in situations with fixed lengths of growing periods *and* in situations with non-fixed lengths of growing periods. In the case of non-fixed lengths of growing periods the area of a crop in a particular period cannot be deduced from the area in the establishment period, as required for Method 2. When using separate variables for each growth stage (Method 1), the area per growth stage is determined every period and, consequently, inputs and outputs can be calculated for each period;
- Description of constraints is easier with Method 1. When the second method with one variable per growing period is used, the inputs and outputs for crops established in former periods have to be explicitly mentioned (compare Equations 6.1a and 6.1b);
- A disadvantage of Method 1 over Method 2 is the larger number of variables required. For instance, for tree plantations four variables are needed when Method 1 is used; now only one variable sufficed. A strong increase in model size caused by the introduction of periods is often mentioned as one of the main problems in multi-period LP-models (Csaki 1977; Ayyad & Van Keulen 1987; Lohmander 1989).

6.2 Fluctuations

Fluctuations between periods can be related to natural variation in weather conditions or to changes in land use. Limitation of fluctuations between periods is often part of policy views. Mostly, stochastic LP-models are used to include variation (O'Hara *et al.* 1989; Hof *et al.* 1993). These models do not always include correlations between values of coefficients. Agrotechnical coefficients for different crops will show correlations, if management effects are excluded, as is the case in long-term explorative studies (Section 2.3). For instance, because of lower than average rainfall, yields of crops will probably be affected negatively; only the relative effect of weather conditions on yield level may differ between crops and terrain types. The same is true for other agrotechnical coefficients: when rainfall is lower, N-leaching will probably be lower on all soils. Fluctuations caused by variation in weather conditions can be included in deterministic LP-models if they are known a priori. In the MALI5 model, a deterministic single-period LP-model, yields in dry years were included in addition to yields in years with average rainfall (Veeneklaas 1990). In a single-period LP-model only average land use allocation per period is known. In multi-period LP-models differences in land use allocation between periods can be addressed explicitly, and restrictions can be put on fluctuations between periods for variables such as the area per crop, total biocide use, total crop production and total employment (Cox & Sullivan 1995).

Multi-period model NAZ

Fluctuations in agrotechnical *coefficients* caused by variation in weather conditions are included in the deterministic multi-period model. Weather data from the six weather stations were divided into four periods of five years. For each period the average potential and water-limited productions per crop were determined. Differences between the periods in production levels are mainly caused by differences in radiation levels (Appendix 2). The average production levels in period 1 are equal to the average production levels in the single-period model. Inputs and outputs for each period were calculated in a "target-oriented" way (Chapter 3), which is why most input and output coefficients changed with changing yield level. Fluctuations caused by variation in management are not taken into account in long-term explorative studies, because production with "best technical means" is assumed. Figure 6.1 presents examples of fluctuations between periods in several coefficients. Relative fluctuations in fertilizer-N requirement are about the same as relative fluctuations in yields, because fertilizer-N requirement is closely related to yield level (Figures 6.1A and 6.1B). Relative fluctuations between periods are largest for economic surplus (Figure 6.1C). Part of the production costs are independent of the production level. For instance, in mechanized production of cassava, labour requirements are the same in each period (Figure 6.1D), i.e. they are not related to yield level. The relative fluctuations in revenue (yield * price of product) are the same as the relative fluctuations in yields. Consequently, the fluctuation between periods in economic surplus (revenue - production costs) could be much larger than the fluctuations in yields.

Fluctuations in coefficients can cause fluctuations in *variables*. In the multi-period LP-model for the NAZ bounds were put on the fluctuations between periods for particular variables. Equation 6.4 shows an example for variable *EMP* (total employment): employment in each period was not allowed to deviate more than a certain factor (*empmax* and *empmin*) from the employment in period 1. In a similar way, the fluctuations in the following variables were restricted: area per crop, number of livestock, total biocide leaching risk, total biocide use, total N-losses, total economic surplus, and total gross domestic product. The bounds used to limit the fluctuations differed per policy view and are presented in Table 6.5.

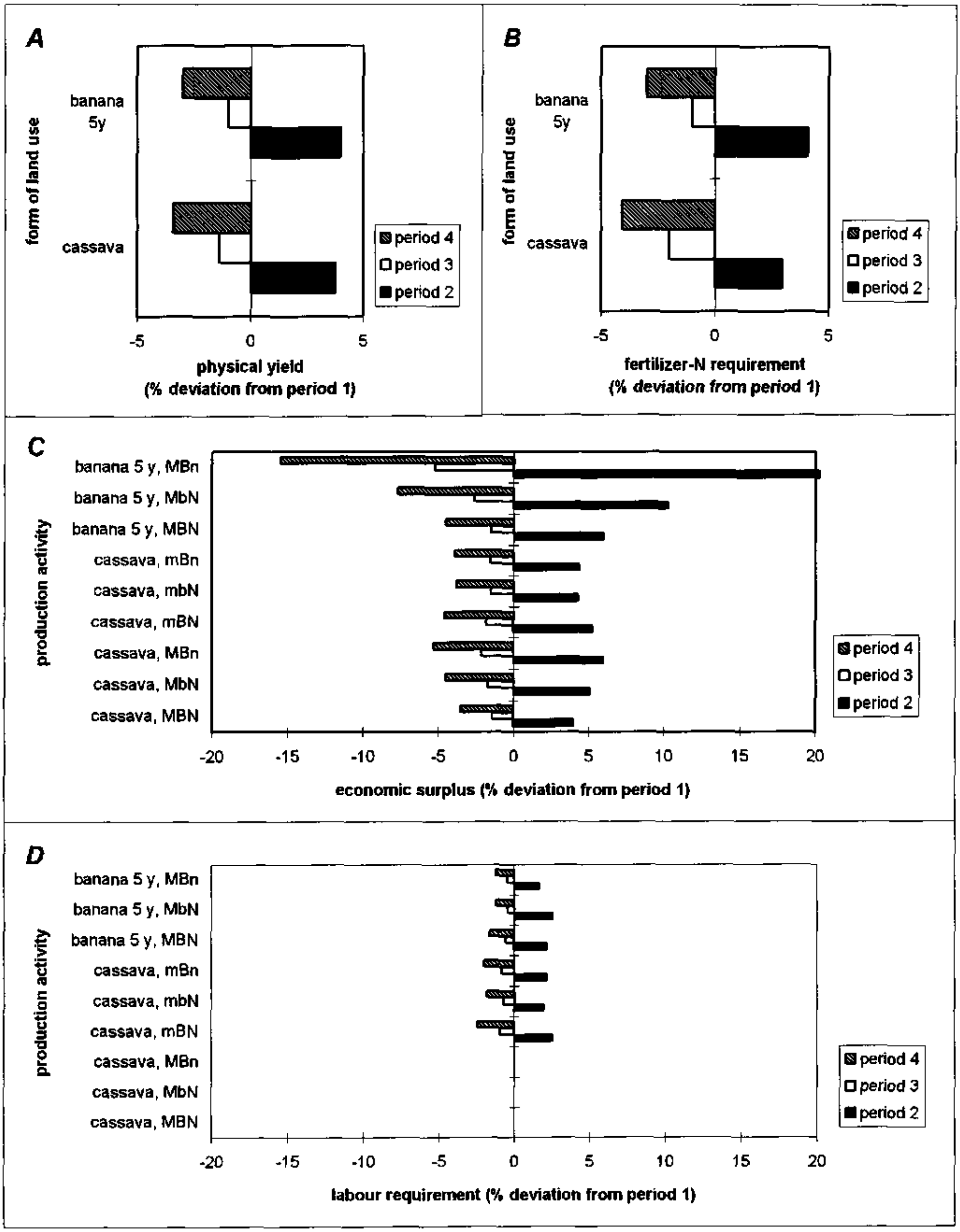

Figure 6.1 Examples of fluctuations in coefficients caused by variation in weather conditions, expressed in % deviation from period 1. A: physical yield; B: fertilizer-N requirement; C: economic surplus; D: labour requirement.

$$EMP_p \leq empmax \times EMP_{p(1)}$$
$$EMP_p \geq empmin \times EMP_{p(1)} \qquad 6.4$$

Discussion

If only annual crops are used, fluctuations in coefficients related to weather conditions can be included in a static and deterministic single-period model, as was done in the MALI5-model (Veeneklaas 1990). For perennial crops it is more complicated to take into account these fluctuations caused by variation in weather conditions, because single-period LP-models do not discriminate between establishing all of a perennial crop in one period, or planting and replacing each period only a particular number of hectares with this perennial crop. When the area per growth stage is unknown, the effect of fluctuations in coefficients on variables cannot be calculated and no restrictions can be put on fluctuations. With the help of multi-period models such differences between periods in land use allocation can be explicitized.

In the present study allowed fluctuations in variables are a function of the value in period 1. Allowed fluctuations can also be defined as a function of the value in the previous period. This may result in slightly different land use scenarios.

6.3 Interactions in time

Options for land use in one period are often determined by activities in the previous periods, or input-output relations in one period are affected by residual effects of activities in previous periods. These temporal interactions can be subdivided into two groups:
- Location-independent interactions (cash flows, building up of stock of products, etc.);
- Location-bound interactions (residual effects of fertilizers, building up of nematode populations in the soil, etc.).

In published multi-period LP-models mostly location-independent interactions are described (Hendriks & Van Beek 1991; Spharim *et al.* 1992). In land use optimization studies specific location-bound interactions occur, i.e. a production activity may change the conditions at a certain location, and thus affects the production activities that can be selected for that location in the next period. Miranowski (1994) and Barbier (1996) both included the degradation of the soil by considering the yield of crops in a particular period to be negatively related to soil loss in the former period. However, both authors ignore possible differences in erosion within spatial units caused by the use of different crops or cropping practices on different locations within the same spatial unit. This can result in aggregation bias. Cox & Sullivan (1995) avoided this bias in their study on wildlife habitat preservation: they used binary variables to assure that only one production activity took place on the entire spatial unit.

Multi-period model NAZ

An example of a location-independent interaction, used in the multi-period LP-model, is the selling and purchasing of livestock. In a period with low pasture production less fodder is available and part of the livestock herd is sold, thus slightly increasing economic surplus in that period. In a period with high yields after a period with lower yields, livestock is purchased again.

Two examples of location-bound temporal interactions, used in the multi-period LP-model, are presented below. The first example concerns cropping sequences. After felling of tree plantations ($_{l=wt}$) or abandoning palmheart plantations ($_{l=pa1,\ pac}$) considerable amounts of woody material remain in the soil and on the soil surface. This impedes mechanized ($_{c=MBN,\ MbN,\ MBn}$) soil preparation for maize ($_{l=ma}$) and cassava ($_{l=ca}$), and it impedes harvesting of cassava. Cassava production and mechanized maize production are, therefore, not allowed directly after felling of tree or palmheart plantations (Equation 6.5). Tree plantations were assumed to have a growing period with a fixed length. They occupy a plot for four consecutive periods. The multi-period model has a cyclic structure with four periods of five years. This means that, when tree plantations are selected, the plot is occupied continuously by trees. The area under tree plantations is, therefore, not available for other crop activities, including cassava and mechanized maize production. For palmheart, on the other hand, no fixed length of the growing period was assumed. At the end of each period it can be decided whether to abandon a palmheart plantation or not. Therefore, only the area under palmheart in period $_{p-1}$ is excluded for cassava and mechanized maize production in period $_{p}$. LP cannot discriminate between locations within the same spatial unit, i.e. a terrain type. However, Equation 6.5 ensures that cassava production and mechanized maize production do not have to take place on locations where palmheart and trees have been cultivated in the previous period.

$$area_{s,p} \geq \sum_{s} CLA_{l(ca),c,s,p} + \sum_{c=MBN}^{MBn} CLA_{l(ma),c,s,p} + \sum_{l=pa1}^{pac} \sum_{c} CLA_{l,c,s,p-1} + \sum_{c} \sum_{p=p1}^{p4} CLA_{l(wf),c,s,p} \qquad 6.5$$

A second example of location-bound temporal interaction concerns the residual effect of fertilizer-P. The description of this aspect is also complicated by the inability of LP-models to discriminate between locations within spatial units. Many additional variables have to be used to describe this location-bound temporal interaction approximately. After application of fertilizer-P residual effects can be observed for many years (see also Section 3.4). In the single-period model the residual effect of P is directly included in the coefficient for fertilizer-P requirement. This is possible, since a single-period model suggests that the land use scenarios continue for an infinite number of years (each production activity is preceded and followed by the same production activity, i.e. an equilibrium situation is assumed). This approach cannot be applied in multi-period models, because cropping sequences are not known a priori. In the multi-period model the residual effect of P applied in the two preceding periods ($mfr1_{l,c,s,p}$, $mfr2_{l,c,s,p}$) is explicitly addressed. The total fertilizer-P requirement per terrain type per period ($UP_{s,p}$) is calculated as the preliminary P requirement ($pmf_{l,c,s,p}$, without residual P effects of P applied in previous periods) minus the residual effects of P applied in the two preceding periods ($mfr1_{l,c,s,p}$ and $mfr2_{l,c,s,p}$) and corrected for the residual P that cannot be used ($R1_{s,p}$, $R2_{s,p}$; Equation 6.6). For tree plantations a fixed growing period of 20 years was assumed. This is equal to the cycle in the multi-period model (4x5 years), i.e. when tree plantations are selected, locations are occupied continuously by trees. Consequently, the land use in previous periods is known, and the amount of residual P and the final fertilizer-P requirement are known a priori. Coefficients $mf1_{l,c,s,p}$, $mf2_{l,c,s,p}$, $mf3_{l,c,s,p}$ and $mf4_{l,c,s,p}$ represent the final fertilizer-P requirements per growth stage in tree plantations. For all other forms of land use ($_{l=ba1}$ to $_{l=glc}$ in Table 6.1) the fertilizer-P requirement is calculated with the help of coefficients for preliminary P requirement and residual effects.

$$
\begin{aligned}
UP_{s,p} = & \sum_{l=ba1}^{glc} \sum_{c} CLA_{l,c,s,p} \times pmf_{l,c,s,p} \\
& - \sum_{l=ba1}^{glc} \sum_{c} CLA_{l,c,s,p-1} \times mfr1_{l,c,s,p-1} + R1_{s,p-1} \\
& - \sum_{l=ba1}^{glc} \sum_{c} CLA_{l,c,s,p-2} \times mfr2_{l,c,s,p-2} + R2_{s,p-2} \\
& + \sum_{c} CLA_{l(wf),c,s,p} \times mf1_{l(wf),c,s,p} + \sum_{c} CLA_{l(wf),c,s,p-1} \times mf2_{l(wf),c,s,p-1} \\
& + \sum_{c} CLA_{l(wf),c,s,p-2} \times mf3_{l(wf),c,s,p-2} + \sum_{c} CLA_{l(wf),c,s,p-3} \times mf4_{l(wf),c,s,p-3}
\end{aligned}
\qquad 6.6
$$

In subsequent periods, not necessarily all available residual P is used. When a plot is not cultivated in period $_{p+2}$, then the residual effect of P applied in periods $_{p+1}$ and $_{p}$ is not used in period $_{p+2}$. To take this into account the correction factors $R1_{s,p}$ and $R2_{s,p}$ are used. $R1_{s,p}$ represents the residual P at the location that is not cultivated in period $_{p+1}$, but which is cultivated in period $_{p}$. $R2_{s,p}$ represents the residual P at the location that is not cultivated in period $_{p+2}$, but which is cultivated in period $_{p}$. To calculate these correction factors, first the difference in cultivated area per crop activity ($D1_{l,c,s,p}$, $D2_{l,c,s,p}$) is determined, because residual P effects vary per crop activity. $D1_{l,c,s,p}$ is the difference in cultivated area per crop activity between period $_{p}$ and period $_{p+1}$ (Equation 6.7). When the cultivated area in period $_{p+1}$ is smaller than the cultivated area in period $_{p}$, then $D1_{l,c,s,p}$ is positive. This means that part of the available residual P cannot be used in period $_{p+1}$. If the cultivated area in period $_{p+1}$ is larger than the cultivated area in period $_{p}$, then $D1_{l,c,s,p}$ is negative. This means that part of the area cultivated in period $_{p+1}$ cannot benefit from residual P, because no P was applied in the previous period. Similar constraints are used to calculate the difference in area per production activity between periods $_{p}$ and $_{p+2}$ ($D2_{l,c,s,p}$). Tree plantations were assumed to have a fixed growing period of 20 years. Consequently, $D1_{l,c,s,p}$ and $D2_{l,c,s,p}$ for tree plantations are fixed at zero.

$$
\begin{aligned}
D1_{l,c,s,p} &= CLA_{l,c,s,p} - CLA_{l,c,s,p+1} \\
D2_{l,c,s,p} &= CLA_{l,c,s,p} - CLA_{l,c,s,p+2}
\end{aligned}
\qquad 6.7
$$

The correction factors $R1_{s,p}$ and $R2_{s,p}$ are calculated per terrain type, since a crop activity can be replaced by another activity in the following period. When the sum of $D1_{l,c,s,p}$'s per terrain type and the sum of $D2_{l,c,s,p}$'s per terrain type are negative or zero, all available residual P can be used, and the correction factors are zero. When the sum of $D1_{l,c,s,p}$'s per terrain type and the sum of $D2_{l,c,s,p}$'s per terrain type are positive, the correction factors $R1_{s,p}$ and $R2_{s,p}$

equal the difference in cultivated area multiplied by the residual P per unit area that cannot be used. This is achieved with Equation 6.8. In principle, $R1_{s,p}$ and $R2_{s,p}$ can reach higher values, however the multi-period model keeps them as low as possible to avoid unnecessary high fertilizer costs. Equations 6.7 and 6.8 assume that the available residual P is used, if possible. For instance, assume the case of one ha of terrain type $_{s2}$ being cultivated with maize in period $_{p}$ and that in period $_{p+1}$ one ha of the same terrain type is cultivated with cassava. The constraints used for calculating the fertilizer-P requirement in the multi-period model assume that the residual effect of fertilizer-P applied in period $_{p}$ in maize is used in period $_{p+1}$ by cassava, i.e. the same location within the spatial unit is used in both periods.

$$
\begin{aligned}
R1_{s,p} &\geq \sum_{l}\sum_{s} D1_{l,c,s,p} \times mfr1_{l,c,s,p} \\
R1_{s,p} &\geq 0 \\
R2_{s,p} &\geq \sum_{l}\sum_{s} D2_{l,c,s,p} \times mfr2_{l,c,s,p} \\
R2_{s,p} &\geq 0
\end{aligned}
\qquad 6.8
$$

With these constraints the fertilizer-P requirement is slightly overestimated. Assume the case of one ha of continued banana on terrain type $_{s2}$ in period $_{p1}$ ($CLA_{l(bac),c(MBN),s(2),p(1)}$) being replaced by one ha of newly established banana in period $_{p2}$ ($CLA_{l(ba1),c(MBN),s(2),p(2)}$). In this situation $D1_{l(ba1),c(MBN),s(2),p(1)} = -1$ and $D1_{l(bac),c(MBN),s(2),p(1)} = 1$, since in the multi-period model the different growth stages of banana are described as separate production activities. In reality, all residual P from fertilizer applied in period $_{p1}$ can be used in period $_{p2}$, therefore $R1_{s(2),p(1)}$ should be zero. However, a $R1_{s(2),p(1)}$ of 29.6 kg P is obtained (1x184.7 - 1x155.1). In the land use scenarios presented in Section 6.4 the resulting overestimation was < 1% of the total fertilizer-P requirement.

Discussion

In multi-period LP-models transfer of location-independent quantities over time or inclusion of location-independent interactions between periods is possible as long as the interactions can be described or approximated with linear functions. Problems can occur with location-bound temporal interactions, because LP cannot discriminate between locations within spatial units. When, simultaneously, a spatial unit is used for several production activities at different locations within that spatial unit, differences may develop within the spatial unit, and the spatial unit is not homogeneous anymore. This results in different points of departure for production activities in the next period within the same spatial unit. In certain situations this can lead to irrealistic land use scenarios. Assume we have a cyclic multi-period LP-model with four periods and a maximum length of the growing period for banana ($_{l=ba1,\ bac}$) and palmheart ($_{l=pa1,\ pac}$) of three periods. The economic surplus is optimized, and banana has a higher economic surplus than palmheart. Figure 6.2A shows a feasible land use scenario obtained with this model that can be carried out in reality. Figure 6.2B shows a feasible solution of the LP-model that cannot be carried out in reality: the LP-model cannot discriminate between different locations within the same spatial unit, so that continued production of palmheart ($_{l=pac}$) in period 2 has to take place on a different location than where the palmheart plantation was established ($_{l=pa1}$) in period 1. With the help of binary variables this problem in LP-models can be solved: for each plot (e.g. of 10 or 100 ha) within a spatial unit a binary variable has to be defined. Examples are presented by Cox & Sullivan (1995) and Hof *et al.* (1993). For regional studies, this implies a large number of binary variables, which causes large models and extremely long computation times. Therefore, the use of binary variables is no option for the NAZ, a region of > 500,000 ha. The problem as illustrated in Figure 6.2 did not occur in the multi-period model for the NAZ, because the number of periods in the multi-period model was chosen so that it was equal to the optimum length of growing periods (20 years, or four periods of five years).

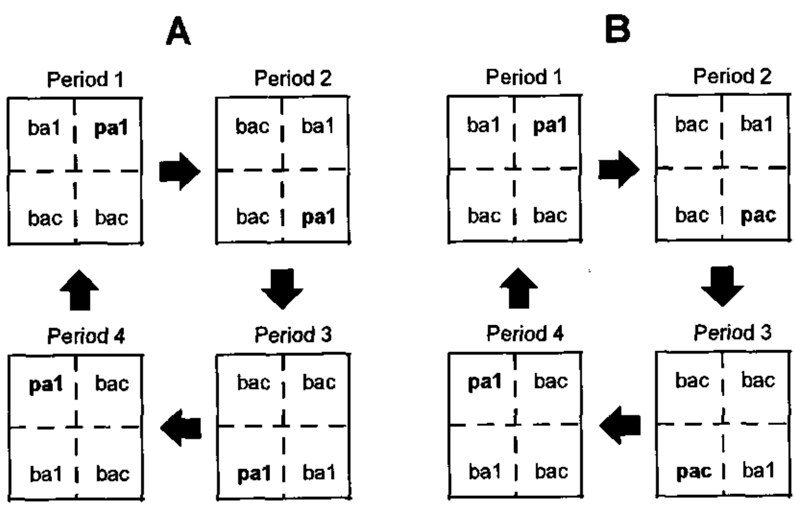

Figure 6.2 Practicable (A) and impracticable (B) land use scenarios for one spatial unit, produced with a cyclic multi-period model with four periods and with a maximum length of the growing period of three periods for banana and palmheart. For codes see Table 6.1.

6.4 Results of the multi-period model and comparison with the results of the single-period model

In the previous sections aspects of the cyclic multi-period LP-model for the NAZ were presented. Some additional information will be given on this multi-period model, before the optimization results are presented and compared with the results of the single-period model for the NAZ (detailed optimization results can be found in Appendix 8).

Table 6.5 Maximum allowed fluctuations between periods, expressed in % deviation from period 1, for the five policy views in the multi-period model.

Variable	Free Enterprise FE	National Development ND	Regional Development RD	Environmental Protection EP	Nature Conservation NC
Animal units	25	25	25	25	25
Area per form of land use	25	25	25	25	25
Biocide leaching risk	10	10	10	10	5
Biocide use	10	10	5	5	10
N-loss	10	10	10	10	5
Employment	10	5	5	10	10
Economic surplus	5	5	10	10	10
Income per person	10	10	5	10	10

In the multi-period model the objective functions are formulated as the totals *over all periods*. For instance, the total biocide leaching risk in 20 years is minimized and the average income per person in 20 years is maximized. Some stability over the periods is required to avoid severe social or environmental problems. This is regulated by restricting fluctuations *between the periods* (i.e. deviation from period 1, Table 6.5). As data on acceptable fluctuations per policy view were missing, the following tentative values were used. For the number of animal units and the area per crop a fluctuation of up to 25 % more or 25 % less than in period 1 is accepted. This corresponds to changes in livestock numbers and area per crop observed in the past in Costa Rica (Van Sluys *et al.* 1987; Kruseman *et al.* 1994). For the other variables mentioned in Table 6.5 the maximum allowed deviation from the value in period 1 is set at 10 %; only up to 5 % fluctuations are allowed when the variables are used in an objective function optimized in a particular policy view, assuming that fewer fluctuations are accepted when a variable is considered important. The restrictions on minimum economic surplus, minimum income, minimum employment and minimum export (Table 2.3) are defined *per period*. Population and prices of inputs and outputs were kept the same for all periods.

The multi-period model was run with "average" prices and "average" coefficients for nutrients and biocides (Chapter 3).

Table 6.6 Multi-period model: maximum observed fluctuation between periods, expressed in % deviation from period 1, for several variables in the five policy views.

Variable	National Free Enterprise FE	Regional Development ND	Environ-Development ment RD	Nature mental Protection EP	Conservation NC
Area under agriculture	0.0	0.0	1.3	0.0	4.7
Biocide leaching risk	1.9	2.9	**10.0**[a]	**10.0**	**5.0**
Biocide use	3.0	4.1	**5.0**	**5.0**	0.0
Biocide use per unit area	2.9	4.2	6.3	0.0	6.0
N-loss	7.3	3.1	3.2	4.4	1.8
Employment	5.1	0.3	0.0	4.1	1.9
Economic surplus	**5.0**	**5.0**	7.6	2.2	1.0
Income per person	3.3	3.0	**5.0**	0.0	0.0

[a] figures in bold = binding constraints (Table 6.5).

Figures 6.3 and 6.4 and Table 6.6 show the results of the optimization runs with the multi-period MGLP-model. Figure 6.3 shows the average yearly values of objective function values in each of the four periods of five years for the five policy views. Average yearly values are used in Figure 6.3 instead of totals per period of five years, to make an easier comparison with the objective function values of the single-period model (Figure 5.1). Below, the most remarkable results of the multi-period MGLP-model are described:

- The *average yearly objective function values* show some fluctuations between periods (Figure 6.3). Table 6.6 presents the observed maximum fluctuations over the periods in objective function values for each policy view. These fluctuations are mainly caused by fluctuations in agrotechnical coefficients caused by variation in weather conditions;
- The bold figures in Table 6.6 indicate when the bounds on fluctuations, presented in Table 6.5, are binding. In other words, changes in these bounds will affect objective function values and land use allocation. With the help of the MGLP-technique the effects of changing bounds can be determined easily;
- The area per crop does not fluctuate much between periods, but the area per growth stage of a crop fluctuates considerably in policy views Free Enterprise (FE), National Development (ND) and Regional Development (RD) (Figure 6.4). By changing the area per growth stage between periods, the fluctuations in variables between periods are smoothed. For instance, in

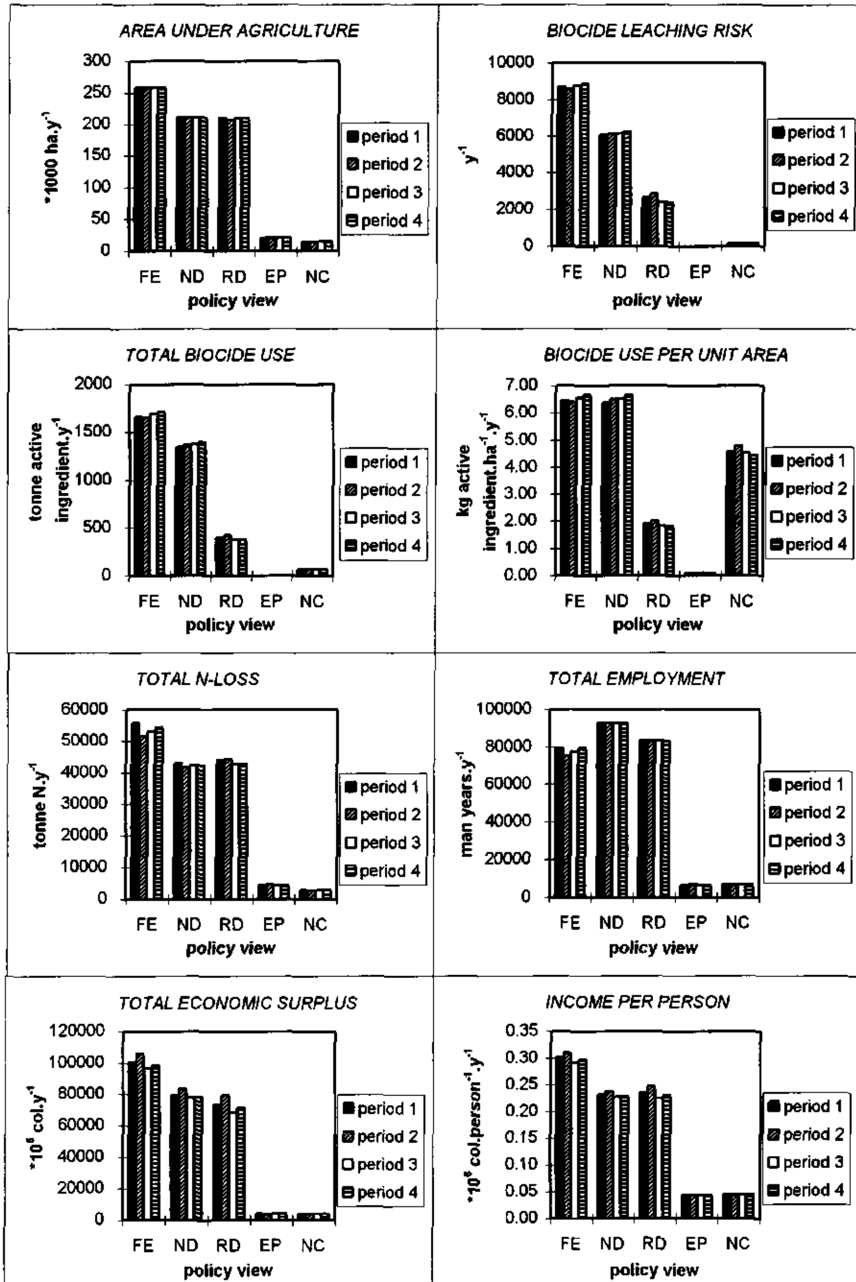

Figure 6.3 Multi-period model: objective function values for the five policy views. For codes see Table 2.2.

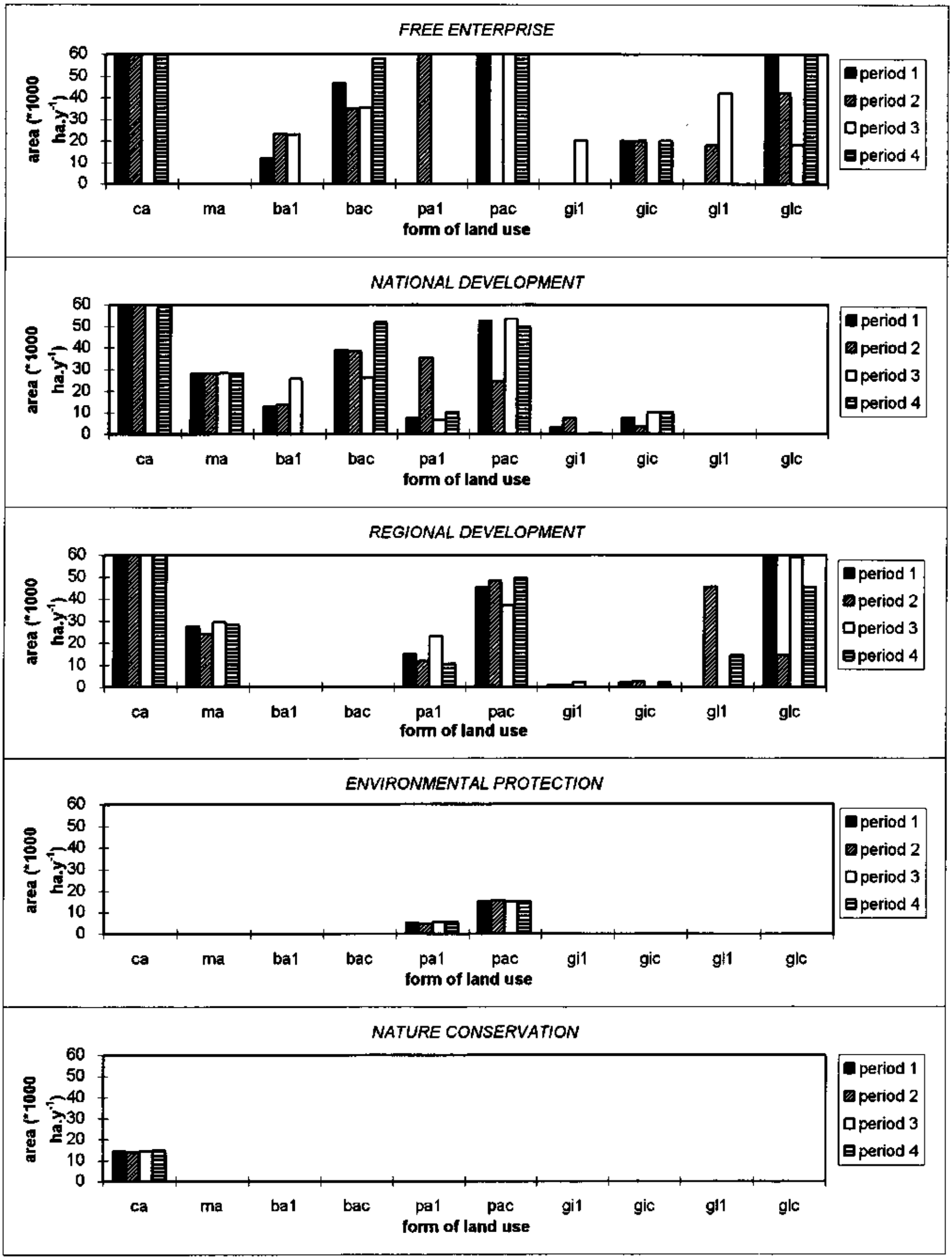

Figure 6.4 Multi-period model: distribution of forms of land use over the periods for the five policy views. For codes see Table 6.1.

policy view FE the maximum allowed deviation in total economic surplus is 5%. The economic surplus under continued production of banana ($_{l=bac}$) is higher than in the establishment period ($_{l=ba1}$). When more banana plantations are established in a period with high yields and more continued banana production takes place in periods with low yields, the fluctuation in the total economic surplus diminishes;

- The bounds on fluctuations between periods for economic surplus and biocide leaching risk are most often binding (Table 6.6). Figure 6.1C shows that the fluctuations in economic surplus caused by variations in weather conditions can be considerable. The strong fluctuations in biocide leaching risk that were found between periods are caused by changes in land use allocation to growth stages (policy views RD and EP (Environmental Protection)), and changes in allocation to production techniques and terrain types (policy views RD and NC (Nature Conservation)).

In Figures 6.5 and 6.6 the results of the single-period model and multi-period model are compared to evaluate whether inclusion of temporal aspects resulted in different objective function values and land use allocation. For this purpose the results of the multi-period model, in terms of objective function values and land use allocation, were transformed to *average yearly values over all four periods*. Most remarkable are the small differences in average yearly objective function values and average yearly land use allocation for policy views FE, ND, EP and NC. Policy view RD, the only policy view with environmental and socio-economic objectives, shows clear differences between the single-period and multi-period model for several objective function values and average land use allocation. Banana and grass pasture in the single-period model are replaced by maize in the multi-period model (Figure 6.6). In policy view RD, also a shift to more environment-oriented production techniques with reduced biocide use ($_{c=MbN,\ c=mbN}$) in the multi-period model takes place. These differences between the two models are caused by the highly conflicting objectives (environmental as well as socio-economic) and the bounds on allowed fluctuations between periods in the multi-period model: the income per unit area from maize is very low, which means that the fluctuations in income per hectare of maize contribute very little to the relative fluctuations in income per person (Figure 6.1). By selecting maize in the multi-period model instead of banana, the fluctuations in income per person are limited. The bound on fluctuations in income per person resulted in a lower income per person compared with the single-period results. However, through the changes in land use allocation it also resulted in more favourable values for total employment and total biocide use in the multi-period model.

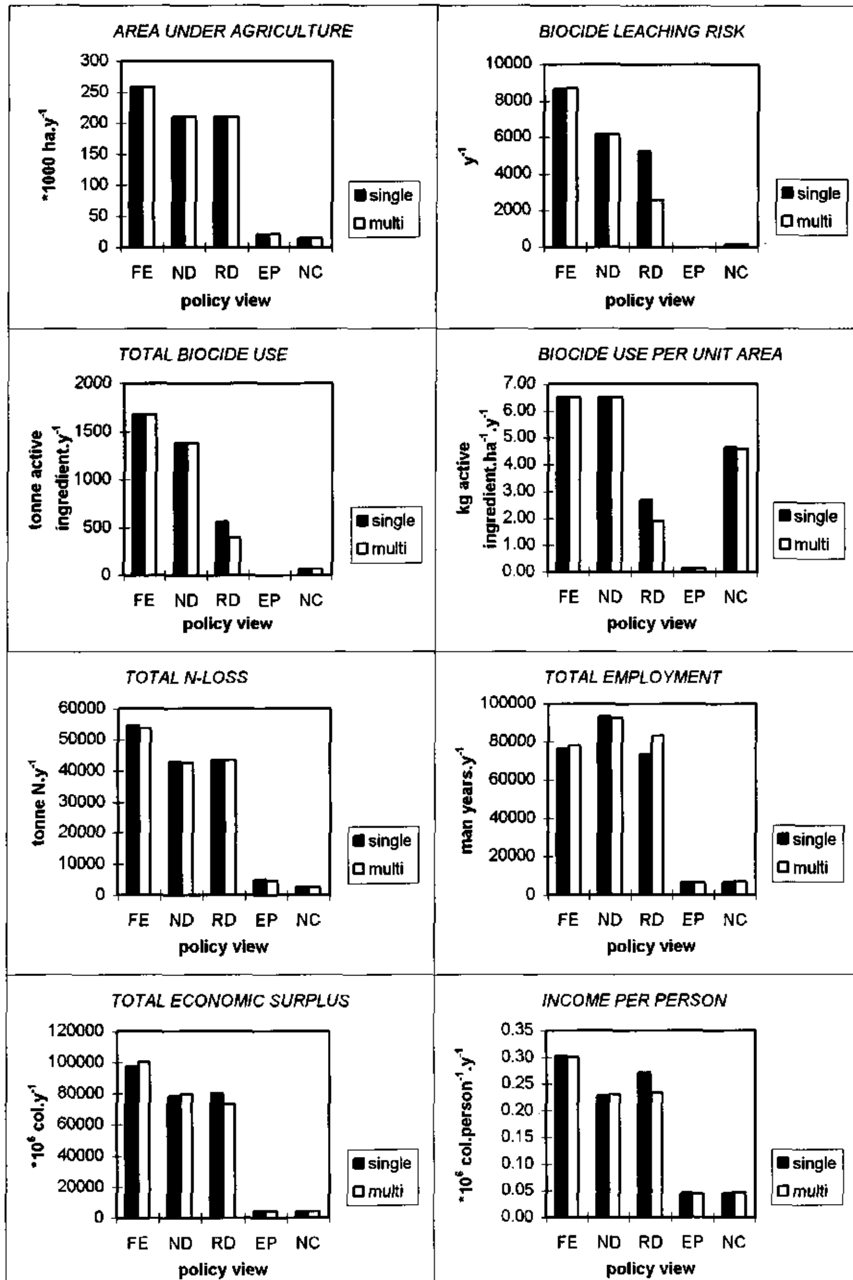

Figure 6.5 Comparison of the single-period and multi-period model for five policy views: average yearly objective function values. For codes see Table 2.2.

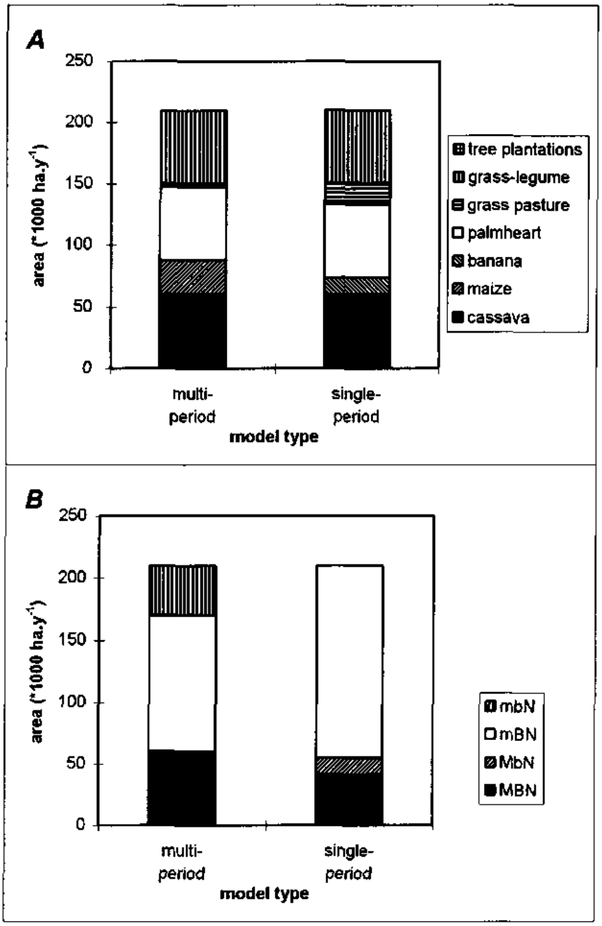

Figure 6.6 Comparison of the single-period and multi-period model for policy view Regional Development: selected forms of land use (A) and selected production techniques (B). For codes see Table 2.4.

6.5 Discussion

Multi-period LP-models offer the possibility to include explicitly temporal aspects (*i.e.* 1. *Growth and ageing*, 2. *Fluctuations*, 3. *Temporal interactions*) in long-term explorations. This has some clear advantages:

- Model-builders are forced to describe explicitly the temporal aspects of land use, and decision makers are made aware of possible fluctuations between periods, differences in inputs and outputs per growth stage and temporal interactions;

- *Cropping sequences and optimum length of growing periods for perennials* (if not fixed) can be determined by the optimization model. Predefining all feasible cropping sequences for use in a single-period model is virtually impossible;
- A multi-period model offers more specified land use scenarios in time. The consequences of temporal aspects on land use scenarios are quantified and bounds can be put on fluctuations between periods.

In theory, all kinds of temporal aspects of land use can be included in multi-period LP-models for long-term explorations, as was demonstrated in this chapter. However, in practice the possibilities are limited owing to the strong increases in model size and computation time with each additional period included. With the cyclic structure used in this study, the number of periods could be limited to four, because no additional periods for starting and ending were needed to avoid effects caused by discontinuity; without the cyclic structure ten periods would have been needed. Unfortunately, the cyclic structure also caused technical problems, as often alternative best solutions were found. If there are no differences between periods in input and output coefficients, it does not make a difference to the LP-model in which period a perennial crop is established. This means that it makes no difference which period in the cyclic model is called the first period.

In long-term explorations much attention is paid to the agro-ecological aspects of land use. These aspects often have strong temporal *and* spatial dimensions. Exactly, *location-bound temporal interactions* are difficult to include in LP-models. LP-models cannot discriminate between locations within one spatial unit. If, simultaneously, different land uses are allowed at different locations within the same spatial unit, the starting conditions within the spatial unit for the next period are not homogeneous anymore. For the description of location-bound temporal interactions in LP-models often many additional variables are needed. This was shown for the approach to include residual P-effects (Section 6.3). With the help of binary variables a more accurate description of location-bound temporal interactions can be obtained. For regional studies, this implies a large number of binary variables, which causes large models and extremely long computation times. For the farm level, the use of binary variables might be an option to solve this problem.

Almost the same *average land use scenarios* were obtained for the NAZ with the single-period as with the multi-period model. In the multi-period exercise, some fluctuations in coefficients between periods were observed. These were caused by variation in weather conditions resulted in fluctuations between periods in variable values. These fluctuations were smoothed by interactions in time (e.g. selling and purchasing livestock, residual P) and, mainly, by adjusting the area per growth stage of a crop between periods. Only for policy view RD, with highly conflicting objectives, slightly different objective function values and land use allocations were obtained with the single-period and multi-period model. In this policy view the bounds on fluctuations between periods resulted in a shift in selected crops. When restrictions on fluctuations between periods were relieved or when there were no fluctuations between periods in input and output coefficients, differences between the single-period and the multi-period model were negligible for all policy views.

All temporal aspects discussed in this chapter can, in principle, be included in static single-period LP-models (Sections 6.1 to 6.3). Perennial crops with different lengths of growing periods have to be included as separate production activities. Fluctuations caused by variation in weather conditions can be included with the help of additional coefficients for extreme values of, for instance, yields (see example in Veeneklaas 1990). Also location-bound temporal interactions can be included (see for instance WRR 1992), but this requires cropping sequences to be predefined. Normally, predefined cropping sequences assume that each crop and growth stage occupy the same area in each year. In these situations smoothing of fluctuations between periods by adjusting the area allocated to forms of land use, growth stages, production techniques, etc. is not possible. Cropping sequences with different areas per crop or growth stage per period can be predefined. However, predefining all possible combinations that can be generated by multi-period models is virtually impossible.

From the above, it can be concluded that the use of multi-period LP-models in long-term explorations is only potentially useful in situations with strong fluctuations in input-output coefficients caused by variation in weather conditions *and* with strong bounds on allowed fluctuations. In all other cases the use of a single-period LP-model suffices.

7 GENERAL DISCUSSION AND CONCLUSIONS

7.1 Uncertainty

Long-term explorative studies confront biophysical or agro-ecological limits and possibilities with various policy views representing different perceptions of sustainability. An optimal combination of production activities is determined by choosing between crops, production techniques and locations. Production activities are characterized by their input-output coefficients. The absolute values of these coefficients determine the values of the objective functions. The ranking of production activities with respect to the coefficient included in the objective function determines the land use allocation. Uncertainties can affect the values of coefficients and the consequent ranking of production activities with respect to these coefficients. Therefore, information on the effect of uncertainties in coefficients on land use scenarios is needed to get an objective and more complete perspective of future land use options (Cleaves 1994). In long-term explorations agro-ecological limits and possibilities for land use under different policy views are explored, and several agro-ecological objectives are included. This resulted in the first research question:

What is the uncertainty in agro-ecological coefficients in long-term explorative studies, and how relevant are these uncertainties compared with other factors, such as differences between forms of land use, production techniques, terrain types and price uncertainties, for determining the objective function values and land use allocation?

Methods and results

To answer this question, first, uncertainties in agro-ecological coefficients related to nutrients and biocides were quantified for the case-study area (Northern Atlantic Zone of Costa Rica, NAZ). Quantification of uncertainties focused on these coefficients, because they were included in the agro-ecological objective functions. The uncertainties in the agro-ecological coefficients were mainly caused by lack of knowledge of underlying biophysical processes and lack of data for quantification. "Optimistic" and "pessimistic" estimates were generated, in addition to the "average" values normally used in deterministic Multiple Goal Linear Programming models (MGLP-models). The "optimistic" values represent the lowest fertilizer requirements, lowest N-loss, and the lowest biocide leaching risk; the "pessimistic" values represent the highest possible values for these coefficients under the assumption of production with "best technical means" (i.e. technically efficient production). The differences between "optimistic", "average" and "pessimistic" estimates are based on different perceptions of the influence of rainfall on leaching, the influence of the soil on retention of nutrients and biocides, etc. Also, the uncertainty in prices was quantified. "Low" and "high" prices were determined, in addition to an "average" price. Price levels were exogenous in the model; relations between price levels and supply and demand were not considered.

The basic assumptions in long-term explorations affect the range of possible values of agro-ecological coefficients. Besides, these assumptions bring about a strong correlation between the values of these coefficients (Section 2.3):

- Agronomic measures are carried out with "best technical means". In other words, uncertainty caused by variation in management of farmers is excluded and inputs are used in the technically most efficient way, as determined by the physical environment, the crop and the production technique. A "target-oriented" approach is used to estimate the inputs for a particular output level;
- Agro-ecological coefficients are often affected by the same processes. For instance, leaching of biocides and leaching of nitrogen are both affected by the absorption capacity of organic matter and the ground water recharge.

The difference in knowledge of underlying biophysical processes and the availability of data for quantification is reflected by the ranges of possible values for coefficients: the relative uncertainty in coefficients concerning biocides and nutrients is larger than that for yield, labour requirements, prices, etc. (Chapter 3 and Appendices 2 and 5). The effect of uncertainties on absolute values of coefficients is in the same order or larger than the effect of forms of land use on values of coefficients and, in general, the differences in coefficients between forms of land use are larger than the differences between production techniques or terrain types (Chapter 3, Table 7.1). Owing to the correlation of values of agro-ecological coefficients, uncertainty did not dramatically change rankings of production activities for agro-ecological objectives.

Table 7.1 Factors affecting values of various input-output coefficients of production activities in the long-term exploration of options for the NAZ.

	Biocide leaching	N-loss	Economic surplus
Form of land use	++[a]	++	++
Production technique	+	+	+
Terrain type	++	+	+
Uncertainty in agro-ecological coefficients	+++	++	+
Uncertainty in prices	-	-	++

[a] +++ = extremely large effect; ++ = large effect; + = small effect; - = no effect.

In Chapter 5 the sensitivity of a single-period MGLP-model (described in Chapter 4) to the uncertainties in agro-ecological coefficients was examined. During sensitivity analyses, values of agro-ecological coefficients were simultaneously changed from "average" to "optimistic" or to "pessimistic" values. Absolute values of the agro-ecological objective functions were strongly affected by the uncertainty (Table 7.2). For instance, the total N-loss decreased up to 66 % or increased up to 137 % as compared with the model runs with "average" coefficients; the total biocide leaching risk decreased up to 100 % or increased up to 7900 % as compared with the model runs with "average" coefficients. Land use allocation hardly changed under the influence of uncertainty in agro-ecological coefficients, because rankings of production activities with respect to agro-ecological coefficients hardly changed (Section 5.3). The effect of uncertainties in agro-ecological coefficients was compared with the effect of uncertainties in product prices (Section 5.4). During sensitivity analysis, prices were simultaneously changed from "average" to "low" or to "high" values. Absolute values of economic objective functions were clearly affected. The total economic surplus decreased up to 80 % or increased up to 50 % as compared with the model runs with "average" coefficients. In contrast to agro-ecological coefficients, a dramatic change in ranking of cassava production for economic coefficients was observed, when "low" prices were used and, consequently, optimal land use allocation changed under the influence of changes in prices. Prices of different agricultural products do not necessarily show correlations. Therefore, with the type of sensitivity analysis executed in this study few conclusions can be drawn on the effects of uncertainties in prices on optimal land use allocation. However, the effects of extreme prices on economic objective function values can be determined.

Table 7.2 Consequences of uncertainties in different types of coefficients on absolute values of objective functions and on land use allocation.

Type of coefficient	Absolute values of objective functions	Land use allocation
Agro-ecological coefficients (nutrients and biocides)	+++[a]	-/+
Economic coefficients (prices of agricultural products)	++	++[b]

[a] +++ = extremely large effect; ++ = large effect; + = small effect; - = no effect;

[b] in the present study only a limited sensitivity analysis was conducted, but if different combinations of price levels are used large effects on land use allocation can be observed.

Conclusions and practical implications

- In long-term explorations, the values of agro-ecological coefficients are often strongly correlated, owing to the type of uncertainty in agro-ecological coefficients and the assumption of production taking place with "best technical means".

In long-term explorations variation in management is not taken into account and only technically efficient production is considered. Production activities are included that are not yet practised. Consequently, lack of knowledge of underlying processes or lack of data for quantification can be important sources of uncertainty in agro-ecological coefficients in these studies. Because of the correlation between values of agro-ecological coefficients only a few additional model runs were required to quantify model sensitivity to uncertainties in these coefficients. Coefficients were simultaneously changed to "optimistic" or "pessimistic" values. This way the effect of uncertainties on *objective function values* as well as *on land use allocation* could be determined. With the help of stochastic approaches identifying the most important knowledge gaps is more difficult, because these approaches "hide" the effects of uncertainties in average best objective function values and land use allocation.

- In the *long-term exploration for the NAZ, differences between forms of land* use, production techniques and terrain types in coefficients related to nutrients and biocides are more important for land use allocation, than uncertainties in these coefficients owing to lack of knowledge or lack of data for quantification.

For the determination of the absolute values of objective functions under different policy views, the uncertainties in coefficients should be carefully determined. However, the uncertainty in agro-ecological coefficients is of minor importance for optimal land use allocation in the long-term explorations for the NAZ, because of the correlation of the values of these coefficients.

- In the NAZ, the "playing field" of policy makers is determined, in the first place, by the aspired objectives of the groups of stakeholders.

The differences between land use scenarios for the five *policy views* were large, regardless which agro-ecological coefficients or price levels were used. Consequently, first the objectives of various groups of stakeholders for future land use have to be explicitized. Only in the next step determination of the effects of uncertainties on land use options becomes important.

Future research

In this study attention was paid to data uncertainties (Section 1.3). However, model uncertainties can also be important. Below, a few model uncertainties that deserve attention in future research are indicated:

- In Linear Programming-models (LP) inputs and outputs are assumed to be spatially independent. The lack of spatial interaction can affect "optimal" land use scenarios (De Ridder 1997). For instance, if nutrient inputs through run-on from adjacent terrain units are not included in a LP-model, then the fertilizer requirement will systematically be overestimated;

- The inclusion of other coefficients to describe the ecological dimension of sustainability could result in different land use scenarios. Until now a limited number of easily quantifiable coefficients were used. Many other input-output coefficients can be used to describe the ecological dimension of sustainability, e.g. organic matter decrease or soil compaction (Senanayake 1991; Jansen *et al.* 1995). However, the selection of coefficients depends on the priorities of the groups of stakeholders (WRR 1995);
- Until now, knowledge of many biophysical processes is insufficient to put objective bounds on agro-ecological variables and, consequently these bounds were often not included. For instance, knowledge of harmful levels of some biocides in water is available, but knowledge is insufficient to translate this into bounds on the total biocide leaching risk (Jansen *et al.* 1995), as used in this study.

As more detailed information on policy views was missing, five tentative policy views were used in the present study. Uncertainty exists on the value-driven bounds in these policy views. Sensitivity analysis of the model to changes in these bounds is required. This was beyond the scope of this study, but a strong point of the MGLP-technique is though, that the model sensitivity to changes in normative bounds can easily be analysed.

7.2 Temporal aspects of land use

In long-term explorative studies generally static single-period LP-models with average yearly coefficients are used. This static approach ignores that temporal aspects can be important for sustainability issues. Four types of temporal aspects were distinguished in Chapter 1 of this thesis: 1. Developments in time; 2. Growth and ageing; 3. Fluctuations; 4. Interactions. In long-term explorations production with "best technical means" is assumed. Inclusion of further developments in production techniques, in policy views, etc. or abrupt changes in the physical environment such as volcanic eruptions (temporal aspect type 1) would be very speculative, therefore, they are not taken into account. The temporal aspects 2 to 4 can result in fluctuations in objective function values and land use allocation between periods. Limitation of these fluctuations is often important in policy views. For instance, large fluctuations in biocide leaching, and consequently high peak values, may be more harmful to the environment than a constant level of biocide leaching that results in the same total biocide leaching. This led to the second research question:

Can temporal aspects of land use be included in multi-period MGLP-models and what is the added value of the results of such models as compared to single-period models?

Methods and results

First, in Chapter 3 the effects of several temporal aspects on values of input-output coefficients were quantified. Input-output coefficients for different growth stages of perennials were determined, and fluctuations in production between periods caused by variation in weather conditions (mainly radiation) were calculated with the help of crop growth simulation models. Also, temporal interactions between production activities in the form of residual P from fertilizer were quantified. Relative fluctuations over time in fertilizer use were about the same as the fluctuation in production (< 4 %), but the relative fluctuation in economic surplus was much larger (up to 20 %; Figure 6.1). Differences in input-output coefficients between growth stages of perennials were larger than the fluctuations caused by variation in weather conditions between periods. For instance, variation in weather conditions between periods resulted in a fluctuation in production of palmheart of less than 4 %, whereas the difference in production between the establishment period and continued production was 35 %.

In Chapter 6 options to include temporal aspects of land use in LP-models were examined with the help of a literature review, and by transforming the single-period MGLP-model for the NAZ into a multi-period version. Growth and ageing of perennials, fluctuations caused by variation in weather conditions as well as temporal interactions could be included in the multi-period model. However, the description of temporal aspects of land use in LP was complicated by interactions between temporal *and* spatial aspects of land use. Land use in one period can affect the suitability for land uses in subsequent periods, or it can affect the input-output coefficients in subsequent periods. For instance, after felling of trees, woody material remains in and on the soil. This impedes mechanized soil preparation for subsequent crops on the same plot. Less fertilizer-P is needed when crops can profit from the residual effect of P applied in former periods on the same plot. Description of these processes requires that locations within spatial units can be traced in time. LP cannot discriminate between locations within one spatial unit. However, approximation of the residual effect of P was possible with the help of additional variables and under specific assumptions (Section 6.3).

The results of the multi-period MGLP-model were compared with the results of the single-period MGLP-model. The differences in average yearly land use allocation and objective function values between both MGLP-models were small. The small differences between land use scenarios produced by these models were due to fluctuations between periods caused by variation in weather conditions, and by restrictions on these fluctuations between the periods in the multi-period model. Fluctuations between periods were smoothed by interactions between periods and by adjusting the selected crops and growth stages per period.

Conclusions and practical implications

- In theory, all temporal aspects of land use can be included in multi-period LP-models, although location-bound interactions in time pose serious problems owing to the limitations of the LP-technique.

Proper description of location-bound interactions in time requires that individual hectares can be traced through time. However, LP cannot discriminate between locations within the same spatial unit. With the help of binary variables tracing locations through time would be possible, but both model size and computation time increase enormously if many binary variables are used. Precisely the strong increase in model size caused by the inclusion of periods is considered one of the main problems of multi-period LP-models. Therefore, the use of binary variables is no option for studies at the regional level, but at the farm level or subregional level this technique could be useful.

- In long-term explorations, a multi-period model may have added value only in situations with large fluctuations between periods, *and* when strong bounds are put on these fluctuations.

Multi-period LP-models are only useful when fluctuations in coefficients are larger than allowed fluctuations in policy views. This can be the case, e.g. in regions with highly erratic rainfall, where water-limited production in one year can differ enormously from production in the next year. In humid regions, such as the Northern Atlantic Zone, this is often not so. In most cases the use of a single-period LP-model suffices. All temporal aspects considered in this study can also be included in static single-period LP-models. Different lengths of growing periods of perennials can be included as separate production activities. Fluctuations in input-output coefficients caused by variation in weather conditions can be included with the help of additional coefficients for extreme values of, for instance yields. Also location-bound temporal interactions can be included in predefined cropping sequences. In all these cases, temporal aspects of land use are than described outside the LP-model and, consequently, the description is not complicated by the limitations of the LP-technique.

Future research

The following aspects related to temporal aspects of land use deserve attention in future research:

- Relatively little is known about the effect of fluctuations between periods on sustainability issues. For instance, negative nutrient balances in one year pose no problems as long as they are compensated in following years, but depletion cannot continue for many years without repercussions. The threshold value before (irreversible) damage to the physical environment occurs, is often unknown. Knowledge of these threshold values is needed to put well-defined bounds on fluctuations;
- LP limits the possibility of describing land use dynamics and spatial dimensions of land use simultaneously, but temporal and spatial aspects of land use are closely interrelated. In agriculture, land use and land features change continuously: crops are alternated in rotations, new areas are reclaimed, etc. It should be determined whether serious aggregation errors are made by not including temporal and spatial interactions in LP-models: with the help of nonlinear models that consider spatial and temporal interactions, the objective function values can be recalculated for the land use allocations obtained with the LP-model, and compared with the objective function values of the LP-model.

7.3 Long-term explorative studies and other land use studies

The aim and related basic assumptions of land use studies have consequences for the methodology, the results and their interpretation (Rabbinge & Van Ittersum 1994; Schoonenboom 1995; Van Ittersum *et al.* 1996). In previous chapters several examples were presented for long-term explorative studies: the assumption of production with "best technical means" affects the range of possible values for agro-ecological values (Chapter 3) and it affects the type of temporal aspects included (Chapter 6). In this section the consequences of aims and basic assumptions of land use studies are further elaborated by confronting the present study with two other land use studies for Costa Rica or parts of Costa Rica, namely CLUE-CR (Veldkamp & Fresco 1996) and USTED-REALM (Schipper 1996). The characteristics of the three studies are summarized in Table 7.3. Below, the consequences of the aim and basic assumptions for the time horizon, the type of production activities, the methods used for determining the input-output coefficients, the bounds on constraints, the definition of land use scenarios, the results and the analysis of model sensitivity are described. The results of the three types of studies can be complementary, and they may provide useful information in different phases of the land use planning process (Figure 1.1).

Aim and basic assumptions

Projective land use studies are based on the assumption that the past is the best predictor of the near future, in other words that future land use is determined in the same way and by the same land use drivers as in the past. They try to simulate or explain land use with the help of regression analysis to obtain *probable land use scenarios for the near future*. CLUE-CR is an example of a projective land use study for Costa Rica. With the help of multiple regression analysis it was determined which land use drivers are important at which spatial level, in order to simulate land use changes in the past and the future. Explorative studies aim at showing decision makers alternatives for current land use. These studies often use LP-techniques to explore optimum land use allocation within particular limits or under alleviated or tightened constraints. Short-term explorations examine the possibilities for land use taking into account current socio-economic and biophysical limits. Effects of small changes in the socio-economic constraints are also studied. USTED-REALM is an example of an explorative study, focusing on *plausible short-term options* for land use in a subregion of the NAZ, i.e. the Neguev. Long-term explorative studies, such as my study for the NAZ, try to show what is technically *possible in the long term* under different policy views, by using knowledge of biophysical processes underlying agricultural production. In long-term explorations it is assumed that socio-economic limits to production may be alleviated, however current biophysical constraints are assumed to be more stable.

Time horizon

Land use in the short term is often more related to current land use than land use in the long run. CLUE-CR and USTED-REALM both have a relatively short time horizon (< 10 years). Therefore, they are searching for probable or plausible land use scenarios. Plausibility of the land use scenarios is evaluated by comparing the results with the current or past situation. In long-term explorations no fixed time horizon is used. However, it is assumed that within the long-term (20-30 years) the socio-economic constraints may be alleviated and that included new production techniques may be adopted. The present study tries to show what is technically possible in the long term, without judging the probability or plausibility of the land use scenarios for the future. Therefore, land use scenarios itself cannot be validated, only individual production activities and constraints are checked on feasibility.

Table 7.3 Some characteristics of three land use studies for Costa Rica or parts of Costa Rica.

	CLUE-CR	USTED-REALM	The present study
Aim	- Projection of future land use (What is the probable land use in the future in Costa Rica if the past land use system is extrapolated?)	- Exploration of land use options for the short term in the Neguev (What are the plausible options for land use under changing constraints or coefficients in the short term?)	- Exploration of land use options for the long term in the NAZ (What are the ultimate options for sustainable land use under different policy views in the long run, and what are the trade offs between objectives?)
Assumptions	- Future land use is determined by the same land use drivers and in the same way as in the past	- Optimization mimics behaviour of land users, and is consistent with regional objectives - Socio-economic constraints will hardly change (e.g. farm structure and size)	- Socio-economic constraints may be alleviated, biophysical constraints hardly change - Production takes place with "best technical means"
Time horizon	- 1-10 years (simulates 21 years)	- 5-10 years	- Not fixed (20-30 years)
Spatial level	- Grid cell to national level (multiple scales)	- Farm level and settlement level	- Regional level
Land uses	- Agriculture, natural vegetation and other uses	- Agricultural land use by small farmers only	- Agricultural land use only
Production activities	- Current input-output relations - Based on surveys and statistical data	- Current, alternative and potential input-output relations - Based on surveys, literature, expert knowledge, experiments and simulation models	- Technically efficient input-output relations - Based on knowledge of biophysical processes, and assuming production with "best technical means"
Modelling approach	- Simulation of changes in land use allocation per year, based on regression analysis - Spatial and temporal interaction in model structure	- Land use optimization with LP for one objective - No spatial interaction in model structure, temporal interaction for labour availability	- Land use optimization with LP for multiple objectives and various policy views - Some temporal interaction in model structure of multi-period model
Land use scenarios	- Probable land use under deviations from the current situation (e.g. outbreak of crop disease, abolition of national parks)	- Optimal land use if coefficients or constraints change slightly	- Optimal land use under different policy views
Model sensitivity	- Extensive sensitivity analysis to be executed	- Standard, partial LP sensitivity analysis with shadow prices, etc.	- Effect of uncertainty in coefficients

Spatial scale
Projective and explorative studies can be executed at various aggregation levels, depending on the research question and assumptions underlying the research question. In CLUE it is assumed that land use drivers can act at different scales, consequently a multi-scale model is used. In USTED-REALM the farmers are regarded the final decision makers on land use, therefore the farm-level and various farm types are included. Long-term explorations, such as the present study, assume that current socio-economic conditions nor farm infrastructure are limiting, which is why these studies are often, but not exclusively, executed at the regional level or higher levels. Results of a study at one aggregation level cannot be used for conclusions or recommendations on another aggregation level. For instance, with the results of CLUE-CR or the present study no conclusions can be drawn on probable land use or options for the farm level, because this aggregation level was not included in the studies.

Type of agricultural production activities
The time horizon affects the type of production activities included in the land use study. CLUE-CR and USTED-REALM have a relatively short time horizon, so that both studies include current production techniques. In CLUE-CR the relation between land use and land use drivers is based on past and actual land use data. Incorporation of new crops or production techniques in this model is difficult, because no relationships with land use drivers are known (Veldkamp & Fresco 1996). USTED-REALM also includes some alternative and more potential production activities as compared with current land use. These may become interesting under the influence of changing external factors or constraints (Jansen & Schipper 1995). In the present study only technically efficient land uses are included, as it aims at showing ultimate options in the long run, according to current knowledge and currently known techniques. Production activities are selected and quantified systematically with the help of predefined production orientations. The selection of production activities is not necessarily limited to crops currently grown. Completely new crops can be introduced and their attractiveness as compared to other crops can be examined.

Methods for describing production activities
Information on current input-output relations is obtained from surveys and field observations. Alternative and potential crop activities and livestock activities in short-term explorations are described with the help of results from experiments, expert knowledge, literature data and simulation models (Jansen & Schipper 1995). For the description of the production activities in long-term explorations knowledge of biophysical processes underlying agricultural production is used exclusively. The potential and water-limited production levels are determined with

simulation models. All input-output coefficients are determined in a "target-oriented" approach, and assuming production with "best technical means" (Table 1.1). As a result only technically efficient production activities are included. All production activities are described in a similar way. This makes comparison for various sustainability dimensions possible. For instance, palmheart appeared to be attractive from an economic point of view at all considered price levels; from an environmental point of view palmheart is attractive owing to the low biocide use, but N-loss is high as compared with other production activities.

Bounds on constraints

Land use studies focusing on the short term, assume that both biophysical and socio-economic constraints or land use drivers will hardly change within the considered time horizon, in other words the constraints are considered "fixed" preconditions. For instance, in USTED-REALM labour availability per farm type is included as a constraint. The effects of deviations from the current situation are examined with scenarios and in sensitivity analyses. In long-term explorative studies *value-driven* information is strictly separated from *technical* information. Biophysical and technical processes define "fixed" constraints. Bounds on value-driven constraints such as minimum income per person or minimum area for nature conservation, on the other hand, may be changed by man. By discriminating between these two types of constraints, the consequences of value-driven choices for long-term options for land use can be examined. For instance, the results of the present study showed that the socio-economic objectives and environmental objectives were highly conflicting in the NAZ, i.e. high values for total economic surplus were invariably combined with a large area under agriculture and high total biocide use and high total N-loss.

Definition of land use scenarios

In CLUE-CR land use scenarios represent probable future land use scenarios under unchanged or changed external conditions. In USTED-REALM land use scenarios represent optimal land use under a set of current constraints or with small changes in external factors (deliberately changed or not). Land use scenarios in the present study show optimal land use under different policy views or different perceptions of sustainability, in other words they show the consequences of different priorities. The differences between land use scenarios for the five tentative policy views in the present study are large, regardless which agro-ecological coefficients or prices are used. This means that the "playing field" for policy makers is large and that, for strategic planning, being clear about the aspired objectives is important.

Results

Tables 7.4 to 7.6 show some results of the three land use studies. In CLUE-CR future land use is simulated taking the measured land use in 1973 as the starting point. The simulated land use for 1994 differs from the measured situation in 1973, but simulated scenarios resemble each other (Table 7.4). The differences between the land use in 1973 and 1994 were mainly caused by changing population size and distribution of population. No abrupt changes in the transition from the measured land use in 1973 to the simulated land use in 1994 occurred, because the relation between land use and human and biophysical land use drivers was kept unchanged. Trends in land use can be adjusted under the influence of, e.g. the outbreak of a crop disease. Because of the disease, crop production decreased and migration to urban centres was stimulated. The land use scenarios produced by USTED-REALM greatly differ from the measured situation in 1985 (no detailed data for 1973 available). The optimized land use scenarios resemble one another (Table 7.5), because they show the effect of relatively small changes in one external factor on land use allocation. The same objective function is used in each scenario, assuming that this represents the objectives of the current land users in the Neguev and that there are no conflicts between the objectives of individual farmers. The land use scenarios generated in the present study were compared with the measured land use in 1973, as was done for CLUE-CR (Table 7.6). Differences between the measured land use and the optimal land use scenarios, as well as mutual differences between several land use scenarios are large. The differences between the land use scenarios are much larger than the differences between the land use scenarios in CLUE-CR and USTED-REALM. The land use scenarios in the present study represent different perceptions of sustainability and are characterized by different objective functions and bounds on value-driven constraints. They also assume that current (socio-economic) constraints may be alleviated in the future. Therefore, optimal land use allocation and objective function values for different policy views can strongly diverge. Land use scenarios can be obtained that would require clear trend breaks with current land use trends. For instance, the present study shows that the area available for nature does not have to decrease, in fact it can strongly increase, whereas in the past the area for nature has only decreased. Long-term explorations do not judge the probability or social acceptability of the land use scenarios, but the results show the ultimate consequences of objectives with respect to land use. Therefore, they may widen perspectives for decision makers.

Table 7.4 CLUE-CR: land use allocation (%) in the NAZ[a] for two land use scenarios (Veldkamp & Fresco 1996).

	Peren-nials	Pas-ture	Arable land	Nature	Rest
Measured land use in 1973[b]	11	21	6	53	9
Simulated land use in 1994	8	37	11	34	9
Simulated land use in 1994 with disease outbreak	7	38	11	35	9

[a] based on overlays of Figure 2.1 and the grid maps in Veldkamp & Fresco (1996);
[b] measured land use in 1973 was used as the starting point for simulations with CLUE-CR.

Table 7.5 USTED-REALM for the subregion Neguev: land use allocation (%) for some land use scenarios (Schipper 1996).

	Peren-nials	Pas-ture	An-nuals	Rest[b]
Measured land use in 1985[a]	6	55	11	28
Optimum land use with 0 % discount rate	64	9	7	20
Optimum land use with 20 % discount rate	64	0	6	30

[a] no detailed data for 1973 for the Neguev available;
[b] "rest" includes "nature", in contrast to Table 7.4.

Table 7.6 Long-term explorative study (present study): land use allocation (%) in the NAZ for various policy views, obtained with "average" prices and "average" agro-ecological coefficients (Chapter 5).

	Peren-nials	Pas-ture	An-nuals	Rest[b]
Measured land use in 1973[a]	11	21	6	62
Optimum land use for Free Enterprise	21	16	11	52
Optimum land use for Regional Development	14	14	11	61
Optimum land use for Nature Conservation	0	0	3	97

[a] *based on Veldkamp & Fresco (1996);*
[b] "rest" includes "nature", in contrast to Table 7.4.

Analysis of model sensitivity

In CLUE-CR and USTED-REALM analysis of model sensitivity focused mainly on the effects of (small) deviations from actual values of coefficients and constraints. These changes represent possible developments in time, such as the outbreak of a disease, or policy measures to influence land use such as an increase in the price of biocides (Stoorvogel *et al.* 1995; Veldkamp & Fresco 1996; Schipper 1996). In the present study sensitivity analysis was used to examine the effect of uncertainty in agro-ecological coefficients and prices on land use options. The effect of value-driven aspects of land use was examined through the use of strongly divergent policy views (Chapter 5).

The results of all three types of studies can be used by decision makers in the land use planning process (Figure 1.1), i.e. they can be complementary. They play a role in distinct phases, each with its own objectives. Projective studies can play a role in the descriptive phase or the phase of problem definition: they show the projected land use in the future if policy and relations between land use and land use drivers do not change. This may reveal which problems can be expected in the future. CLUE-CR is still in development; the simulated land allocation for 1984 showed differences with the measured land use in 1984 (22-24 % for Costa Rica as a whole; Veldkamp & Fresco 1996). When the relation between land use drivers and spatial distribution of land use is correctly described, it can be used to project land use in Costa Rica. In the next step of land use planning, alternatives for land use should be explored. Short-term explorations show the options for land use and land use change under current restrictions. An adapted version of USTED-REALM (e.g. with inclusion of multiple goals, and constraints describing the access to inputs) could be used for exploring options in the short term. Long-term explorations serve to widen the perspectives of decision makers by releasing the current socio-economic bounds. These explorative studies can help by showing the consequences and possibilities under particular objectives and constraints, and they help to structure and organize a discussion on desires for the future and the consequences of these desires for other land use variables. Such explorations should be carried out in interaction with potential user groups or stakeholders. The present study was not carried out in an interactive way, because the aim of the study was to further develop some methodological aspects of explorative studies using MGLP. However, if the results of the model runs can be presented fast and in a comprehensible way to the groups of stakeholders, it can be used to organize and structure discussions on the desires for the future. In the design phase, comparison of land use options with projected land use reveals whether trend breaks or discontinuities are needed to reach a particular desired future. In this phase, studies are required that support the search for appropriate policy measures to direct land use. An attempt of such a study has been published by Kruseman *et al.* (1995) and Kruseman & Bade (1996).

This thesis contributed to some methodological aspects of long-term explorative studies. The case study for the NAZ showed that the inclusion of temporal aspects and uncertainties in agro-ecological coefficients did not greatly affect the results and implications of the study for policy makers. Rather than in further refinement of current methodologies for long-term explorative studies, the great challenge for future research lies in the application of the methodology in close interaction with user groups and in the complementary use of different types of land use studies. The first prerequisite for complementary use of results of different land use studies for use in land use planning is that researchers and decision makers are aware of the consequences of different aims and basic assumptions for the different types of studies.

Long-term explorations serve to widen the perspectives of decision makers. By quantifying the ultimate consequences and possibilities under particular objectives and constraints, they help to structure and organize a discussion on desires for the future and the consequences of these desires for other land use variables. Such long-term explorations may be vital in economies in transition such as many developing countries. They provide crucial information for well-informed strategic planning of sustainable land use.

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SUMMARY

The subject of this thesis

The increasing number of conflicts between groups of land users and the increasing awareness of the necessity for sustainable land use and sustainable development require strategic planning of land use. Long-term explorations can provide an important contribution to well-informed land use planning. The perception of future possibilities is often determined by extrapolations from the past and the present to the future. Long-term explorations do not take the current situation for granted. They explore future land use options by confronting biophysical and technical possibilities and constraints with the value-driven objectives of stakeholders.

The main characteristics of long-term explorations are (Chapter 1): exploration of options for the long-term (20-30 years), use of knowledge of biophysical processes to quantify new production techniques in a target-oriented approach, the assumption that production takes place with "best technical means" (i.e. inputs are used with the highest technical efficiency according to available knowledge and techniques), the discrimination between technical and value-driven information, and showing consequences of different perceptions of sustainability by generating land use scenarios for various policy views. These explorations often use Multiple Goal Linear Programming (MGLP) to explore the ultimate options for sustainable land use.

Two methodological aspects of long-term explorations are elaborated on in this thesis. Long-term explorations result in various land use scenarios, i.e. optimal land use allocation and optimal objective function values for various policy views. Model coefficients may be uncertain and different coefficients may result in different land use scenarios. Therefore, information on uncertainties and their effects is needed to obtain an objective picture of future land use options and constraints for future land use. This prompted the first research question:

- What is the uncertainty in agro-ecological coefficients in long-term explorative studies and how relevant are these uncertainties for objective function values and land use allocation, compared with other factors, such as differences between forms of land use, production techniques, terrain types and price uncertainties?

Land use has strong temporal aspects. Mostly, static single-period models are used for land use optimization. This suggests and implies that differences in time do not exist or are not important. Temporal aspects can affect the objective function values and land use allocation per period, and limitation of fluctuations between periods is often important in policy views. These observations led to the second research question:

- Can temporal aspects of land use be included in multi-period MGLP-models and what is the added value of the results of such models as compared to single-period models?

These research questions were elaborated on with data for the Northern Atlantic Zone of Costa Rica (NAZ; Chapter 2).

Uncertainty

To answer the first question, uncertainties in agro-ecological coefficients concerning nutrients and biocides and uncertainties in prices were quantified (Chapter 3). Next, a single-period MGLP-model was constructed for the NAZ (Chapter 4). With the help of sensitivity analyses the effect of uncertainties on land use scenarios was determined for five tentative policy views (Chapter 5).

The uncertainties in the agro-ecological coefficients were mainly caused by lack of knowledge of underlying biophysical processes and by lack of data for quantification. Consequently, no probability distributions could be determined. For a fixed production level, "optimistic" and "pessimistic" estimates for agro-ecological coefficients were generated in addition to the "average" estimates for agro-ecological coefficients. The "optimistic" values represent the lowest fertilizer requirements, the lowest N-loss and the lowest biocide leaching risk; the "pessimistic" values represent the highest possible values for these coefficients under the assumption of production with "best technical means". The differences between "optimistic", "average" and "pessimistic" estimates were based on different perceptions of the influence of rainfall on leaching, the influence of the soil on retention of nutrients and biocides, etc. For prices "low" and "high" levels were determined, in addition to an "average" price. It was assumed that the uncertainty in prices was caused by randomness or variation. Relations between supply and demand and price levels were not determined. The effect of uncertainties on absolute values of the agro-ecological and economic coefficients was in the same order or larger than the effect of the form of land use on values of coefficients while, in general, the differences in coefficients between forms of land use were larger than the differences between production techniques or terrain types (Chapter 3).

MGLP-models compare the contribution of alternative production activities to different objectives. The ranking of production activities with respect to the coefficient included in the objective function greatly determines the optimal combination of production activities. The absolute values of these coefficients determine the value of the objective functions. The assumptions in long-term explorations affect the range of possible values of agro-ecological coefficients to be considered and lead to a strong correlation of values of these coefficients:

- Agronomic measures are carried out with "best technical means", i.e. uncertainty caused by variation in management of farmers is excluded and inputs are used in the technically most efficient way, as determined by the physical environment, the crop and the production technique;
- Agro-ecological coefficients are often affected by the same environmental processes.

In Chapter 5 the sensitivity of a single-period MGLP-model (described in Chapter 4) to the uncertainties in agro-ecological coefficients was examined. Analysis of model sensitivity to these uncertainties required only a few additional model runs owing to the correlation of values of agro-ecological coefficients in long-term explorations: during sensitivity analysis, values of agro-ecological coefficients were simultaneously changed from "average" to "optimistic" or to "pessimistic" values. Absolute values of the environmental *objective functions* were strongly affected by the uncertainty in agro-ecological coefficients. However, *land use allocation* hardly changed under the influence of uncertainty, because rankings of production activities hardly changed. The effects of uncertainties in agro-ecological coefficients on objective function values were compared with the effects of uncertainties in product prices.

From the above it was concluded that, in long-term explorations, uncertainties in agro-ecological coefficients owing to lack of knowledge or lack of data for quantification strongly affect the objective function values. However, they *hardly affect the optimal land use allocation, because the ranking of production* activities hardly changes.

Temporal aspects of land use

To answer the second research question, several temporal aspects of land use were quantified (Chapter 3). After an inventory of possibilities and limitations to describing these temporal aspects with Linear Programming (LP), a multi-period version of the single-period MGLP-model was constructed. In Chapter 6 the results of this multi-period model were compared with the results of the single-period model.

In long-term explorations the following temporal aspects are relevant: 1. Growth and ageing of crops and livestock, 2. Fluctuations due to variation in weather conditions, 3. Interactions in time (Chapter 2). As stated before, in these studies production with "best technical means" is assumed. Inclusion of further developments in production techniques and in policy views, or abrupt changes in the physical environment such as volcanic eruptions (i.e. irreversible developments) would be very speculative, therefore, they are not taken into account. In Chapter 3 the effects of temporal aspects on values of input-output coefficients were determined. The coefficients for different growth stages of perennials were quantified, and fluctuations in production between periods owing to variation in weather conditions were calculated with the help of crop growth simulation models. Also, several temporal interactions were described: limitations to cropping sequences and residual effects of fertilizer-P.

In Chapter 6, the options to include temporal aspects of land use in LP-models were examined with the help of a literature review and by transforming the single-period MGLP-model for the NAZ into a multi-period version. In theory, all temporal aspects can be described within LP-models, however, the description of location-bound temporal aspects of land use is very complicated. Land use on a spatial unit in one period can affect the suitability for various land uses in subsequent periods, or it can affect the input-output coefficients in subsequent periods. For instance, after felling of trees woody material remains in and on the soil, which impedes mechanized soil preparation for subsequent crops on the same plot. Or, less fertilizer-P is needed if crops can profit from the residual effect of P applied in former periods on the same plot. Exact description of these aspects requires that locations within one spatial unit can be traced in time. However, LP cannot discriminate between locations within one spatial unit. With the help of binary variables it would be possible to trace locations through time, but both model size and computation time increase enormously if many binary variables are used. Precisely the strong increase in model size caused by the inclusion of periods is considered one of the main problems of multi-period LP-models. Therefore, the use of binary variables is no option for studies at the regional level.

A multi-period version of the single-period model was constructed, which includes examples of all three temporal aspects mentioned above. The results of this multi-period MGLP-model were compared with the results of the single-period model. The differences between both models in average yearly land use allocation and objective function values are small. They are caused by fluctuations in input-output coefficients between periods owing to variation in weather conditions, and by restrictions on the fluctuations in variables between periods in the multi-period model. Fluctuations in variables between periods are smoothed by interactions between periods and by adjusting the selected crops and growth stages per period.

From the above it can be concluded that, in theory, all temporal aspects can be described in multi-period LP-models, although location-bound interactions pose serious problems owing to the limitations of the LP-technique. It is discussed, however, that in long-term explorations the use of a multi-period model may have added value only in situations with large differences between periods and growth stages *and* if strong bounds are put on fluctuations. In most cases, single-period LP-models suffice, because in these models the relevant types of temporal aspects can also be included with the help of predefined cropping sequences. In that case, the description of temporal aspects takes place outside the LP-model and, consequently, it is not complicated by the limitations of the LP-technique.

Long-term options for land use in the NAZ

On the basis of the analyses in Chapters 3 and 5 the following conclusions can be drawn with respect to long-term options for land use in the NAZ and future research needs:

- The large differences between potential and water-limited productions on the one hand and the current production levels on the other, indicate that the production potential of the land is far from fully exploited;
- The forms of land use included in the present study for the NAZ show a wide range in biocide use, biocide leaching risk, fertilizer requirement and N-loss. These differences between forms of land use are larger than the differences between the included production techniques or terrain types. Therefore, if production takes place with "best technical means", adjusting the form of land use will result in a larger gain for the environmental objective functions, than shifting to another terrain type or production technique;
- The low *AF*-values indicate that the risk of biocide leaching in the NAZ is probably not very high when biocides are properly handled;
- In the NAZ conflicts over space need not necessarily arise between intensive agricultural land use and nature conservation, because more than 50 % of the area outside the national parks is unsuitable for intensive agriculture, pasture and tree plantations, and objectives of stakeholders can be achieved on the suitable area;
- In the present study, high values for socio-economic objective functions were associated with high values for environmental objective functions, i.e. the socio-economic objectives were clearly conflicting with the environmental objectives. Only in the runs with "optimistic" estimates for agro-ecological coefficients, high values for socio-economic objectives could

be combined with low values for biocide leaching risk. The environmental impact per unit economic surplus does not necessarily increase with increasing total economic surplus (Figure 5.3);

- The differences between land use scenarios for the five policy views were large, regardless which agro-ecological coefficients or price levels were used and regardless the temporal aspects of land use, i.e. the "playing field" for policy makers in the NAZ is large. Consequently, first the objectives with respect to future land use of various groups of stakeholders have to be explicitized. Only in the next step determination of the effects of uncertainties on land use options becomes important.

Concluding remarks

Long-term explorations serve to widen the perspectives of decision makers by showing ultimate consequences of policy objectives. As such they can be complementary to studies that aim at projection or short-term exploration of future land use, and they can provide vital information for land use planning. By quantifying the consequences and possibilities under particular objectives and constraints, they help to structure and organize a discussion on desires for the future and the consequences of these desires for other land use variables.

This thesis contributes to some methodological aspects of long-term explorative studies. The case study for the NAZ showed that the inclusion of temporal aspects and uncertainties in agro-ecological coefficients did not greatly affect the results and implications of the study for policy makers. The great challenge for future research rather lies in the application of the methodology in interaction with user groups and in the complementary use of different types of land use studies, than in further refinement of current methodologies for long-term explorative studies.

SAMENVATTING

Het onderwerp van dit proefschrift

Het toenemend aantal conflicten tussen landgebruikers en het groeiend inzicht in de noodzaak van duurzaam landgebruik en duurzame ontwikkeling vragen om strategische planning van landgebruik. Langetermijnverkenningen kunnen hieraan een belangrijke bijdrage leveren. De perceptie van de mogelijkheden in de toekomst is meestal gebaseerd op een extrapolatie van het verleden en heden naar de toekomst. Langetermijnverkenningen nemen de huidige situatie niet als uitgangspunt. Deze studies inventariseren de langetermijnopties voor duurzaam landgebruik, door biofysische en technische mogelijkheden en beperkingen te confronteren met normative doelstellingen van verschillende belangengroepen.

De belangrijkste kenmerken van langetermijnverkenningen zijn (hoofdstuk 1): verkenning van de lange termijn (20-30 jaar), het gebruik van kennis over biofysiche processen om nieuwe productietechnieken te kwantificeren, de aanname dat productie plaatsvindt met "best technical means" (d.w.z. het technisch meest efficiënte inputgebruik volgens de beschikbare kennis en technieken), scheiding van technische en normatieve informatie, het demonstreren van de effecten van verschillende opvattingen over duurzaamheid voor de opties voor landgebruik. Deze verkennende studies gebruiken meestal lineaire meervoudige doelprogrammering (MGLP) om de uiterste opties voor duurzaam landgebruik te verkennen.

Twee methodologische aspecten zijn nader bestudeerd en beschreven in dit proefschrift. Langetermijnverkenningen presenteren de opties voor landgebruik in de vorm van landgebruiksscenarios, d.w.z. optimale landtoewijzing en doelfunctiewaarden voor bepaalde beleidsvisies. Onzekerheden in modelcoëfficiënten kunnen invloed hebben op de landgebruiksscenarios. Kennis over onzekerheden en hun invloed op landgebruiksscenarios is dus noodzakelijk om een objectiever beeld te krijgen van de langetermijn-opties en -beperkingen voor landgebruik. Dit leidde tot de eerste onderzoeksvraag:

- Wat is de onzekerheid in agro-ecologische coëfficiënten in langetermijnverkenningen en hoe belangrijk zijn deze onzekerheden voor doelfunctiewaarden en landtoewijzing t.o.v. de verschillen tussen gewassen, productietechnieken, terreintypen en onzekerheden in prijzen?

Landgebruik heeft duidelijke tijdsaspecten. Meestal worden statische 1-periode modellen gebruikt voor landgebruiksoptimalisatie. Daarmee wordt impliciet aangenomen dat er geen verschillen in de tijd zijn, of dat deze niet belangrijk zijn. Tijdsaspecten kunnen de landgebruiksscenarios per periode beïnvloeden, en beperking van fluctuaties tussen perioden is vaak onderdeel van beleidsvisies. Deze observaties leidden tot de tweede onderzoeksvraag:

- Is het mogelijk om de tijdsaspecten van landgebruik te beschrijven binnen een meer-perioden MGLP-model en wat is de toegevoegde waarde van zulke modellen t.o.v. een 1-periode MGLP-model?

Deze onderzoeksvragen zijn uitgewerkt m.b.v. gegevens over de Noordelijke Atlantische Zone van Costa Rica (NAZ; hoofdstuk 2).

Onzekerheden

Voor het beantwoorden van de eerste vraag zijn de onzekerheden in agro-ecologische coëfficiënten m.b.t. nutriënten en biociden en de onzekerheden in prijzen gekwantificeerd (hoofdstuk 3). Vervolgens is een 1-periode model voor de NAZ geconstrueerd (hoofdstuk 4). M.b.v. gevoeligheidsanalyses is de invloed van deze onzekerheden op de landgebruiksscenarios voor 5 mogelijke beleidsvisies geanalyseerd (hoofdstuk 5).

De onzekerheden in agro-ecologische coëfficiënten werden vooral veroorzaakt door gebrek aan kennis over biofysische processen en gebrek aan gegevens voor kwantificering. Slechts de grenzen waartussen de mogelijke waarden per coëfficiënt liggen, konden worden aangegeven. Voor elk productieniveau zijn "optimistische" en "pessimistische" schattingen voor de agro-ecologische coëfficiënten gegenereerd, naast een "gemiddelde" waarde voor deze coëfficiënten. De "optimistische" schattingen vertegenwoordigen de laagste kunstmestbehoefte, de laagste N-verliezen en het laagste risico of biocidenuitspoeling. De "pessimistische" schattingen vertegenwoordigen de hoogste waarden voor deze coëfficiënten, aangenomen dat de productie plaatsvindt met "best technical means". De verschillen tussen "optimistische" en "pessimistische" schattingen zijn gebaseerd op verschillende inschattingen van de invloed van regenval op uitspoeling, de invloed van de bodem op adsorptie van nutriënten en biociden, etc. Voor prijzen is een "hoog" en "laag" prijsniveau bepaald, naast een "gemiddeld" niveau. Er is aangenomen dat de onzekerheden in prijzen worden veroorzaakt door variatie. Relaties tussen vraag en aanbod en prijsniveaus zijn niet geanalyseerd. Het effect van de onzekerheden op de absolute waarden van agro-ecologische en economische coëfficiënten was gelijk aan of groter dan het effect van het type gewas. Over het algemeen waren de verschillen tussen gewassen groter dan de verschillen tussen productietechnieken of terreintypen (hoofdstuk 3).

MGLP-modellen vergelijken de bijdrage van alternatieve productieactiviteiten aan verschillende doelfuncties met elkaar. Voor de selectie van activiteiten is vooral de rangorde van de activiteiten m.b.t. een doelfunctie van belang. Voor de doelfunctiewaarden is vooral de absolute waarde van de coëfficiënten belangrijk. De aannames binnen langetermijnverkenningen beperken het aantal mogelijke waarden van agro-ecologische coëfficiënten en ze hebben tot gevolg dat de waarden van deze coëfficiënten sterk gecorreleerd zijn:

- Productie vindt plaats met "best technical means". Onzekerheden als gevolg van variatie in management tussen boeren worden daarom buiten beschouwing gelaten en inputs worden op de technische meest efficiënte manier aangewend;
- Agro-ecologische coëfficiënten worden vaak door dezelfde omgevingsfactoren beïnvloed.

In hoofdstuk 5 is de gevoeligheid van het 1-periode MGLP-model geanalyseerd. Door de sterke correlatie was het effect van onzekerheden in agro-ecologische coëfficiënten op modeluitkomsten te analyseren met slechts een beperkt aantal extra "runs": de waarden van agro-ecologische coëfficiënten zijn gelijktijdig omgezet van "gemiddelde" naar "optimistische" of "pessimistische" waarden. De absolute waarden van de *doelfuncties* werden sterk beïnvloed door de onzekerheden in agro-ecologische coëfficiënten. Echter, de onzekerheden hadden slechts beperkte veranderingen in *landtoewijzing* tot gevolg, omdat de rangorde van de produktieactiviteiten nauwelijks veranderde. De effecten van onzekerheden in agro-ecologische coëfficiënten zijn vergeleken met de effecten van onzekerheden in prijzen.

Uit het bovenstaande kan worden geconcludeerd dat de doelfunctiewaarden in langetermijnverkenningen sterk worden beïnvloed door onzekerheden in agro-ecologische coëfficiënten als gevolg van gebrek aan kennis van biofysische processen of gebrek aan gegevens voor kwantificering. Echter, deze onzekerheden hebben nauwelijks consequenties voor de optimale landtoewijzing, omdat de rangorde van de productieactiviteiten nauwelijks veranderd.

Tijdsaspecten van landgebruik

Voor het beantwoorden van de tweede vraag zijn verschillende tijdsaspecten gekwantificeerd (hoofdstuk 3). Vervolgens zijn de mogelijkheden voor en de problemen bij het incorporeren van tijdsaspecten in Lineaire Programmerings-modellen (LP) bestudeerd d.m.v. literatuurstudie. Deze informatie is gebruikt om een meer-perioden versie van het 1-periode MGLP-model te maken. De resultaten van het 1-periode model en het meer-perioden model zijn met elkaar vergeleken in hoofdstuk 6.

Binnen langetermijnverkenningen zijn de volgende tijsaspecten van landgebruik relevant: 1. Groei en ontwikkeling van gewassen en vee, 2. Fluctuaties a.g.v. variatie in het weer, 3. Interacties in de tijd (hoofdstuk 2). Zoals eerder vermeld, gaan langetermijnverkenningen uit van productie met "best technical means". Het opnemen van verdere ontwikkelingen in productietechnieken en beleidsvisies, of abrupte veranderingen in de fysische omgeving zoals vulkaanuitbarstingen (d.w.z. onomkeerbare ontwikkelingen) zou speculatief zijn. Daarom is dit type tijdsaspect niet meegenomen. In hoofdstuk 3 is geanalyseerd in hoeverre de drie eerstgenoemde tijdsaspecten invloed hebben op input- en outputcoëfficiënten. Coëfficiënten voor verschillende groeistadia van meerjarige gewassen zij gekwantificeerd, en fluctuaties in productie a.g.v. variatie in weersomstandigheden tussen perioden, zijn berekend m.b.v. gewasgroeisimulatiemodellen. Ook enkele interacties in de tijd zijn beschreven: beperkingen op de opeenvolging van gewassen en het residuair effect van P.

In hoofdstuk 6 zijn de mogelijkheden voor het incorporeren van tijdsaspecten in LP-models verkend m.b.v. literatuurstudie en door het 1-periode model te transformeren in een meer-perioden model. In theorie zijn alle tijdsaspecten te beschrijven binnen LP, echter de beschrijving van plaatsgebonden tijdsaspecten is gecompliceerd. Landgebruik in een periode kan de mogelijkheden voor landgebruik en de input-output-coëfficiënten in een volgende periode op dezelfde plaats beïnvloeden. Bijv. na het kappen van houtplantages blijft er veel hout achter op een veld, dit kan problemen veroorzaken bij gemechaniseerde grondbewerking voor een volgend gewas op hetzelfde veld. Of, er is minder P nodig als een gewas kan profiteren van het residuair effect van P dat is toegediend in vorige perioden op hetzelfde veld. Voor een goede beschrijving van deze plaatsgebonden tijdsaspecten is het nodig dat locaties binnen een ruimtelijke eenheid getraceerd kunnen worden in de tijd. LP-modellen kunnen echter geen onderscheid maken tussen verschillende locaties binnen 1 ruimtelijke eenheid. M.b.v. binaire variabelen zou dit wel mogelijk zijn, maar zowel de modelgroote als de rekentijd nemen sterk toe als veel binaire variablen worden gebruikt. Juist de sterke toename van modelgrootte a.g.v. de introductie van perioden wordt gezien als een van de grootste problemen van meer-perioden modellen. Het gebruik van binaire variabelen is dus geen optie voor studies op regionale schaal.

Het meer-perioden model bevat voorbeelden van de drie typen tijdsaspecten. De resultaten van dit model zijn vergeleken met de resultaten van het 1-

periode model. De verschillen tussen beide modellen in gemiddelde landtoewijzing en doelfunctiewaarden zijn gering. De kleine verschillen die er zijn, werden veroorzaakt door fluctuaties tussen perioden in input-output-coëfficiënten a.g.v. variatie in weersomstandigheden en door beperkingen op de fluctuaties in modelvariabelen tussen perioden. Fluctuaties in modelvariabelen tussen perioden konden worden verminderd door temporele interacties en door de landtoewijzing per periode aan te passen.

Uit het bovenstaande kan worden geconcludeerd dat, in theorie, alle tijdsaspecten beschreven kunnen worden in meer-perioden MGLP-modellen, hoewel plaatsgebonden interacties ernstige praktische problemen opleveren a.g.v. de beperkingen van LP. Echter, in langetermijnverkennigen resulteert het gebruik van meer-perioden modellen alleen in een toegevoegde waarde wanneer de verschillen in input-output-coëfficiënten tussen perioden en groeistadia groot zijn *en* wanneer er sterke beperkingen zijn opgelegd aan de fluctuaties in modelvariabelen. In de meeste gevallen voldoet een 1-periode model, omdat de meeste tijdsaspecten ook met dit type model meegenomen kunnen worden m.b.v. voorgedefinieerde gewasrotaties. In dat geval vindt de beschrijving van tijdsaspecten buiten het LP-model plaats en zijn de beperkingen van LP niet van belang.

Langetermijnopties voor landgebruik in de NAZ

Op grond van de uitgevoerde analyses in hoofdstuk 3 en 5 kunnen de volgende conclusies worden getrokken m.b.t. de opties voor landgebruik in de NAZ en de behoefte aan toekomstig onderzoek:

- De grote verschillen tussen potentiële en water-gelimiteerde producties en de huidige productieniveaus gegeven aan dat het productiepotentieel van de NAZ niet volledig wordt benut;
- De vormen van landgebruik in deze studie laten een grote verscheidenheid aan biocidengebruik, biocidenuitspoeling, kunstmestbehoefte en N-verlies zien. Deze verschillen tussen gewassen zijn groter dan de verschillen tussen productietechnieken of terreintypen. Bij productie met "best technical means" kan een verandering van gewas dan ook een grotere winst voor milieudoelstellingen opleveren, dan een verandering in productietechnieken of terreintypen;
- De lage *AF*-waarden geven aan dat het risico van biocidenuitspoeling waarschijnlijk niet erg hoog is bij juist gebruik van biociden;
- Conflicten over het areaal voor intensief gebruik voor landbouw en het areaal voor natuur zijn niet nodig, omdat meer dan 50 % van het areaal buiten de nationale parken ongeschikt is voor intensieve landbouw, grasland

en houtplantages. Bovendien kunnen de doelstellingen van belangengroeperingen ook gerealiseerd worden op het areaal dat wel geschikt is voor intensief landgebruik;

- In de huidige studie zijn hoge waarden voor sociaal-economische doelfuncties gekoppeld aan hoge waarden voor milieukundige doelfuncties. M.a.w. deze twee groepen van doelfuncties zijn sterk conflicterend. Alleen wanneer "optimistische" waarden worden gebruikt voor agro-ecologische coëfficiënten, kan een lage waarde voor biocidenuitspoeling worden gekoppeld aan hoge waarden voor sociaal-economische doelfuncties. De milieubelasting per eenheid economisch surplus vertoont niet noodzakelijkerwijs een toename wanneer het totale economisch surplus toeneemt (figuur 5.3);
- De verschillen tussen de landgebruiksscenarios voor de vijf beleidsvisies zijn groot, ongeacht welke agro-ecologische coëfficiënten worden gebruikt en ongeacht of tijdsaspecten wel of niet expliciet worden meegenomen. M.a.w. het "speelveld" voor beleidsmakers is groot. Voor strategische planning is het daarom van belang eerst te bepalen wat de doelstellingen voor toekomstig landgebruik zijn. Pas in een volgende stap is het van belang de conseqenties van onzekerheden op landgebruiksopties te bepalen.

Afsluitende opmerkingen

Langetermijnverkenningen hebben tot doel het toekomstbeeld van beleidsmakers te verruimen door de uiterste consequenties van doelstellingen te laten zien. Als zodanig kunnen ze kortetermijnverkenningen en extrapolaties van het huidige landgebruik aanvullen, en onmisbare informatie verschaffen voor een weloverwogen planning van landgebruik. Door de consequenties en mogelijkheden onder verschillende doelstellingen en beperkingen te kwantificeren, helpen langetermijnverkenningen discussies over wensen voor de toekomst en consequenties van die wensen te organiseren en te structureren.

Dit proefschrift heeft een bijdrage geleverd aan enkele methodologische aspecten van langetermijnverkenningen. De case-study voor NAZ liet zien dat het expliciet beschrijven van tijdsaspecten en het incorporeren van onzekerheden in agro-ecologische coëfficiënten de consequenties en implicaties voor beleidsmakers nauwelijks beïnvloedde. De uitdaging voor de toekomst ligt dan ook vooral in het toepassen van de methodologie in samenwerking met belangengroepen en in onderzoek naar hoe verschillende typen landgebruiksstudies elkaar kunnen aanvullen binnen landgebruiksplanning.

RESUMEN

El tema de esta tesis

El aumento en el número de conflictos entre los grupos de usuarios de tierra, la creciente noción de la necesidad del uso racional de la misma y el desarrollo sostenible requiere una planificación estratégica de utilización de la tierra. Los reconocimientos a largo plazo pueden contribuir de manera importante a esta planificación. La percepción de las posibilidades en el futuro está muchas veces determinada por las extrapolaciones del pasado y presente hacia el futuro. Los reconocimientos a largo plazo toman al presente como punto de partida. Ellos investigan las opciones para el uso futuro de la tierra confrontando las posibilidades y limitaciones biofísicas y técnicas con los objetivos normativos de los grupos involucrados.

En el Capítulo 1 se describe la metodología de los reconocimientos a largo plazo. Las características mas importantes son: la investigación de opciones a largo plazo (20-30 años), el uso del conocimiento de los procesos biofísicos para cuantificar nuevas técnicas de producción, el supuesto que la producción toma lugar de la manera técnicamente mas eficaz (o sea la utilización de insumos mas eficiente según el conocimiento y la técnica disponible), la separación entre la información normativa y técnica, y mostrar las consecuencias de las diferentes percepciones de sostenibilidad al generar escenarios de uso de tierra para las varias perspectivas políticas. Este tipo de estudios muchas veces utilizan la programación linear multi objetiva (MGLP) con el objeto de investigar las opciones extremas para el uso sostenible de tierra.

En el marco de esta tesis se investigaron dos aspectos metodológicos del reconocimiento a largo plazo. Estos reconocimientos presentan varios escenarios para la utilización de la tierra, es decir, la adjudicación óptima del uso de tierra y los valores óptimos de la función de objetivo para las respectivas perspectivas políticas. Las incertidumbres en los coeficientes del modelo influyen los escenarios. Por eso, se requiere de información acerca de las incertidumbres y sus efectos para obtener un cuadro mas objetivo de las opciones futuras del uso de tierra y las limitantes para su utilización futura. Lo anterior dio como resultado a la primera pregunta de investigacion:

- ¿Cuál es la incertidumbre en los coeficientes agro-ecológicos en los reconocimientos a largo plazo y que tan relevante son estas incertidumbres para los valores de la función de objetivo y la adjudicación del uso de tierra, en comparación con otros factores como diferencias entre formas de uso de tierra, técnicas de producción, tipo de terreno e incertidumbres de precio?

El uso de tierra tiene fuertes aspectos temporales. Usualmente se utilizan modelos

estáticos para un período para la optimalización del uso de la tierra. Esto sugiere e implica que no hay diferencias en tiempo o que no son importantes. Los aspectos temporales pueden afectar los valores de la función de objetivo y la adjudicación del uso de tierra por período, y la limitación de las fluctuaciones entre períodos es con frecuencia importante en las perspectivas políticas. Estas observaciones dieron como resultado la segunda pregunta de investigación:

- ¿Pueden los aspectos temporales del uso de tierra ser incluidos en los modelos MGLP multi-periódicos y cuál es el valor adicional de los resultados de este tipo de modelos en comparación con los modelos para un período?

Estas preguntas de investigación se elaboraron con datos de la zona noratlántica de Costa Rica (NAZ; Capítulo 2).

Incertidumbre

Para contestar la primera pregunta, se cuantificaron las incertidumbres de los coeficientes agro-ecológicos en cuanto a los nutrientes y biocidas y se cuantificaron además las incertidumbres de los precios (Capítulo 3). Luego, se construyó un modelo MGLP para un período para la NAZ (Capítulo 4). Se determinaron con la ayuda del análisis de sensibilidad los efectos de las incertidumbres sobre los escenarios del uso de la tierra para cinco perspectivas políticas proviosionales (Capítulo 5).

Las incertidumbres en los coeficientes agro-ecológicos generalmente fueron causadas por falta de conocimiento acerca de los procesos biofísicos y por falta de datos para la cuantificación. Consecuentemente, no se pudieron determinar las distribuciones de probabilidad. Para un nivel fijo de producción se generaron fuera de "promedios", estimaciones "optimistas" y "pesimistas" para los coeficientes agro-ecológicos. El valor "optimista" representa los requerimientos mas bajos de fertilización, la pérdida mas baja de N y el riesgo mas mínimo de lixiviación de biocidas; la estimación "pesimista" representa los valores mas alto posibles para estos coeficientes bajo el supuesto de producción de la mejor manera tecnicamente posible. Las diferencias entre las estimaciones "optimistas", "promedios" y "pesimistas" fueron basadas en diferentes percepciones de la influencia de la precipitación sobre la lixiviación, la influencia del suelo sobre la retención de nutrientes y biocidas, etc. Para los precios se determinaron precios "bajo" y "alto" en adición al precio "promedio". Se supuso que la incertidumbre en los precios fue causada por variación. Las relaciones entre oferta, demanda y los niveles de precio no se determinaron. El efecto de las incertidumbres sobre los valores absolutos de los coeficientes agro-ecológicos y económicos estaba por el mismo rango o por encima de los efectos de la forma del uso de tierra sobre los valores de coeficientes. En general, las diferencias en coeficientes entre las formas del uso de tierra eran mas grandes que las diferencias entre técnicas de producción o tipos de terreno (Capítulo 3).

Los modelos MGLP comparan la contribución de diferentes actividades de producción con diferentes objetivos. El orden de las actividades de producción con respecto al coeficiente incluido en la función de objetivo determina de forma importante la combinación óptima de actividades de producción. Los valores absolutos de estos coeficientes determinan el valor de la función de objetivo. Los supuestos en los reconocimientos a largo plazo afectan el gama de los posibles valores de los coeficientes agro-ecológicos a considerar y resultan en una fuerte correlación entre los valores de estos coeficientes.

- Medidas agronómicas se hacen de la mejor manera tecnicamente posible, es decir, la incertidumbre causada por la variación en el manejo del campesino está excluida y se utilizan los insumos de la manera mas eficaz, determinada por el ambiente físico, los cultivos y la técnica de producción.
- Los coeficientes agro-ecológicos muchas veces se ven afectados por los mismos procesos ambientales.

En el Capítulo 6 se examinó la sensibilidad de un modelo MGLP para un período (descrito en Capítulo 4) a las incertidumbres en los coeficientes agro-ecológicos. El análisis de sensibilidad del modelo a estas incertidumbres requerió tan solo de muy pocas simulaciones debido a la correlación de los valores de los coeficientes agro-ecológicos; durante el análisis de sensibilidad se cambiaron los valores de los coeficientes agro-ecológicos simultaneamente de “promedio” a “optimista” o a “pesimista”. Los valores absolutos de las funciones de objetivo se vieron fuertemente afectados por la incertidumbre en los coeficientes agro-ecológicos. Sin embargo, la adjudicación de uso de tierras no cambiaba mucho bajo la influencia de la incertidumbre puesto que el orden de las actividades de producción no cambiaba mucho tampoco. Los efectos de las incertidumbres en los coeficientes agro-ecológicos sobre los valores de la función de objetivo fueron comparados con el efecto de la incertidumbre en los precios de los productos.

De lo anterior se pudo concluir que en los reconocimientos a largo plazo, las incertidumbres en los coeficientes agro-ecológicos, debido a la falta de conocimiento o la falta de datos para la cuantificación, influyen fuertemente los valores de la función de objetivo. Sin embargo, poco afectan la adjudicación óptima del uso de suelo, por que el orden de actividades de producción no cambia mucho.

Aspectos temporales del uso del suelo

Para contestar la segunda pregunta de investigación, se cuantificaron varios aspectos temporales del uso de tierra (Capítulo 3). Luego de un inventario de las posibilidades y limitaciones para describir estos efectos temporales con programación linear (LP), se construyó una versión multi-periódica del modelo MGLP para un período. Los resultados de este modelo multi-periódico fueron comparados con los del modelo para un período en el Capítulo 6.

En los reconocimientos a largo plazo los siguientes aspectos temporales son relevantes: 1. Crecimiento y desarrollo de cultivos y ganado; 2. Fluctuaciones debidas a variaciones en condiciones meteorológicas; 3. Interacciones en tiempo (Capítulo 2). Como se mencionó anteriormente, en estos estudios se asumió que la producción toma lugar de la manera técnicamente mas eficaz. La inclusión de más desarrollo en técnicas de producción y en perspectivas políticas, o cambios abruptos en el ambiente físico como erupciones volcánicos (es decir, desarrollos irreversibles) sería muy especulativa y por lo tanto no se efectuó. En el Capítulo 3 se determinaron los efectos de los aspectos temporales sobre los valores de los coeficientes insumo-producto. Se cuantificaron los coeficientes para varios etapas de crecimiento de los cultivos perrenes. Tambien se calcularon las fluctuaciones en la producción entre los períodos debidas a variaciones en condiciones meteorológicos con la ayuda de modelos de simulación de crecimiento de cultivos. Además se describieron varias interacciones temporales: limitaciones para la secuencia de cultivos y efectos residuales del fertilizante-P.

En el Capítulo 6 se examinaron las opciones para incluir aspectos temporales del uso de tierras de la programación linear (LP) con la ayuda de una revisión literaria y al transformar el modelo MGLP para un período para la zona noratlántica en una versión multi-periódica. En teoría, se pueden describir todos los aspectos temporales dentro del marco de los modelos LP, pero la descripción de aspectos temporales específicos confinados a un sitio del uso de tierra es muy complicada. El uso de tierra en una unidad espaciale durante un período determinado puede afectar las posibilidades y coeficientes para otros cultivos en períodos subsecuentes. Por ejemplo, después de cortar árboles se queda material vegetal en el suelo y por encima. Esto impide la preparación de la tierra para cultivos subsecuentes en el mismo sitio. Menos fertilizante-P se necesitará si los cultivos pueden aprovecharse de los efectos residuales de P administrado durante períodos anteriores en el mismo sitio. Una descripcion exacta de estos aspectos requiere que se pueda reencontrar los sitios dentro de las unidades espaciales en el tiempo. Eso es posible con ayuda de variables binarias, pero tanto el tamaño del modelo como el tiempo de computación aumentan enormemente si se utilizan muchas variables binarias. Es justo el gran aumento en tamaño de modelo causado por la inclusión de los períodos que se considera como problema mas importante de los modelos multi-periódicos. Por eso, la utilización de variables binarias no es una opción para los estudios a nivel regional.

Se construyó una versión multi-periódica con ejemplos de los tres aspectos temporales arriba mencionados. Los resultados de este modelo MGLP multi-periódico fueron comparados con los resultados del modelo para un período. Las diferencias entre los dos modelos en cuanto a la adjudicación anual de tierra y los valores anuales de las funciones de objetivo fueron pequeñas. Ellas fueron causadas por las fluctuaciones en los coeficientes de insumo-producto entre los períodos debidas a variaciones en condiciones meteorológicas y por restricciones de las fluctuaciones de las variables entre los períodos en el modelo multi-periódico. Las fluctuaciones de las variables entre períodos fueron niveladas por las interacciones entre los períodos y al ajustar el cultivo escogido y las etapas de crecimiento escogidas por período.

De lo anterior se puede concluir que, en teoría, se pueden describir todos los aspectos temporales en modelos LP multi-periódicos, aunque interacciones específicas confinadas a un sitio ponen serios problemas debido a las limitaciones de la técnica LP. Sin embargo, hay que tomar en cuenta que en los reconocimientos a largo plazo la utilización de un modelo multi-periódico pudiera tener un valor adicional tan solo en situaciones con grandes diferencias entre períodos y etapas de crecimiento y si se ponen fuertes restricciones a las fluctuaciones. En la mayoría de los casos, los modelos para un período son suficientes, porque en este tipo de modelos se pueden tambien incluir los relevantes aspectos temporales con la ayuda de secuencias de cultivos predefinidas y variables adicionales. En ese caso, la descripción de los aspectos temporales se hace fuera del modelo LP y consecuentemente no está complicada por las limitaciones de la técnica de LP.

Opciones a largo plazo para el uso de suelo en la zona noratlántica

Con base en los análisis en los Capítulos 3 y 5, se pueden sacar las siguientes conclusiones con respecto a las opciones a largo plazo para el uso de tierra en la NAZ de Costa Rica y con respecto a necesidades adicionales de investigación:

- Las grandes diferencias entre la producción potencial y la producción limitada por el agua de un lado, y los niveles actuales de producción al otro, indican que el potencial de producción de la tierra está lejos de ser completamente explotado.
- Las formas del uso de tierra en este estudio para la NAZ muestran un amplio gama de utilización de biocidas, riesgos de lixiviación de biocidas, requerimientos de fertilizante y pérdida de N. Estas diferencias entre las formas de la utilización de la tierra son mas grandes que las diferencias entre las técnicas de producción o los tipos de terrenos. Si entonces la producción toma lugar de la manera tecnicamente mas eficaz, el ajuste en la forma del uso del tierra resultará en un mayor rendimiento para las funciones de objetivo ambiental que cambiar de tipo de terreno o de técnica de producción.
- Los bajos valores-AF indican que el riesgo de la lixiviación de biocidas

probablemente no sera muy alto si se las manejan apropiadamente.

- En la zona los conflictos acerca del espacio entre la utilización agrícola y conservación de la naturaleza no tienen que presentarse necesariamente, ya que mas que 50 % de los suelos fuera de los parques nacionales no es adecuada para la agricultura intensiva, ganadería o plantaciones de árboles. Los objetivos de todos los grupos involucrados pueden lograrse en los sitios apropiados.
- En este estudio los valores elevados para las funciones de objetivo socio-económico resultaron asociados con altos valores para los objetivos de las funciones de objetivo ambiental, es decir, los objetivos socio-económicos eran claramente conflictivos con los objetivos ambientales. Tan solo en las simulaciones con las estimaciones "optimistas" para los coeficientes agro-ecológicos se pudo combinar los valores elevados para los objetivos socio-económicos con valores muy bajos para los riesgos de la lixiviación de biocidas. El impacto ambiental por unidad de excedente económico no necesariamente aumenta con el creciente total de excedente económico (Figura 5.3).
- Las diferencias entre los escenarios para las cinco perspectivas políticas fueron muy grandes, sin tomar en cuenta cuales coeficientes agro-ecológicos o los precios se utilizaron. Tampoco los aspectos temporales del uso de suelo importaban, o sea el margen para los tomadores de decisiones es grande en la zona. Consecuentemente, primero hay que hacer mas explícito los objetivos de los grupos involucrados y solamente después la determinación de los efectos de las incertidumbres sobre las opciones del uso del suelo vuelve importante.

Comentarios finales

Los reconocimientos a largo plazo sirven para ampliar las perspectivas de los tomadores de decisiones mostrandoles las consecuencias extremas de los objetivos políticos. Para eso, ellos pueden complementar los estudios de proyección o los reconocimientos a corto plazo para el uso de la tierra, asi que pueden dar información crucial para la planificación del uso de tierras. Al cuantificar la consecuencias y posibilidades bajo ciertos objetivos y limitaciones, los reconocimientos a largo plazo pueden ayudar a estructurar y organizar una discusión acerca de los deseos para el futuro.

Esta tesis ha contribuido a algunos aspectos metodológicos de los reconocimientos a largo plazo. El caso de la zona noratlántica de Costa Rica mostró que la inclusión de los aspectos temporales e incertidumbres en los coeficientes agro-ecológicos no afectó fuertemente los resultados e implicaciones del estudio para los tomadores de decisiones. El gran reto para la investigación futura queda mas bien en la aplicación de la metodología en interacción con los grupos involucrados y en la utilización complementaria de los estudios diferentes de uso de tierra, en lugar de mas refinar las actuales metodologías de los reconocimientos a largo plazo.

CURRICULUM VITAE

Janette Bessembinder was born on the 18th of April 1967 in Nieuw-Heeten, The Netherlands. In 1985, she obtained her VWO-diploma at the Florens Radewijns College in Raalte, and, in the same year, started her study of Tropical Crop Science at the Agricultural University in Wageningen. In 1991, she obtained her "ingenieurs"-diploma with specialisations in Tropical Crop Science, Plant Nutrition and Soil Fertility, and Theoretical Production Ecology. During the year 1989, she spent her practical training period in Ivory Coast, assisting in research on the transition from shifting cultivation to more permanent agriculture near the "Tai" National Park. For her first major subject, she did research on the maintenance of soil fertility, also in Ivory Coast. After returning to The Netherlands, she did thesis research on *Amaranthus* cultivation and *in vitro* propagation of cassava for the Department of Tropical Crop Science. Before graduating in 1991, she did a third thesis research on simulation of water-limited potato production for the Department of Theoretical Production Ecology.

From October to December 1991 she made an inventarisation of the research on long term *in vitro* storage of *Colocasia esculenta* at the Department of Tropical Crop Science in the past years. This resulted in the publication of an article.

In 1992, she was appointed as a trainee research assistant at the multi-disciplinary research project of the Wageningen Agricultural University on the Northern Atlantic Zone of Costa Rica. From October 1992 to January 1994 she stayed in Costa Rica for data collection. After her return to The Netherlands, she continued her research on the long-term options for the Northern Atlantic Zone and some methodological aspects of long-term explorative studies, which resulted in this thesis.

APPENDIX 1: *Qualitative land evaluation*

The aim of the qualitative land evaluation was to discriminate between potentially suitable soils and unsuitable soils. Information on soil depth, drainage, pH, slope, stoniness and texture was used for this purpose. The requirements of each form of land use and production technique (Table A1.1) were compared with the characteristics of the 169 terrain units in SIESTA (*Sistema de Información para la Evaluacion de los Suelos y Tierras de la zona Atlántica*; Wielemaker & Vogel 1993). The land mapping units in SIESTA are associations of terrain units. In case of missing data the terrain unit was considered unsuitable. After comparison of terrain characteristics with crop requirements seven groups of terrain units were distinguished (Table 3.1). To avoid a large number of terrain types ($_s$) a minimum of 2,000 ha per $_s$ was included. These seven "terrain types" are the seven physical production environments used in this study. For further use of these terrain types a quantitative description is needed. Quantitative data on chemical and hydrological characteristics of the soil types were collected, and a weighted average was calculated for each terrain type (Table A1.2). Quantitative data were often missing, but the average chemical data in Table A1.2 are based in all cases on data for at least 75 % of the area of each $_s$ (Wielemaker & Vogel 1993). Only a small number of *pF*-curves and hydraulic conductivity curves were available for "fertile well drained soils" ($_{s2}$ and $_{s3}$), "unfertile well drained soils" ($_{s5}$ to $_{s7}$) and "poorly drained soils" ($_{s4}$).

Table A1.1 Limits of suitability for various forms of land use and techniques. The conditions indicated are considered unsuitable.

Soil/terrain characteristics	Form of land use and production technique: Banana[a]	Mechanized cassava	Manual cassava	Mechanized maize	Manual maize	Mechanized palmheart[a]	Manual palmheart	Grass/ Grass-legume	Tree plantations
Drainage class	excessively, very poor	imperfect, poor, very poor	imperfect, poor, very poor	imperfect, poor, very poor	imperfect, poor, very poor	excessively, very poor	imperfect, poor, very poor excessively	poor, very poor	poor, very poor
pH	<4.5	-	-	<4.5	<4.5	<4.5	<4.5	-	-
Slope (%)	>7	>13	>25	>13	>25	>13	>25	>25	>25
Soil depth (cm)	<20	<20	<20	-	-	<20	<20	-	<20
Stones (%)	>3	>3	>15	>3	>15	>3	>15	>15	>15
Texture	sand	-	-	sand	sand	sand	sand	-	-

[a] construction of drainage system assumed.

Table A1.2 Characterization of the terrain types (average data for top 20 cm).

Terrain type (s)	pH (H_2O)	CEC meq. 100 g^{-1}	Base saturation %	P mg.l^{-1}	Exchangeble K meq. kg^{-1}	Clay %	Sand %	Bulk OM %	Soil density (-)	depth cm	Slope %	Stoniness %	Drainage
s1[a]	-	-	-	-	-	-	-	-	-	-	-	-	-
s2	5.8	33	12	9.8	4	28	33	5.8	0.71	90	2	0.1	moderate-well
s3	5.6	28	8	11.3	7	13	46	8.1	0.76	70	1	0	moderate-well
s4	5.6	30	26	11.0	5	30	20	5.3	0.81	90	1	0	poor-imperfect
s5	4.9	34	2	12.0	3	38	32	5.9	-[b]	>160	16	1.5	well
s6	4.4	31	2	-	11	57	17	5.5	0.84	160	20	0	well
s7	6.4	17	8	12.4	9	7	65	4.6	-[b]	10	2	7	well-excessive

[a] *s1* unsuitable for any land use, wide variation in characteristics;
[b] in case of missing data, a bulk density of 0.8 kg.l^{-1} was assumed.

APPENDIX 2: *Crop and livestock production*

Crop production

In the quantitative land evaluation potential and water-limited production were calculated, if possible with crop growth simulation models. These simulation models require data on crop characteristics (Section 3.1.2), soil characteristics (Appendix 1) and weather data. Analyses of available radiation data showed some years with considerably lower radiation than other years (Kamstra, pers. comm.). Clearly, measurement errors were made. The relation between measured sunshine hours and radiation data differed strongly per weather station and per year (Herrera Reyes & Janssen 1994). Therefore, adjustment of the radiation data with sunshine hours and the Ångström formula could not increase accuracy (Martínez-Lozano *et al.* 1984). Years with very low average radiation (< 10 $MJ.m^{-3}.d^{-1}$) were not used in crop growth simulations. Table A2.1 presents an example of the crop growth simulation results for six weather stations and various sites (with different pF-curves and hydraulic conductivity). The productions for each weather station and site combination are averages of several years each with twelve sowing dates (first day of each month), calculated with daily weather data.

The water-limited productions obtained for a ground-water level of 1.6 m are equal to the potential production. For the yield-oriented production activities (production techniques $_{c=MBN,\ c=mBN}$) the water-limited or potential productions are utilized. In the environment-oriented production activities biocide use is reduced (production techniques $_{c=MbN,\ c=mbN}$) or N-losses are reduced (production techniques $_{c=MBn,\ c=mBn}$). Lower yield levels were accepted in these production activities. Table A2.3 presents an overview of the production levels used for all crop activities in the single-period MGLP-model. In the multi-period model input-output coefficients are presented for periods of five years; for perennial crops growth stages are distinguished. The average productions for the multi-period MGLP-model can easily be calculated with the data for the single-period model, for example $_{ba1} = 5 * _{ba5},\ _{bac} = (20 * _{ba20} - 5 * _{ba5}) / 3$. In the multi-period model fluctuations between periods caused by variation in weather conditions were taken into account. The variation between periods was mainly caused by differences in radiation. Table A2.2 presents the factors used for obtaining the production levels per period in the multi-period model. The production levels per growth stage for tree plantations cannot be calculated with the data in Table A2.3, which is why they are presented in Table A2.4.

Table A2.1 Average water-limited dry matter grain production of maize[a] (tonne.ha^{-1} per growing cycle) for six weather stations at sites with different ground water levels, calculated with WOFOST 6.0. The sites represent different pF-curves and hydraulic conductivity curves.

Site	Weather stations Carmen	Cobal	Diamantes	Lola	Limon	Mola
Ground water level 70 cm (terrain type *s3*)						
I	7.2[b]	6.6	7.8	6.0	7.2	6.2
II	7.7	7.2	8.5	6.6	7.8	6.8
III	7.4	6.8	8.2	6.3	7.5	6.5
IV	7.0	6.1	7.6	5.8	6.8	5.7
V	7.3	6.6	7.9	6.1	7.3	6.2
VI	7.8	7.3	8.6	6.7	7.9	7.0
avg.	7.4	6.8	8.1	6.3	7.4	6.4
std.	1.3	1.0	1.0	0.6	1.0	0.9
Ground water level 90 cm (terrain type *s2*)						
I	7.5	7.0	8.3	6.4	7.6	6.6
II	7.7	7.3	8.5	6.7	7.9	6.9
III	7.5	7.1	8.4	6.5	7.7	6.7
IV	7.3	6.6	8.1	6.2	7.4	6.3
V	7.5	6.9	8.1	6.4	7.6	6.6
VI	7.8	7.3	8.6	6.7	8.0	7.0
avg.	7.5	7.0	8.3	6.5	7.7	6.7
std.	1.2	0.9	0.8	0.6	0.9	0.7
Ground water level 160 cm (terrain types *s5* to *s7*)						
VII	7.7	7.3	8.5	6.7	7.9	6.9
VIII	7.8	7.3	8.6	6.7	8.0	7.0
avg.	7.8	7.3	8.6	6.7	7.9	7.0
std.	0.7	0.6	0.8	0.5	0.8	0.6

[a] average harvest index 0.48, average length growing season 99 days;
[b] average of many years each with twelve sowing dates per year.

Table A2.2 Estimated yields for yield-oriented production in the four periods of the multi-period MGLP-model, formulated as a fraction of the potential production (Table 3.3, ground water level 160 cm).

Form of land use	Ground water level (cm)	Period ($_p$) *p1*	*p2*	*p3*	*p4*
Banana	160	1.00	1.04	0.99	0.97
Cassava	160	1.00	1.04	0.99	0.97
	90	0.98	1.01	0.96	0.94
	70	0.95	0.98	0.94	0.92
Maize	160	1.00	1.04	0.99	0.97
	90	0.96	0.99	0.94	0.93
	70	0.93	0.96	0.92	0.90
Pasture[a]	160/90/70	1.00	1.04	0.99	0.97
Palmheart	160	1.00	1.04	0.99	0.97
	90	0.95	0.98	0.94	0.92
	70	0.90	0.93	0.89	0.87
Trees	160	1.00	1.04	0.99	0.97
	90	0.95	0.98	0.94	0.92
	70	0.90	0.93	0.89	0.87

[a] no distinction made between grass pasture and grass-legume pasture.

Table A2.3 Estimated yields (tonne fresh product.ha^{-1}.y^{-1}, tonne dry matter.ha^{-1}.y^{-1}, or tonne dry matter.ha^{-1}.growing cycle^{-1}) for crop activities in the single-period model. For explanation of codes see Table 4.1.

Form of land use[g]	Code ()	Production technique ($_c$)	Terrain type ($_s$) *s2*	*s3*	*s4*	*s5*	*s6*	*s7*
Banana[a]	*ba5*	*MBN*	90.0	90.0	79.2	-[h]	-	-
		MbN	67.6	67.6	59.4	-	-	-
		MBn	54.0	54.0	47.6	-	-	-
	ba20	*MBN*	106.1	106.1	103.5	-	-	-
		MbN	79.6	79.6	77.6	-	-	-
		MBn	63.7	63.7	63.1	-	-	-
Cassava[b]	*ca*	*MBN*	39.3	38.3	-	-	-	-
		MbN	31.5	30.7	-	-	-	-
		MBn	23.6	23.0	-	-	-	-
		mBN	39.3	38.3	-	40.4	40.4	-
		mbN	31.5	30.7	-	32.3	32.3	-
		mBn	23.6	23.0	-	24.2	24.2	-
Maize[c]	*ma*	*MBN*	21.2	20.6	-	-	-	-
		MbN	18.0	17.5	-	-	-	-
		MBn	12.7	12.4	-	-	-	-
		mBN	21.2	20.6	-	22.1	-	-
		mbN	18.0	17.5	-	18.8	-	-
		mBn	12.7	12.4	-	13.3	-	-
Grass-legume pasture[d]	*gl5*	*mBN*	17.6	17.6	-	17.6	17.6	14.0
		mBn	10.5	10.5	-	10.5	10.5	8.5
	gl20	*mBN*	19.0	19.0	-	19.0	19.0	15.2
		mBn	11.4	11.4	-	11.4	11.4	9.1
Grass pasture[d]	*gi5*	*mBN*	21.2	21.2	-	21.2	21.2	16.9
		mBn	12.7	12.7	-	12.7	12.7	10.2
	gi20	*mBN*	22.9	22.9	-	22.9	22.9	18.3
		mBn	13.8	13.8	-	13.8	13.8	11.0
Palmheart[e]	*pa5*	*MBN*	21.2	21.2	18.0	-	-	-
		MBn	12.7	12.7	10.8	-	-	-
		mBN	20.2	19.0	-	21.2	-	-
		mBn	12.1	11.4	-	12.7	-	-
	pa20	*MBN*	29.8	29.8	28.9	-	-	-
		MBn	17.9	17.9	17.4	-	-	-
		mBN	28.3	26.7	-	29.7	-	-
		mBn	17.0	16.0	-	17.9	-	-
Trees[f]	*wt*	*MBN*	13.6	12.9	-	14.3	14.3	-
		MBn	8.2	7.7	-	8.6	8.6	-

[a] exportable fresh product, 22.5 % of production rejected for export (Flores 1992; Lopez 1992), dry matter concentration of bananas 23 %;
[b] exportable fresh product, 10 % of production rejected for export (MAG 1983), growing cycle ten months, dry matter concentration of cassava 35 %;
[c] fresh product, 2.5 growing cycles per year, dry matter concentration of maize 86 %;
[d] amount of dry matter consumed by livestock (tonne.ha^{-1}.y^{-1}), 50 % of total dry matter production is consumed;
[e] fresh gross palmheart production, first production 18 months after planting, dry matter concentration of palmhearts 11 % (Jongschaap 1992), net palmheart production is 10 % of gross palmheart production;
[f] total dry matter stem production in 20 years (tonne.ha^{-1}), first thinning after five years yields only pulpwood, for the thinnings after 10 and 15 years and the final cut 75% of stem production is timber and 25 % is pulpwood, density 0.6 kg.dm^{-3};
[g] only coefficients for growth cycle of five years and 20 years are presented;
[h] not relevant.

Table A2.4 Production level per growth stage in tree plantations in the multi-period MGLP-model (total dry matter stem production[a], tonne.ha^{-1}.5 years^{-1}). For explanation of codes of production techniques see Table 4.1.

Growth stage	Period ($_p$)	Production technique ($_c$)	Terrain type ($_s$) s2	s3	s4	s5	s6	s7
First, years 0-5	*p1*	*MBN*	17.7	16.7	-	18.6	18.6	-
		MBn	10.6	10.0	-	11.2	11.2	-
	p2	*MBN*	18.3	17.3	-	19.3	19.3	-
		MBn	10.9	10.4	-	11.5	11.5	-
	p3	*MBN*	17.5	16.6	-	18.4	18.4	-
		MBn	10.5	9.9	-	11.0	11.0	-
	p4	*MBN*	17.1	16.2	-	18.0	18.0	-
		MBn	10.4	9.7	-	10.8	10.8	-
Second, years 6-10	*p1*	*MBN*	30.4	28.8	-	32.0	32.0	-
		MBn	18.3	17.3	-	19.2	19.2	-
	p2	*MBN*	31.4	29.8	-	33.3	33.3	-
		MBn	18.8	17.9	-	20.0	20.0	-
	p3	*MBN*	30.1	28.5	-	31.7	31.7	-
		MBn	18.0	17.1	-	19.0	19.0	-
	p4	*MBN*	29.4	27.8	-	31.0	31.0	-
		MBn	17.7	16.7	-	18.6	18.6	-
Third, years 11-15	*p1*	*MBN*	38.9	36.9	-	41.0	41.0	-
		MBn	23.3	22.1	-	24.6	24.6	-
	p2	*MBN*	40.2	38.1	-	42.6	42.6	-
		MBn	24.1	22.9	-	25.6	25.6	-
	p3	*MBN*	38.5	36.5	-	40.6	40.6	-
		MBn	23.1	22.0	-	24.4	24.2	-
	p4	*MBN*	37.7	35.7	-	39.8	39.8	-
		MBn	22.6	21.4	-	23.9	23.9	-
Fourth, years 16-20	*p1*	*MBN*	185.2	175.5	-	195.0	195.0	-
		MBn	111.2	105.3	-	117.0	117.0	-
	p2	*MBN*	191.1	181.4	-	202.8	202.8	-
		MBn	114.7	108.8	-	121.7	121.7	-
	p3	*MBN*	183.3	173.6	-	193.1	193.1	-
		MBn	110.0	104.1	-	115.8	115.8	-
	p4	*MBN*	179.4	169.7	-	189.2	189.2	-
		MBn	107.6	101.8	-	113.5	113.5	-

[a] production in first growth stage is only used as pulpwood, 25 %of production in other growth stages is used as pulpwood and 75 % is used as timber.

Livestock production

Livestock production is related to pasture production. The method used for estimating livestock production is presented in Section 3.1.2. Below some additional information is shown. Table A2.5 presents information on the quality of pasture dry matter.

Table A2.5 Energy and protein concentrations of the pasture types.

Pasture type	Code ($_{cp}$)	Diges-tibility %	Digestible energy[a] MJ.kg DM^{-1}	Digestible protein[b] %
Grass pasture	*gig*	65	10.1	7.6
Grass-legume pasture	*glg*	65	10.1	10.4

[a] calculated with: metabolic energy (Mcal.kg^{-1})= -0.45 + (1.01 * digestible energy (Mcal.kg^{-1})) (NRC 1988; Sanchez *et al.* 1993);
[b] calculated with: digestible protein = (0.929 * total crude protein) - 3.52 (Riviere 1978).

For calculating the production per animal unit the following assumptions were made:

- Milking cow unit ($_{au=mcu}$): one calf per year, first calf after 24 months, lactation period 270 days, mortality calves 2 %, mortality older animals 0.5 %, calves not used for replacement are sold soon after birth, weaning of calves at 3 months, average weight mature cow is 500 kg, diet of grass-legume only, cows replaced at age of 8 years;
- Beef cattle unit 1 ($_{au=bcu}$): mortality calves 2 %, mortality older animals 0.5 %, weaning of calves at 3 months, diet of grass only, animals sold at weight of 500 kg, milk for calves bought;
- Beef cattle unit 2 ($_{au=bcup}$): mortality calves 2 %, mortality older animals 0.5 %, weaning of calves at 3 months, diet of grass only, animals sold at weight of 500 kg, a cow is kept for milk production for calves, calving every 12 months, first calf after 24 months, lactation period 270 days, cow replaced at age of 8 years.

Feeding patterns ($_d$) with different amounts of pasture dry matter and other crop products were formulated for all animal units:

- only pasture dry matter ($_{d=po}$);
- 90 % pasture dry matter and 10 % banana dry matter ($_{d=b10}$);
- 80% pasture dry matter and 20 % banana dry matter($_{d=b20}$);
- 90% pasture dry matter and 10 % maize dry matter ($_{d=m10}$);
- 80% pasture dry matter and 20 % maize dry matter ($_{d=m20}$);
- 90% pasture dry matter and 10 % cassava dry matter ($_{d=c10}$).

The various feeding patterns resulted in slightly different production levels per animal unit, as energy and protein concentrations in the consumed dry matter differ per feeding pattern. In the case of "average", "optimistic" and "pessimistic" nutrient concentrations the nutritional value of pasture dry matter and crop products changed and, consequently, livestock production and required inputs changed. Tables A2.6 to A2.8 show an overview of the inputs and outputs of all livestock activities in the case of three levels of nutrient concentrations.

Table A2.6 Inputs of milk (*mlk*) and calves (*clvi*) per livestock activity in the case of "average", "optimistic" and "pessimistic" nutrient concentrations in pasture and crop products.

Animal unit	Code ($_{au}$)	Feeding pattern ($_d$)	Milk (tonne.y^{-1}) avg.	opt.	pess.	Calves (number.y^{-1}) avg.	opt.	pess.
Milking cow unit	*mcu*	*po*	0	0	0	0	0	0
		b10	0	0	0	0	0	0
		b20	0	0	0	0	0	0
		m10	0	0	0	0	0	0
		m20	0	0	0	0	0	0
		c10	0	0	0	0	0	0
Beef cattle unit 1	*bcu*	*po*	0.28	0.15	0.31	0.68	0.37	0.75
		b10	0.26	0.10	0.31	0.63	0.25	0.74
		b20	0.21	0.05	0.30	0.50	0.13	0.72
		m10	0.27	0.12	0.31	0.66	0.30	0.75
		m20	0.25	0.09	0.31	0.60	0.23	0.74
		c10	0.24	0.08	0.31	0.58	0.20	0.74
Beef cattle unit 2	*bcup*	*po*	0	0	0	0.57	0.30	0.63
		b10	0	-[a]	0	0.53	-	0.63
		b20	0	-	0	0.42	-	0.61
		m10	0	0	0	0.57	0.24	0.64
		m20	0	-	0	0.51	-	0.64
		c10	0	-	0	0.49	-	0.63

[a] "-" not a relevant feeding pattern with"optimistic" nutrient concentrations.

Table A2.7 Inputs of crop products (*Ineed*$_{cp}$) per livestock activity in the case of "average", "optimistic" and "pessimistic" nutrient concentrations in pasture and crop products.

Animal unit	Code ($_{au}$)	Feeding pattern ($_{d}$)	Pasture dry matter (tonne.y^{-1}) avg.	opt.	pess.	Fresh crop products (tonne.y^{-1}) avg.	opt.	pess.
Milking cow unit	*mcu*	*po*	3.16	3.10	3.17	0	0	0
		b10	2.83	2.76	2.84	1.37	1.33	1.37
		b20	2.50	2.41	2.52	2.72	2.62	2.73
		m10	2.83	2.78	2.84	0.37	0.36	0.37
		m20	2.51	2.44	2.52	0.73	0.71	0.73
		c10	2.83	2.75	2.84	0.90	0.87	0.90
Beef cattle unit 1	*bcu*	*po*	1.98	1.85	2.21	0	0	0
		b10	1.69	1.68	1.90	0.82	0.81	0.92
		b20	1.49	1.55	1.60	1.62	1.68	1.74
		m10	1.70	1.67	1.93	0.22	0.22	0.25
		m20	1.49	1.50	1.66	0.43	0.44	0.48
		c10	1.67	1.69	1.86	0.53	0.54	0.59
Beef cattle unit 2	*bcup*	*po*	2.71	2.27	3.04	0	0	0
		b10	2.26	-[a]	2.62	1.09	-	1.26
		b20	1.91	-	2.18	2.08	-	2.37
		m10	2.28	1.98	2.61	0.30	0.26	0.34
		m20	1.96	-	2.19	0.57	-	0.64
		c10	2.19	-	2.54	0.70	-	0.81

[a] "-" not a relevant feeding pattern with "optimistic" nutrient concentrations.

Table A2.8 Outputs (*yield*$_{ap}$) per livestock activity in the case of "average", "optimistic" and "pessimistic" nutrient concentrations in pasture and crop products.

Animal unit	Code ($_{au}$)	Feeding pattern ($_{d}$)	Milk (tonne.y^{-1}) avg.	opt.	pess.	Beef[a] (# animals.y^{-1}) avg.	opt.	pess.	Calves[a] (# animals.y^{-1}) avg.	opt.	pess.
Milking cow unit	*mcu*	*po*	1.12	1.11	1.11	0.15	0.15	0.15	0.59	0.59	0.59
		b10	1.18	1.18	1.18	0.15	0.15	0.15	0.59	0.59	0.59
		b20	1.26	1.07	1.26	0.15	0.15	0.15	0.59	0.59	0.59
		m10	1.27	1.27	1.27	0.15	0.15	0.15	0.59	0.59	0.59
		m20	1.43	1.20	1.43	0.15	0.15	0.15	0.59	0.59	0.59
		c10	1.25	1.21	1.25	0.15	0.15	0.15	0.59	0.59	0.59
Beef cattle unit 1	*bcu*	*po*	0	0	0	0.67	0.36	0.74	0	0	0
		b10	0	0	0	0.62	0.25	0.74	0	0	0
		b20	0	0	0	0.49	0.13	0.71	0	0	0
		m10	0	0	0	0.66	0.29	0.74	0	0	0
		m20	0	0	0	0.59	0.22	0.73	0	0	0
		c10	0	0	0	0.57	0.19	0.73	0	0	0
Beef cattle unit 2	*bcup*	*po*	0	0	0	0.78	0.38	0.77	0	0	0
		b10	0	-[b]	0	0.64	-	0.76	0	-	0
		b20	0	-	0	0.51	-	0.73	0	-	0
		m10	0	0	0	0.68	0	0.77	0	0	0
		m20	0	-	0	0.61	-	0.75	0	-	0
		c10	0	-	0	0.59	-	0.75	0	-	0

[a] beef cattle 500 kg, calves 30 kg;
[b] "-" not a relevant feeding pattern with "optimistic" nutrient concentrations.

APPENDIX 3 *Nutrient inputs and outputs*

Section 3.3 described the methods used for calculating nutrient inputs and N-losses for each crop activity. Additional information on the coefficients in the Equations 3.5 to 3.12 is presented below.

For many processes qualitative knowledge is available, but quantification is often difficult. For the quantification of apparent nutrient recoveries (*ANR*) in various crop activities, the qualitative information was translated into a ranking system for crop and soil characteristics. "3" indicates favourable conditions for high nutrient recoveries and "1" stands for unfavourable conditions (Tables A3.1 and A3.2). With the help of the sum of rankings the nutrient recoveries and nutrient losses were determined. E.g. for estimating N-recovery, root distribution and depth, application frequency, water holding capacity, organic matter concentration and soil depth were scored. The maximum sum of rankings is 13 and this was assumed to correspond with equal to a N-recovery of 0.70. The minimum sum of rankings is 8, which was set equal to an N-recovery of 0.45. The rankings were utilized for estimating *ANR*, *IMM*, *SBF* and *REP*.

The estimates presented in Tables A3.3 to A3.10 were used to calculate the nutrient balances, as described in Section 3.3. "Average", "optimistic" as well as "pessimistic" estimates are presented below and Section 3.3 describes how they were obtained.

Table A3.1 Rankings[a] for crop characteristics and management characteristics, used for estimating nutrient recoveries.

Form of land use	Root distribution + depth	Application frequency
Banana	2	3
Cassava	1	2
Maize	1	2
Palmheart	2	3
Pasture	2	3
Trees	3	2

[a] 3 = most favourable for high nutrient recovery, 1 = least favourable for high nutrient recovery.

Table A3.2 Rankings for soil characteristics, used for estimating nutrient recoveries.

Terrain type (s)	Water holding capa-city	Organic matter	Base satu-ration	pH	Soil depth	P reten-tion
s2	3	2	2	3	2	2
s3	2	3	2	3	2	1
s4	3	2	3	3	2	2
s5	2	2	1	2	3	2
s6	2	2	1	1	3	1
s7	1	1	2	3	1	3
Limits for rankings						
1-2	a	6%	5%	5.5	0.5 m	75%
2-3	a	5%	15%	4.5	1.5 m	50%

[a] based on texture (1= coarse, 2=coarse medium/coarse medium fine/fine, 3= medium).

Table A3.3 Estimated "average" nutrient recoveries (*ANR*). In the case of "optimistic" and "pessimistic" estimates higher and lower recoveries were used (see Section 3.3).

Nutrient	Form of land use ($_l$)	Terrain type ($_s$) *s2*	*s3*	*s4*[a]	*s5*	*s6*	*s7*
N	banana	0.65	0.65	0.70	-	-	-
	cassava	0.55	0.55	-	0.55	0.55	-
	maize	0.55	0.55	-	0.55	-	-
	palmheart	0.65	0.65	0.70	0.65	-	-
	pasture[b]	0.65	0.65	-	0.65	0.65	0.45
	trees	0.65	0.65	-	0.65	0.65	-
P	banana	0.20	0.15	0.20	-	-	-
	cassava	0.15	0.10	-	0.10	0.10	-
	maize	0.15	0.10	-	0.10	-	-
	palmheart	0.20	0.15	0.20	0.15	-	-
	pasture	0.20	0.15	-	0.15	0.15	0.20
	trees	0.20	0.15	-	0.15	0.15	-
K	banana	0.65	0.65	0.70	-	-	-
	cassava	0.55	0.55	-	0.50	0.50	-
	maize	0.55	0.55	-	0.50	-	-
	palmheart	0.65	0.65	0.70	0.60	-	-
	pasture	0.65	0.65	-	0.60	0.60	0.45
	trees	0.65	0.65	-	0.60	0.60	-

[a] in the case of high-input production systems (production techniques *MBN*, *MbN* and *MBn* for banana and palmheart) the constructed drainage system improves the drainage of terrain type *s4*;
[b] no distinction is made between grass pasture and grass-legume pasture.

Table A3.4 "Average", "optimistic", and "pessimistic" estimates for N-fixation (%) in grass-legume pasture on different terrain types.

Terrain type ($_s$)	"average"	"pessimistic"	"optimistic"
s2	80	65	90
s3	80	65	90
s4	-	-	-
s5	70	55	80
s6	65	50	75
s7	80	60	90

Estimates for wet atmospheric deposition are based on Parker (1985), Forti & Neal (1992) and Imbach *et al.* (1989). The highest values of Imbach *et al.* (1989) were left out, because they were the result of burning of sugar cane residues on adjacent farms and to pollution from a nearby sugar cane processing plant.

Table A3.5 "Average" values and ranges[a] for wet atmospheric deposition (*AD*) in the Atlantic Zone of Costa Rica ($kg.ha^{-1}.y^{-1}$).

Nutrient	"average"	range
N	10.95	1.5 - 17.0
P	0.38	0.15 - 0.5
K	10.15	4.7 - 13.0

[a] "average" calculated with rainfall of 4,000 $mm.y^{-1}$, minimum with rainfall of 3,500 $mm.y^{-1}$, and maximum with rainfall of 5,000 $mm.y^{-1}$.

Table A3.6 Summary of nutrient concentrations (%; *NCP* and *NCR*), based on dry weight.

	N			P			K			
	avg.[a]	range[b]	max.[c]	avg.	range	max.	avg.	range	max.	Reference
Banana bunch	0.83	0.71-0.94	1.05	0.11	0.09-0.12	0.13	2.58	2.33-2.82	3.05	Nijhof 1987b
Banana residues	0.88	0.79-0.97	1.05	0.10	0.09-0.12	0.12	3.28	2.39-4.17	5.05	
Cassava tubers	0.38	0.29-0.47	0.55	0.12	0.10-0.14	0.16	0.58	0.44-0.85	1.02	Nijhof 1987a
Cassava tops	0.83	0.66-0.99	1.15	0.21	0.15-0.27	0.32	0.79	0.62-0.96	1.13	
Maize grain	1.23	1.06-1.39	1.55	0.32	0.24-0.40	0.48	0.28	0.22-0.33	0.39	Nijhof 1987a
Maize straw	0.65	0.53-0.78	0.90	0.13	0.09-0.18	0.22	0.90	0.65-1.15	1.40	
Gross palmhearts	0.86	0.78-0.93	1.00	0.16	0.14-0.18	0.20	0.99	0.70-1.29	1.58	Tonjes 1994
Residues	2.01	1.86-2.16	2.30	0.18	0.17-0.19	0.20	1.01	0.79-1.23	1.46	Pluijmers,unpublished
Stems/trunk[d]	0.29	0.23-0.35	0.36	0.04	0.03-0.05	0.05	0.25	0.20-0.30	0.30	Poels 1995
Residues[d]	0.87	0.70-1.04	1.09	0.09	0.07-0.10	0.11	0.58	0.46-0.69	0.72	
Grass pasture[f]	1.92	1.60-2.24	2.24	0.23	0.19-0.30	0.30	0.65	0.65-0.65	0.65	NRC 1988; 1996
Residues grass pasture[e]	1.34	1.08-1.61	1.61	0.16	0.13-0.19	0.19	0.46	0.36-0.55	0.55	
Grass-legume pasture	2.40	1.92-2.56	2.56	0.33	0.28-0.37	0.37	0.90	0.90-0.90	0.90	Ibrahim 1994;
Residues grass-legume[e]	1.68	1.34-2.02	2.02	0.23	0.18-0.28	0.28	0.63	0.50-0.76	0.76	NRC 1988
Milk[g]	0.64	0.58-0.70	0.70	0.09	0.08-0.10	0.10	0.14	0.13-0.15	0.15	Holland *et al.*
Meat[g]	2.88	2.59-3.17	3.17	0.18	0.16-0.20	0.20	0.35	0.31-0.39	0.39	1991

[a] average of minimum and average value found in literature;
[b] lower range: average of the minimum value in literature and the average used in this study; higher range: average of average value found in literature and average used in this study;
[c] average value found in literature;
[d] only average data from Poels (1995) available, 20 % higher and lower values used for range, maximum is 1.25 times the average concentration;
[e] nutrient concentrations of the residues were set at 70 % of the concentrations in the consumed parts;
[f] nutrient concentrations needed for high secondary production were used (NRC, 1988; 1996);
[g] on fresh weight basis, only average values available, for the range 10 % higher and lower values were used.

In case of "optimistic" estimates the lowest nutrient concentrations of the range in Table A3.6 were used for all production activities. For environment-oriented production activities the highest values of the range were used for the "pessimistic" estimates; for the yield-oriented production activities the nutrient concentrations under "max." were used, assuming increased nutrient concentrations with increased production levels.

Table A3.7 "Average" fractions of applied or released N and K that are lost by leaching or by gaseous losses (*FL*, fraction of amount not taken up by the crop)[a]. In the case of "optimistic" and "pessimistic" estimates lower and higher values are used (Section 3.3).

Nutrient	Form of land use ()	Terrain type () *s2*	*s3*	*s4*	*s5*	*s6*	*s7*
N	banana	0.60	0.70	0.60	-	-	-
	cassava	0.70	0.70	-	0.70	0.70	-
	maize	0.70	0.70	-	0.70	-	-
	palmheart	0.60	0.60	0.60	0.60	-	-
	pasture[b]	0.60	0.60	-	0.60	0.60	0.60
	trees	0.60	0.60	-	0.60	0.60	-
K	banana	0.80	0.80	0.75	-	-	-
	cassava	0.80	0.80	-	0.85	0.85	-
	maize	0.80	0.80	-	0.85	-	-
	palmheart	0.80	0.80	0.75	0.85	-	-
	pasture	0.80	0.80	-	0.85	0.85	0.85
	trees	0.80	0.80	-	0.85	0.85	-

[a] the fraction 1-*FL* is temporary immobilized and will be available for the next crop;
[b] *no distinction made between grass pasture and grass-legume pasture.*

Table A3.8 Estimated "average" fraction of applied phosphorus taken up as residual P. In case of "optimistic" and "pessimistic" estimates the residual effect of P changes together with the recovery (Section 3.3).

Form of land use ()	Terrain type () *s2*	*s3*	*s4*	*s5*	*s6*	*s7*
Single-period MGLP-model (residual effect 0-14 years after application)[a]						
Banana	0.374	0.326	0.374	-	-	-
Cassava	0.326	0.256	-	0.256	0.256	-
Maize	0.326	0.256	-	0.256	-	-
Palmheart	0.374	0.326	0.374	0.326	-	-
Pasture[c]	0.374	0.326	-	0.326	0.326	0.374
Trees	0.374	0.326	-	0.326	0.326	-
Multi-period MGLP-model (residual effect in period (l) of P applied in period (l))[a]						
Banana	0.203	0.162	0.203	-	-	-
Cassava	0.162	0.116	-	0.116	0.116	-
Maize	0.162	0.116	-	0.116	-	-
Palmheart	0.203	0.162	0.203	0.162	-	-
Pasture	0.203	0.162	-	0.162	0.162	0.203
Trees	0.203	0.162	-	0.162	0.162	-
Multi-period MGLP-model (residual effect in period (l) of P applied in period (l-1))[b]						
All crops	0.126	0.119	0.127	0.118	0.119	0.127
Multi-period MGLP-model (residual effect in period (l) of P applied in period (l-2))[b]						
All crops	0.012	0.016	0.010	0.016	0.016	0.010

[a] formulated as fraction of *(1-ANR)*NI* in period (l);
[b] formulated as fraction of the mineral fertilizer P applied in period (l-1) or period (l-2); discrimination between crops is not possible, because only linear functions can be used in MGLP; an average for all relevant crops per terrain type is used;
[c] no distinction made between grass pasture and grass-legume pasture.

Table A3.9 Estimated "average" erosion losses (tonne soil.ha^{-1}.y^{-1}) per land use per terrain type, and values used in the USLE-equation. "Optimistic" estimates are 25% of the "average" erosion loss, and "pessimistic" estimates 150 % of the "average" erosion loss.

			Terrain type (*s*)					
			s2	*s3*	*s4*	*s5*	*s6*	*s7*
		R	650	650	650	650	650	650
		K	0.03	0.025	0.085	0.01	0.005	0.04
		LS	0.2	0.1	0.1	2.8	4.0	0.2
		P	0.6	0.6	0.6	0.7	0.8	0.6
Form of land use (*l*)	Growth stage	*C*						
Banana	> 3 years	0.08	0.40	0.16	0.56	-	-	-
	first year	0.26(0.32)[a]	1.37	0.56	2.37	-	-	-
	second year	0.18(0.30)	0.94	0.40	2.22	-	-	-
	third year	0.08(0.10)	0.40	0.16	0.56	-	-	-
Cassava		0.34	1.79	0.74	-	9.70	7.93	-
Maize		0.34	1.79	0.74	-	9.70	-	-
Palmheart	> 2 years	0.06	0.31	0.13	0.45	1.70	-	-
	first year	0.37(0.36)[a]	1.95	0.81	2.67	10.6	-	-
	second year	0.08(0.28)	0.43	0.18	2.08	2.29	-	-
Pasture[b]	> 1 year	0.03	0.16	0.07	-	0.85	0.70	0.20
	first year	0.21	1.10	0.45	-	6.01	4.89	1.48
Trees	5-20 years	0.09	0.47	0.20	-	2.58	2.11	-
	first year	0.29	1.52	0.63	-	8.29	6.76	-
	second year	0.21	1.12	0.45	-	6.00	4.88	-
	third year	0.15	0.78	0.34	-	4.28	3.49	-
	fourth year	0.12	0.63	0.22	-	3.43	2.80	-

[a] values between brackets for terrain type *s4*, planting starts later on this terrain type;
[b] no distinction made between grass pasture and grass-legume pasture.

Table A3.10 Estimated total N, P and K in the soil for each terrain type (g.kg soil^{-1}).

	Terrain type (*s*)					
	s2	*s3*	*s4*	*s5*	*s6*	*s7*
Total N	3.36	4.70	3.07	3.42	3.19	2.67
Total P	0.19	0.19	0.34	0.17	0.17	0.17
Total K	0.16	0.27	0.20	0.12	0.43	0.35

APPENDIX 4: *Biocide use and biocide leaching risk*

Biocide use per crop activity was estimated with the help of minimum advised and used amount of biocides (Section 3.4). The correction factors used for soil herbicides are shown in Table A4.2. Insufficient information was available to assume relative differences in uncertainty in biocide use between production activities. Uncertainty in biocide use is relatively small compared with uncertainty in biocide leaching risk, therefore no separate average, "optimistic" and "pessimistic" estimates were used. Table A4.1 presents an overview of the biocide use in all crop activities in the single-period MGLP-model. In the multi-period model input-output coefficients were presented for periods of 5 years and for perennial crops growth stages were distinguished. The average biocide use per growth stage of 5 years can easily be calculated with the data for the single-period model, for example $_{ba1} = 5 * _{ba5}, _{bac} = (20 * _{ba20} - 5 * _{ba5}) / 3$.

Table A4.1 Biocide use (kg active ingredient.$ha^{-1}.y^{-1}$) per crop activity in the single-period model.

Form of land use[a]	Code ()	Terrain type ($_s$)	Production technique ($_c$)					
			MBN	*MbN*	*MBn*	*mBN*	*mbN*	*mBn*
Banana	*ba5*	*s2*	25.09	11.72	22.39	-[b]	-	-
		s3	25.12	11.75	22.42	-	-	-
		s4	22.45	10.47	20.05	-	-	-
	ba20	*s2*	26.62	12.53	23.69	-	-	-
		s3	26.63	12.54	23.70	-	-	-
		s4	25.96	12.22	23.11	-	-	-
Cassava	*ca*	*s2/s3*	5.15	0.74	5.15	5.15	0.74	5.15
		s5/s6	-	-	-	5.15	0.74	5.15
Maize	*ma*	*s2/s3*	12.23	2.55	12.03	12.23	2.55	12.03
		s5	-	-	-	12.23	2.55	12.03
Palmheart[c]	*pa5*	*s2/s3*	0.47	-	0.47	0.47	-	0.47
		s4	0.47	-	0.47	-	-	-
		s5	-	-	-	0.47	-	0.47
	pa20	*s2/s3*	0.12	-	0.12	0.12	-	0.12
		s4	0.12	-	0.12	-	-	-
		s5	-	-	-	0.12	-	0.12
Pasture[d]	*gi5/gl5*	*s2/s3/s5/s6/s7*	-	-	-	1.36	-	1.36
	gi20/gl20	*s2/s3/s5/s6/s7*	-	-	-	1.04	-	1.04
Trees[c]	*wt*	*s2/s3/s5/s6*	0.27	-	0.27	-	-	

[a] only coefficients for growth cycles of 5 and 20 years presented;
[b] "-" not relevant;
[c] only biocide application during establishment of the plantation;
[d] no distinction made between grass pasture and grass-legume pasture.

Table A4.2 Adjustment factors for herbicides used as soil herbicide (Luyten 1995).

Terrain type ($_s$)	Texture	Adjustment factor
s2	medium	1.0
s3	coarse medium	0.85
s4	medium	1.0
s5	coarse medium fine	1.15
s6	fine	1.60
s7	coarse	0.70

The biocide leaching risk was estimated by multiplying the amounts of biocide used per hectare with their AF-index in the different physical production environments (Section

3.4). Table A4.3 shows the biocide leaching risks as used in the single-period model. Coefficients for the multi-period model were distilled from the coefficients in the single-period model in a similar way as for biocide use. Tables A4.4 and A4.5 present the data needed for calculating the AF-index (formulas 3.13 and 3.14 in Section 3.4.2).

Table A4.3 "Average" and "pessimistic" biocide leaching risk per production activity in the single-period model ($ha^{-1}.y^{-1}$). "Optimistic" estimates are always < 0.0001.

Form of land use[a]	Code ()	Terrain type ()	Production technique (c) *MBN*	*MbN*	*MBn*	*mBN*	*mbN*	*mBn*
"average" estimates								
Banana	*ba5*	*s2*	0.125	0.060	0.125	-[b]	-	-
		s3	0.087	0.043	0.087	-	-	-
		s4	0.065	0.032	0.065	-	-	-
	ba20	*s2*	0.134	0.065	0.134	-	-	-
		s3	0.094	0.046	0.094	-	-	-
		s4	0.077	0.038	0.077	-	-	-
Cassava	*ca*	*s2*	0.077	0.026	0.077	0.077	0.026	0.077
		s3	0.066	0.025	0.066	0.066	0.025	0.066
		s5	-	-	-	0.009	0.004	0.009
		s6	-	-	-	0.026	0.011	0.026
Maize	*ma*	*s2*	0.142	0.0.37	0.142	0.142	0.037	0.142
		s3	0.125	0.040	0.125	0.125	0.040	0.125
		s5	-	-	-	0.010	0.005	0.010
Palmheart[c]	*pa5*	*s2*	0.001	-	0.001	0.003	-	0.003
		s3	0.000	-	0.000	0.002	-	0.002
		s4	0.000	-	0.000	-	-	-
		s5		-	-	0.000	-	0.000
	pa20	*s2*	0.000	-	0.000	0.001	-	0.001
		s3	0.000	-	0.000	0.000	-	0.000
		s4	0.000	-	0.000	-	-	-
		s5	-	-	-	0.000	-	0.000
Pasture[d]	*gi5/gl5*	*s2*	-	-	-	0.006	-	0.006
		s3	-	-	-	0.004	-	0.004
		s5	-	-	-	0.000	-	0.000
		s6	-	-	-	0.001	-	0.001
		s7	-	-	-	0.004	-	0.004
Pasture[d]	*gi20/gl20*	*s2*	-	-	-	0.004	-	0.004
		s3	-	-	-	0.003	-	0.003
		s5	-	-	-	0.000	-	0.000
		s6	-	-	-	0.001	-	0.001
		s7	-	-	-	0.003	-	0.003
Trees[c]	*wt*	*s2*	0.001	-	0.001	-	-	-
		s3	0.001	-	0.001	-	-	-
		s5	0.000	-	0.000	-	-	-
		s6	0.000	-	0.000	-	-	-
"pessimistic" estimates								
Banana	*ba5*	*s2*	1.670	0.550	1.668	-[b]	-	-
		s3	1.454	0.491	1.454	-	-	-
		s4	1.072	0.369	1.072	-	-	-
	ba20	*s2*	1.733	0.570	1.731	-	-	-
		s3	1.510	0.508	1.510	-	-	-
		s4	1.210	0.418	1.210	-	-	-
Cassava	*ca*	*s2*	1.093	0.150	1.093	1.093	0.150	1.093
		s3	1.056	0.150	1.056	1.056	0.150	1.056
		s5	-	-	-	0.532	0.084	0.532
		s6	-	-	-	0.847	0.114	0.847

Table A4.3 Continued.

Form of land use[a]	Code ()	Terrain type ()	Production technique ()					
			MBN	*MbN*	*MBn*	*mBN*	*mbN*	*mBn*
Maize	*ma*	*s2*	2.665	0.335	2.664	2.665	0.335	2.664
		s3	2.617	0.348	2.617	2.617	0.348	2.617
		s5	-	-	-	1.295	0.169	1.295
Palmheart[c]	*pa5*	*s2*	0.060	-	0.060	0.090	-	0.090
		s3	0.050	-	0.050	0.086	-	0.086
		s4	0.039	-	0.039	-	-	-
		s5	-	-	-	0.041	-	0.041
	pa20	*s2*	0.015	-	0.015	0.022	-	0.022
		s3	0.013	-	0.013	0.021	-	0.021
		s4	0.010	-	0.010	-	-	-
		s5	-	-	-	0.010	-	0.010
Pasture[d]	*gi5/gl5*	*s2*	-	-	-	0.189	-	0.189
		s3	-	-	-	0.179	-	0.179
		s5	-	-	-	0.086	-	0.086
		s6	-	-	-	0.147	-	0.147
		s7	-	-	-	0.166	-	0.166
	gi20/gl20	*s2*	-	-	-	0.136	-	0.136
		s3	-	-	-	0.129	-	0.129
		s5	-	-	-	0.061	-	0.061
		s6	-	-	-	0.106	-	0.106
		s7	-	-	-	0.119	-	0.119
Trees[c]	*wt*	*s2*	0.036	-	0.036	-	-	-
		s3	0.035	-	0.035	-	-	-
		s5	0.017	-	0.017	-	-	-
		s6	0.028	-	0.028	-	-	-

[a] only coefficients for growth cycles of 5 and 20 years are presented;
[b] "-" not relevant;
[c] only biocide application during establishment of the plantation;
[d] no distinction made between grass pasture and grass-legume pasture.

Table A4.4 Soil data per terrain type for different ground water levels, used in the AF-index (average soil data for the profile to ground water depth).

Terrain type ()	Clay %	OC[a] %	Bulk density.[b] kg.dm^2	Approximate[c] ground water level cm	Soil air-filled porosity[c] %	Water content field capacity[c] %	Average net ground water recharge[e] m.y^{-1}
s1[d]	-	-	-	-	-	-	-
s2	29	1.60	0.81	90	15	56	2.5
	27	1.05	0.91	160	15	56	2.5
s3	12	2.33	0.86	70	15	56	2.5
	10	1.27	0.96	160	15	56	2.5
s4	30	3.02	0.81	10	9	56	2.5
	27	1.34	1.01	160	9	56	2.5
s5	48	1.53	1.00	160	20	49	2.2
s6	69	0.69	1.04	160	20	49	2.0
s7	8	0.70	1.00	160	25	49	2.5

[a] assuming that organic matter contains 58 % organic carbon;
[b] amount of data too limited to determine minimum and maximum value, for a depth of 160 cm bulk density is assumed to be 0.20 higher than for the top 20 cm, for depths of 70 cm and 90 cm 0.10 higher values were used;
[c] estimated with the help of drainage condition and soil depth, maximum of 160 cm used;
[d] terrain type s1 is unsuitable for all forms of land use, wide variation in unsuitable soils, no biocides used on this terrain type;
[e] average rainfall 4,000 mm.y^{-1}, minimum precipitation 3,500 mm.y^{-1} ("optimistic"), maximum precipitation 5,000 mm.y^{-1} ("pessimistic"), evapotranspiration 1,500 mm.y^{-1}.

Table A4.5 Data on some biocide properties (if not specified otherwise, "average" values from Oshiro *et al.* (1993) were used, plus and minus the standard deviation for the "pessimistic" and "optimistic" values).

Biocide	Half life "average" (days)	"optimistic"	"pessimistic"	K_{OC} "average" (-)	"pessimistic"	"optimistic"	K_H "average" (-)	"pessimistic"	"optimistic"
2,4-D	19	5	34	56	16	101	$2.6\ e^{-10}$	$9.1\ e^{-11}$	$4.9\ e^{-10}$
Atrazine	53	27	89	129	47	213	$1.3\ e^{-7}$ [e]	$2.6\ e^{-9}$	$2.5\ e^{-7}$
Benomyl	248[c]	90	365	2,100	2,100	2,100	$2.4\ e^{-9}$ [e]	$6.5\ e^{-10}$	$4.2\ e^{-9}$
Cadusafos	38[e]	30	45	5,712	5,570	5,854	$2.0\ e^{-6}$	na[a]	na
Carbofuran	74[b]	24	124	57	22	92	$2.1\ e^{-8}$ [e]	$2.2\ e^{-10}$	$4.2\ e^{-8}$
Chlorothalonil	24	10	43	14,626	2,984	26,268	$7.5\ e^{-7}$ [e]	$5.8\ e^{-7}$	$9.1\ e^{-7}$
Chlorpyriphos	52	24	83	7,420	5,290	10,891	$1.4\ e^{-5}$ [e]	$4.2\ e^{-6}$	$2.3\ e^{-5}$
Deltamethrin	27	9	45	988	60	1,916	$4.1\ e^{-3}$	na	na
Diuron	84[d]	37	130	389	183	595	$3.9\ e^{-8}$ [e]	$2.3\ e^{-8}$	$5.4\ e^{-8}$
Ethoprophos	32	8	56	105	63	147	$2.0\ e^{-7}$ [e]	$1.5\ e^{-7}$	$2.5\ e^{-7}$
Fenamiphos	29	14	44	327	100	576	$1.2\ e^{-8}$ [e]	$7.0\ e^{-10}$	$2.4\ e^{-8}$
Glyphosate	45	34	56	2,640	na[a]	na	$1.2\ e^{-11}$ [e]	$3.4\ e^{-12}$	$2.0\ e^{-11}$
Malathion	0.9	0.8	1.0	1,800	1,800	1,800	$1.4\ e^{-7}$ [e]	$1.2\ e^{-7}$	$1.5\ e^{-7}$
Mancozeb	42[d]	16	68	1,500[e]	1,000	2,000	$<1.0\ e^{-100}$	na	na
Methomyl	34	19	49	73	10	137	$3.2\ e^{-10}$ [e]	$1.8\ e^{-10}$	$4.6\ e^{-10}$
Oxamyl	21	9	28	7	2	14	$2.3\ e^{-7}$ [e]	$9.9\ e^{-9}$	$4.5\ e^{-7}$
Oxyfluorfen	45[d]	36	54	60,703[d]	21,425	100,000	$1.0\ e^{-5}$ [e]	$9.5\ e^{-6}$	$1.1\ e^{-5}$
Propiconazol	49[d]	23	75	935	339	1,531	$3.4\ e^{-9}$ [e]	$1.7\ e^{-9}$	$5.0\ e^{-9}$
Terbufos	15	8	27	6,379	1,050	21,795	$6.6\ e^{-3}$	na	na
Terbuthylazine	64[c]	30	105	726	na	na	$1.0\ e^{-7}$ [e]	$7.2\ e^{-8}$	$1.2\ e^{-7}$
Tridemorph	33	21	42	7,580	na	na	$1.7\ e^{-4}$ [e]	$4.9\ e^{-5}$	$3.0\ e^{-4}$

[a] not available;
[b] data from Oshiro *et al.* (1993) used, but some additional outliers left out;
[c] "average" based on various literature sources; "optimistic" and "pessimistic" values are the minimum and maximum values found in literature;
[d] "average" based on various literature sources, and standard deviation used for "optimistic" and "pessimistic" values;
[e] only two values available, "average" of minimum and maximum values.

APPENDIX 5: *Labour requirements*

Labour requirements were determined for each production activity by summing the time needed for the individual practices. The time needed for the individual practices was based on information form literature on the NAZ or other regions. It was assumed that 1 man day is 8 hours, and that the number of working days per year is 225 days. In Table A5.1 the coefficients for the production activities that are used in the single-period MGLP-model are presented. Coefficients for period 1 in the multi-period MGLP-model (with average climatic conditions) can be calculated with these coefficients: e.g. $_{ba1} = 5 * _{ba5}$, $_{bac} = (20 * _{ba20} - 5 * _{ba5}) / 3$. Only for tree plantations these coefficients can not be calculated with the data in Table A5.1, therefore the labour requirements per growth stage of tree plantations are presented in a separate table (Table A5.2). Table A5.3 shows some examples of the consequences of fluctuations in production level on labour requirements (Section 6.2). Table A5.4 presents the labour needs of livestock activities.

Table A5.1 Labour requirement (man years.ha^{-1}.y^{-1}) per crop activity in the single-period model. For explanation of codes see Table 4.1.

Form of land use[a]	Code ()	Terrain type ($_s$)	Production technique ($_c$)					
			MBN	*MbN*	*MBn*	*mBN*	*mbN*	*mBn*
Banana	*ba5*	*s2/s3*	0.455	0.463	0.356	-[b]	-	-
		s4	0.405	0.416	0.318	-	-	-
	ba20	*s2/s3*	0.518	0.505	0.402	-	-	-
		s4	0.505	0.494	0.392	-	-	-
Cassava	*ca*	*s2*	0.046	0.047	0.046	0.421	0.437	0.304
		s3	0.046	0.047	0.046	0.413	0.431	0.300
		s5	-	-	-	0.469	0.485	0.337
		s6	-	-	-	0.503	0.513	0.359
Maize	*ma*	*s2*	0.068	0.069	0.068	0.505	0.603	0.430
		s3	0.068	0.069	0.068	0.500	0.599	0.427
		s5	-	-	-	0.555	0.662	0.469
Palmheart	*pa5*	*s2*	0.273	-	0.202	0.267	-	0.200
		s3	0.273	-	0.202	0.258	-	0.194
		s4	0.240	-	0.180	-	-	-
		s5	-	-	-	0.304	-	0.226
	pa20	*s2*	0.324	-	0.224	0.311	-	0.216
		s3	0.324	-	0.224	0.298	-	0.208
		s4	0.316	-	0.219	-	-	-
		s5	-	-	-	0.355	-	0.242
Grass pasture	*gi5*	*s2/s3*	-	-	-	0.082	-	0.082
		s5/s6	-	-	-	0.090	-	0.090
		s7	-	-	-	0.082	-	0.082
	gi20	*s2/s3*	-	-	-	0.080	-	0.080
		s5/s6	-	-	-	0.088	-	0.088
		s7	-	-	-	0.080	-	0.080
Grass-legume	*gl5*	*s2/s3*	-	-	-	0.089	-	0.089
		s5/s6	-	-	-	0.098	-	0.098
		s7	-	-	-	0.089	-	0.089
	gl20	*s2/s3*	-	-	-	0.083	-	0.083
		s5/s6	-	-	-	0.090	-	0.090
		s7	-	-	-	0.082	-	0.082
Trees	*wt*	*s2*	0.017	-	0.014	-	-	
		s3	0.016	-	0.013	-	-	-
		s5/s6	0.020	-	0.016	-	-	-

[a] only production activities with growth cycles of 5 and 20 years presented;
[b] "-" not relevant.

Table A5.2 Labour requirements (man years.$ha^{-1}.y^{-1}$) per growth stage in tree plantations in period $_{p1}$ in the multi-period MGLP-model. For explanation of codes see Table 4.1.

Growth stage	Production technique ($_c$)	Terrain type ($_s$) s2	s3	s4	s5	s6	s7
Years 0-5	*MBN*	0.051	0.050	-	0.059	0.061	-
	MBn	0.040	0.040	-	0.046	0.047	-
Years 6-10	*MBN*	0.042	0.041	-	0.048	0.049	-
	MBn	0.036	0.036	-	0.041	0.042	-
Years 11-15	*MBN*	0.046	0.045	-	0.053	0.054	-
	MBn	0.039	0.038	-	0.044	0.045	-
Years 16-20	*MBN*	0.134	0.128	-	0.164	0.173	-
	MBn	0.086	0.082	-	0.105	0.110	-

Table A5.3 Example of fluctuations in labour requirements (man years.$ha^{-1}.y^{-1}$) in maize activities (terrain type $_{s2}$), caused by variation in weather conditions (see also Section 6.2). For explanation of codes see Table 4.1.

Period ($_p$)	Production technique ($_c$) *MBN*	*MbN*	*MBn*	*mBN*	*mbN*	*mBn*
p1	0.340	0.347	0.340	2.526	3.016	2.149
p2	0.340	0.347	0.340	2.576	3.059	2.179
p3	0.340	0.347	0.340	2.526	3.016	2.149
p4	0.340	0.347	0.340	2.516	3.007	2.143

Table A5.4 Labour requirements (man years.animal $unit^{-1}.y^{-1}$) per livestock activity in the single-period model. For explanation of codes see Table 4.1.

Animal unit ($_{au}$)		Feeding pattern ($_d$) *po*	*b10*	*b20*	*m10*	*m20*	*c10*
Milking cow unit	*mcu*	0.035	0.035	0.035	0.035	0.035	0.035
Beef cattle unit 1	*bcu*	0.011	0.011	0.010	0.011	0.011	0.010
Beef cattle unit 2	*bcup*	0.016	0.015	0.013	0.015	0.014	0.014

APPENDIX 6: *Prices and production costs*

Section 3.2.3 presented the methods used for calculating production costs. Tables A6.1 and A6.2 present the prices of inputs and outputs. The "low" and "high" prices for agricultural products were used in a sensitivity analysis (Section 5.4). Costs of fertilizer use and labour use were calculated in the MGLP-model by multiplying the amount with a unit price. The cost of biocide use per unit area was calculated as the amount of a biocide times the average price per kg active ingredient (Table A6.5) summed over all biocides. Only these aggregate costs of biocides were used in the MGLP-models (Table A6.6). Most production costs were not included separately in the MGLP-models. Costs of the use of machines, small equipment, planting material, etc. were calculated separately, however only the aggregate costs (Tables A6.3 and A6.4) were included in the MGLP-models. The coefficients in Tables A6.3 and A6.6 are presented for the production activities used in the single-period MGLP-model. Average coefficients (for period $_{p1}$ with average climatic conditions) for the multi-period MGLP-model can easily be calculated with these coefficients: for instance $_{ba1} = 5 * _{ba5},\ _{bac} = (20 * _{ba20} - 5 * _{ba5}) / 3$. Only for tree plantations these coefficients cannot be calculated with the data in Tables A6.3, therefore the costs of machines, implements, etc. per growth stage of tree plantations are presented in Table A6.4. Table A6.5 presents the costs implements, machines, etc. for livestock activities; no biocides are used in livestock activities. Production costs, except for costs of labour and fertilizer, are hardly affected by fluctuations in production levels between periods. $ 1 was equal to 130 col. in 1990 (Schipper, 1996).

Table A6.1 Prices (*1,000 col.) of inputs and outputs.

Input/ Output	Code	"average" price	"low" price	"high" price
Banana, first class (per tonne FM[b])	$price_{cp=ban}$	8.71	6.15	11.38
Banana, second class (per tonne FM)	$price_{cp=banr}$	0.00	0.00	0.00
Cassava, first class (per tonne FM)	$price_{cp=cas}$	25.10	6.28[a]	30.87
Cassava, second class (per tonne FM)	$price_{cp=casr}$	0.00	0.00	0.00
Maize (per tonne FM)	$price_{cp=mai}$	22.00	18.70	25.30
Palmheart (per tonne FM)	$price_{cp=pal}$	23.54	15.75	31.30
Pulpwood (per tonne DM)	$price_{cp=wop}$	5.00	3.96	5.77
Timber wood (per tonne DM)	$price_{cp=wot}$	9.25	7.33	10.67
Milk (per tonne)	$price_{ap=mlk/mlki}$	38.00	26.00	46.00
Beef cattle (per animal of 500 kg)	$price_{ap=bf}$	56.50	45.50	71.00
Calves (per animal of 30 kg)	$price_{ap=clv/clvl}$	11.70	9.42	14.70
N (per kg)	$pricef_{n=N}$	0.096	nr	nr
P (per kg)	$pricef_{n=P}$	0.178	nr	nr
K (per kg)	$pricef_{n=K}$	0.052	nr	nr
Labour (per man day)	*pricelab*	1.50	nr	nr
Transport (per tonne FM)	*pricetr*	0.33	nr	nr

[a] the lowest price used for cassava was 75% lower than the "average" price (in stead of 25 % lower when based on variation in export prices only), because farmgate prices fluctuate enormously;
[b] FM is fresh material.

Table A6.2 Prices (col.) for use of several implements and inputs.

	col. per 8 hours		col.	per
Airplane	40,640	Banana plants	70	unit
Bucket	8	Grass plants	10,950	ha
Cutting knife	8	Legume plants	15,000	ha
Electric saw	2,800	Maize seed	135	kg
Gloves	16	Palmheart seedlings	7.5	unit
Hammer	8	Tree seedlings	11	unit
Hand saw	16			
Hoe	16	Artificial insemination	400	time
Knapsack	80	Plastic bag	3.5	unit
Ladder	8	Banana box	23.1	unit
Machete	8	Banana processing plant	24,300	ha
Machine	26,400	Cable system	18,000	ha
Machine (heavy)	36,000	Licking stone	1,450	$animal.y^{-1}$
Wheelbarrow	80	Pole	200	unit
		Rope	500	kg
		Vaccination/deparasiting	58,00	$animal.y^{-1}$
		Wire	91	m

Table A6.3 Aggregate costs (*1,000 $col.ha^{-1}.y^{-1}$) of machinery, implements, planting, etc. per crop activity in the single-period model. For explanation of codes see Table 4.1.

Form of land use[a]	Code ($_l$)	Terrain type ($_s$)	Production technique ($_c$) *MBN*	*MbN*	*MBn*	*mBN*	*mbN*	*mBn*
Banana	*ba5*	*s2/s3*	107	99	97	-[b]	-	-
		s4	105	99	97	-	-	-
Banana	*ba20*	*s2/s3*	85	73	74	-	-	-
		s4	85	73	74	-	-	-
Cassava	*ca*	*s2/s3*	158	165	158	4	3	3
		s5/s6	-	-	-	5	4	4
Maize	*ma*	*s2/s3*	312	320	312	11	11	11
		s5	-	-	-	12	11	11
Palmheart	*pa5*	*s2/s3*	33	-	33	10	-	10
		s4	39	-	39	-	-	-
		s5	-	-	-	10	-	10
Palmheart	*pa20*	*s2/s3*	22	-	22	5	-	4
		s4	11	-	11	-	-	-
		s5	-	-	-	5	-	4
Grass pasture	*gi5*	*s2/s3*	-	-	-	17	-	17
		s5/s6	-	-	-	17	-	17
		s7	-	-	-	17	-	17
	gi20	*s2/s3*	-	-	-	9	-	9
		s5/s6	-	-	-	10	-	10
		s7	-	-	-	9	-	9
Grass-legume	*gl5*	*s2/s3*	-	-	-	20	-	20
		s5/s6	-	-	-	20	-	20
		s7	-	-	-	20	-	20
	gl20	*s2/s3*	-	-	-	12	-	12
		s5/s6	-	-	-	13	-	13
		s7	-	-	-	12	-	12
Trees	*wt*	*s2*	30	-	19	-	-	-
		s3	28	-	18	-	-	-
		s5	36	-	23	-	-	-
		s6	38	-	24	-	-	-

[a] only production activities with growth cycles of 5 or 20 years presented;
[b] "-" not relevant.

Table A6.4 Aggregate costs (*1,000 col.ha^{-1}.y^{-1}) of machinery, implements, planting materials, etc. per growth stage in tree plantations in period $_{p1}$ in the multi-period MGLP-model. For explanation of codes see Table 4.1.

Growth stage	Production technique ($_t$)	Terrain type ($_s$) *s2*	*s3*	*s4*	*s5*	*s6*	*s7*
Years 0-5	*MBN*	117	116	-	129	130	-
	MBn	113	113	-	125	126	-
Years 6-10	*MBN*	60	58	-	72	75	-
	MBn	42	40	-	49	50	-
Years 11-15	*MBN*	73	70	-	89	92	-
	MBn	49	48	-	59	61	-
Years 16-20	*MBN*	408	387	-	503	533	-
	MBn	250	238	-	307	325	-

Table A6.5 Costs of machinery, implements, vaccinations, etc. (*1,000 col.animal unit^{-1}.y^{-1}) for all livestock activities in the multi-period model and the single-period model. For explanation of codes see Table 4.1.

Animal unit	Code ($_{au}$)	Feeding pattern ($_d$) *po*	*b10*	*b20*	*m10*	*m20*	*c10*
Milking cow unit	*mcu*	4.0	4.0	4.0	4.0	4.0	4.0
Beef cattle unit 1	*bcu*	1.5	1.5	1.5	1.5	1.5	1.5
Beef cattle unit 2	*bcup*	2.2	2.1	2.0	2.1	2.0	2.0

Table A6.6 Price (*1,000 col.) of biocides (per kg active ingredient).

Biocide	Price	Biocide	Price
Atrazine	1.26	*Bacillus*	61.61
Benomyl	7.00	Cadusafos	4.50
Carbofuron	4.43	Chlorothalonil	2.50
Chlorpyriphos	37.85	*Deltamethrin*	113.73
Diuron	1.34	Ethoprophos	9.99
Fenamiphos	2.31	Glyphosate	4.25
Malathion	2.06	Mancozeb	0.80
Methomyl	7.54	Oxamyl	2.34
Oxyfluorfen	12.36	Propiconazol	40.68
Terbufos	3.45	Terbuthylazine	2.09
Tridemorph	12.75		

Table A6.7 Costs of biocide use (*1,000 col.ha^{-1}.y^{-1}) per crop activity in the single-period model. For explanation of codes see Table 4.1.

Form of land use[a]	Code ()	Terrain type ($_s$)	Production technique ($_c$) *MBN*	*MbN*	*MBn*	*mBN*	*mbN*	*mBn*
Banana	*ba5*	*s2*	118	60	104	-[b]	-	-
		s3	118	60	105	-	-	-
		s4	106	53	93	-	-	-
	ba20	*s2/s3*	126	64	111	-	-	-
		s4	123	62	108	-	-	-
Cassava	*ca*	*s2/s3*	21	5	21	21	5	21
		s5/s6	-	-	-	21	5	21
Maize	*ma*	*s2/s3*	51	17	50	51	17	50
		s5	-	-	-	51	17	50
Palmheart[c]	*pa5*	*s2/s3*	2	-	2	2	-	2
		s4	2	-	2	-	-	-
		s5	-	-	-	2	-	2
	pa20	*s2/s3*	0	-	0	0	-	0
		s4	0	-	0	-	-	-
		s5	-	-	-	0	-	0
Pasture[d]	*gi1/gl1*	*s2/s3/s5/s6/s7*	-	-	-	5	-	5
	gic/glc	*s2/s3/s5/s6/s7*	-	-	-	4	-	4
Trees[c]	*wt*	*s2/s3/s5/s6*	1	-	1	-	-	-

[a] only production activities with growth cycles of 5 or 20 years presented;
[b] "-" not relevant;
[c] only biocides applied during establishment of the plantation;
[d] no distinction made between grass pasture and grass-legume pasture.

APPENDIX 7: *Population and consumption by humans*

Growth rate
The estimated population in the NAZ for 1990 is about 152,000 persons (28 km^{-2}). Population growth in the NAZ (4 %; Lok 1992) is to a large extent caused by immigration, mainly from other regions in Costa Rica. The population growth in Costa Rica is about 2 % (INICEM-Market data 1994).The estimated population in the NAZ in 2020, with different growth rates between 1990 and 2020 is:
growth rate 4 %: 493,150 persons
growth rate 2 %: 275,418 persons
In this study a 2 % growth rate was considered to be the minimum for the NAZ. Higher growth rates were assumed to be caused by immigration.

Age structure
In 1990 the age structure in the NAZ was (Lok 1992):

0-19 year	51 %
20-65 year	46 %
> 65 year	3 %

The percentage of persons under 20 years of age is relatively high; this is caused by the high immigration. In this study the age structure as found by Lok was used.

Ratio men/women
In 1990 the ratio between men and women was 1.09. This is relatively high, because many young man migrate from other regions to the Atlantic Zone. CELADE 6 (1990) expects this ratio to decrease slowly. In this study a ratio of 1.0 was used for 2020. In most countries in the world the ratio is about 1.0.

Consumption
For estimating the consumption of different products per person (Table A7.4) the following was assumed:

- Data on energy and protein needs for humans were based on information from Passmore *et al.* (1978; Table A7.1). The annual energy needs of one average person in the NAZ is about 3,690 MJ. The annual protein need is 11.0 kg. The energy needs mentioned by Luyten (1995) are in the same range (10 - 11.5 $MJ.d^{-1}$);
- All proteins are obtained from milk and beef. Holman *et al.* (1992) mention a domestic consumption of dairy products of 149 $kg.person^{-1}$ in '80. Jansen et al. (1996; Table A7.3) mention a lower dairy product consumption, however cheese and milkpowder are not included in the data of Jansen *et al* (1996). The average milk consumption was assumed to be 100 $kg.y^{-1}$. The rest of the protein need is consumed in the form of beef. All energy minus the energy from animal products is obtained from grains and roots and tubers (in this study from maize and cassava). Maize and cassava are consumed in the same proportions as presented in Table A7.3 for the NAZ;
- Other diets are not relevant. The animal product consumption is already relatively high in Costa Rica and is not expected to increase much;
- If other nutrient concentrations were used in the "optimistic" and "pessimistic" estimates, the amount of products needed changed as well.

Table A7.1 Energy and protein needs of persons of different ages (based on Passmore *et al.* (1978).

	Age years	Energy needs $MJ.d^{-1}$	Protein needs $g.d^{-1}$
Men	0-19	9.77	28.1
	20-65	12.55	37.0
	>65	12.55	37.0
Women	0-19	8.67	25.3
	20-65	9.50	30.0
	<65	9.20	29.0

Table A7.2 Nutritive value of products for human consumption (Source: Voorlichtingsbureau voor de voeding).

Product	Energy $MJ.kg^{-1}$	Protein $g.kg^{-1}$	Water %
Maize corn	17.02	105	0
Cassava tubers	15.15	20	0
Meat (lean)	4.52	226	70
Milk	2.93	34	88

Table A7.3 Domestic consumption of various products (kg fresh product.y^{-1}.$person^{-1}$) in 1991(Jansen *et al.* 1996).

Product	Costa Rica	NAZ
Banana	8.7	11.3
Cassava	5.8	8.0
Roots/tubers	25.5	24.6
Rice	44.0	60.6
Milk	56.3	47.9

Table A7.4 Consumption of crop products and animal products (fresh products; kg. y^{-1}.$person^{-1}$) in the NAZ used in this study.

Product	"average"	"optimistic"	"pessimistic"
Banana	11.3[a]	11.3	11.3
Cassava	77.9	77.2	78.5
Maize	191.8	190.0	193.3
Palmheart	1[d]	1	1
Timber	240[c]	240	240
Milk	100	100	100
Beef	0.156[b]	0.182	0.133

[a] based on consumption mentioned by Jansen et al. (1996);
[b] number of animals of 500 kg with 50 % meat, based on protein contents mentioned in Table A3.6;
[c] 0.4 m^3, based on data from Costa Rica in WRI (1994): (total wood production - fuel wood - pulpwood)/population;
[d] arbitrary value for net palmheart consumption, equal to 10 kg gross palmheart.

APPENDIX 8: *Results of the single-period and multi-period MGLP-models.*

In this appendix the results of the MGLP-models are presented. Tables A8.2 to A8.6 show the results of the single-period model and the sensitivity analyses; Tables A8.7 to A8.11 show the results of the multi-period model.

Below the steps that are followed during optimization are illustrated for policy view 'National Development' (ND; single-period model with 'average' coefficients). Arbitrarily, the same weights were attached to all relevant objective functions per policy view. In the first step after the zero-round, the optimum and worst values of the relevant objectives for policy view ND (maximization of employment and maximization of economic surplus) were determined, using the bounds presented in Table 2.3. These worst and optimum values are shown in Table A8.1. In the next step an optimal compromise between the two objective function was sought. For this purpose additional objective functions were used, which simultaneously minimized the relative deviation (% of difference between optimum and worst value) from the optimum values of the two relevant objective functions. In Equation A8.1 these additional constraints are described for policy view ND. *PERC* was minimized, so that the values of *EMP* and *ESP* remained as close as possible to their optimum value mentioned in Table A8.1.

$$\begin{aligned} EMP &\geq 104794 - 795.1 \times PERC \\ ESP &\geq 90004 - 798.0 \times PERC \end{aligned} \qquad \text{A8.1}$$

The optimum land use scenario for a policy view is obtained when the lowest percentage deviation from the optimum values, valid for all relevant objective functions, is found. In the case of policy view ND with 'average' coefficients *PERC* was 14.63 %: *EMP* was 14.61 % lower than the optimum value, and *ESP* was 14.63 % lower than the optimum value in Table A8.1.

Table A8.1 Optimum and worst values for policy view National Development obtained with the single-period MGLP-model with "average" coefficients.

Objective function			Optimum	Worst	Optimum-worst
EMP	employment	man years.y^{-1}	104,794	25,280	79,506
ESP	economic surplus	10^6 col.y^{-1}	90,004	10,202	79,802

Table A8.2 Results of the single-period MGLP-model for the NAZ: policy view Free Enterprise. For explanation of codes see Tables 4.1 and 4.2.

Prices Agro-ecological coefficients		"average" "average"	"average" "optimistic"	"average" "pessimistic"	"high" "average"	"low" "average"
Objective function values						
ARM	$ha.y^{-1}$	257,991	257,991	257,991	257,991	255,982
BLM	y^{-1}	8,671	4	115,076	8,745	5,389
BUM	tonne a.i.. y^{-1}	1,682	1,682	1,367	1,682	1,711
BUHA	$kg.ha^{-1}.y^{-1}$	6.52	6.52	5.30	6.52	6.68
NLM	$tonne.y^{-1}$	54,601	23,038	102,646	53,552	59,596
EMP	man $years.y^{-1}$	76,436	75,290	74,448	78,531	85,267
ESP	10^6 $col.y^{-1}$	97,494	104,183	69,204	145,855	23,210
INP	10^6 $col.person^{-1}.y^{-1}$	0.304	0.324	0.242	0.410	0.122
Land use allocation						
Forms of land use ($_j$)						
ma	$ha.y^{-1}$	-	-	-	-	-
ca	$ha.y^{-1}$	60,000	60,000	60,000	60,000	1,397
ba20	$ha.y^{-1}$	52,616	60,000	60,000	60,000	60,000
pa20	$ha.y^{-1}$	60,000	60,000	60,000	60,000	60,000
gi20	$ha.y^{-1}$	25,375	5,317	-	17,991	60,000
gl20	$ha.y^{-1}$	60,000	60,000	60,000	60,000	60,000
wt	$ha.y^{-1}$	-	12,674	17,991	-	14,585
Production techniques ($_c$)						
MBN	$ha.y^{-1}$	119,128	126,248	91,204	112,970	89,174
MbN	$ha.y^{-1}$	6,681	19,618	42,106	20,222	-
MBn	$ha.y^{-1}$	-	-	17,873	-	-
mBN	$ha.y^{-1}$	132,183	112,125	106,808	124,799	166,808
mbN	$ha.y^{-1}$	-	-	-	-	-
mBn	$ha.y^{-1}$	-	-	-	-	-
Terrain types ($_s$)						
s2	$ha.y^{-1}$	63,257	63,257	63,257	63,257	63,257
s3	$ha.y^{-1}$	82,799	82,799	82,799	82,799	82,799
s4	$ha.y^{-1}$	45,245	45,245	45,245	45,245	45,245
s5	$ha.y^{-1}$	46,808	46,808	46,808	46,808	46,808
s6	$ha.y^{-1}$	17,873	17,873	17,873	17,873	17,873
s7	$ha.y^{-1}$	2,009	2,009	2,009	2,009	-
Animal units ($_{au}$)						
mcu	$number.y^{-1}$	455,607	430,696	449,434	455,607	455,607
bcu	$number.y^{-1}$	-	-	-	-	-
bcup	$number.y^{-1}$	211,189	49,593	-	148,748	507,400
Population	$persons.y^{-1}$	436,775	430,230	425,418	448,747	487,241

Table A8.3 Results of the single-period MGLP-model for the NAZ: policy view National Development. For explanation of codes see Tables 4.1 and 4.2.

Prices Agro-ecological coefficients		"average" "average"	"average" "optimistic"	"average" "pessimistic"	"high" "average"	"low" "average"
Objective function values						
ARM	$ha.y^{-1}$	210,311	210,311	210,311	210,311	210,311
BLM	y^{-1}	6,181	3	95,147	6,904	4,927
BUM	tonne a.i..y^{-1}	1,371	1,371	1,115	1,371	1,371
BUHA	$kg.ha^{-1}.y^{-1}$	6.52	6.52	5.30	6.52	6.52
NLM	$tonne.y^{-1}$	42,795	19,947	89,050	43,031	47,276
EMP	man years.y^{-1}	93,174	90,393	90,993	93,828	84,249
ESP	10^6 col.y^{-1}	78,327	82,698	56,730	115,017	18,827
INP	10^6 col.person^{-1}.y^{-1}	0.228	0.242	0.188	0.300	0.114
Land use allocation						
Forms of land use ($_j$)						
ma	$ha.y^{-1}$	33,260	32,987	19,284	44,065	19,887
ca	$ha.y^{-1}$	60,000	60,000	60,000	60,000	1,386
ba20	$ha.y^{-1}$	46,530	35,456	59,723	34,878	53,996
pa20	$ha.y^{-1}$	60,000	55,838	60,000	57,931	60,000
gi20	$ha.y^{-1}$	10,522	26,030	9,315	13,438	15,042
gl20	$ha.y^{-1}$	-	-	1,988	-	60,000
wt	$ha.y^{-1}$	-	-	-	-	-
Production techniques ($_c$)						
MBN	$ha.y^{-1}$	88,169	91,294	36,649	92,809	73,272
MbN	$ha.y^{-1}$	18,369	-	59,723	-	13,221
MBn	$ha.y^{-1}$	-	-	-	-	-
mBN	$ha.y^{-1}$	70,522	86,030	94,655	73,438	103,930
mbN	$ha.y^{-1}$	33,260	32,987	19,284	44,065	19,887
mBn	$ha.y^{-1}$	-	-	-	-	-
Terrain types ($_s$)						
s2	$ha.y^{-1}$	59,333	59,333	59,333	59,333	59,333
s3	$ha.y^{-1}$	72,071	72,071	72,071	72,071	72,071
s4	$ha.y^{-1}$	35,545	35,545	35,545	35,545	35,545
s5	$ha.y^{-1}$	27,503	27,503	27,503	27,503	27,503
s6	$ha.y^{-1}$	15,799	15,799	15,799	15,799	15,799
s7	$ha.y^{-1}$	60	60	60	60	60
Animal units ($_{au}$)						
mcu	$number.y^{-1}$	-	-	14,937	-	455,517
bcu	$number.y^{-1}$	142,503	-	-	-	-
bcup	$number.y^{-1}$	-	262,508	98,042	113,537	127,204
Population	$persons.y^{-1}$	532,423	516,534	519,963	536,160	481,421

Table A8.4 Results of the single-period MGLP-model for the NAZ: policy view Regional Development. For explanation of codes see Tables 4.1 and 4.2.

Prices Agro-ecological coefficients		"average" "average"	"average" "optimistic"	"average" "pessimistic"	"high" "average"	"low" "average"
Objective function values						
ARM	$ha.y^{-1}$	210,311	196,102	210,251	210,311	210,311
BLM	y^{-1}	5,238	4	75,510	4,921	4,704
BUM	tonne a.i..y^{-1}	560	564	456	568	732
BUHA	$kg.ha^{-1}.y^{-1}$	2.66	2.88	2.17	2.70	3.48
NLM	$tonne.y^{-1}$	43,469	17,582	92,719	45,964	48,605
EMP	man $years.y^{-1}$	73,436	73,407	73,343	72,976	70,798
ESP	10^6 $col.y^{-1}$	80,385	86,744	56,835	111,371	16,280
INP	10^6 $col.person^{-1}.y^{-1}$	0.272	0.289	0.215	0.352	0.115
Land use allocation						
Forms of land use ($_l$)						
ma	$ha.y^{-1}$	-	1,615	3,821	14,086	7,868
ca	$ha.y^{-1}$	60,000	60,000	60,000	60,000	38,557
ba20	$ha.y^{-1}$	13,410	14,486	5,351	-	15,959
pa20	$ha.y^{-1}$	60,000	60,000	60,000	60,000	60,000
gi20	$ha.y^{-1}$	16,902	-	21,080	32,226	60,000
gl20	$ha.y^{-1}$	60,000	60,000	60,000	44,000	27,928
wt	$ha.y^{-1}$	-	-	-	-	-
Production techniques ($_c$)						
MBN	$ha.y^{-1}$	40,981	33,130	32,497	61,769	48,456
MbN	$ha.y^{-1}$	13,410	14,486	5,351	-	-
MBn	$ha.y^{-1}$	-	-	-	-	-
mBN	$ha.y^{-1}$	155,921	146,870	164,095	148,542	153,987
mbN	$ha.y^{-1}$	-	1,615	8,309	-	7,868
mBn	$ha.y^{-1}$	-	-	-	-	-
Terrain types ($_s$)						
s2	$ha.y^{-1}$	59,333	59,333	59,333	59,333	59,333
s3	$ha.y^{-1}$	72,071	72,071	72,071	72,071	72,071
s4	$ha.y^{-1}$	35,545	35,545	35,545	35,545	35,545
s5	$ha.y^{-1}$	27,503	27,503	27,503	27,503	27,503
s6	$ha.y^{-1}$	15,799	1,649	15,799	15,799	15,799
s7	$ha.y^{-1}$	60	-	-	60	60
Animal units ($_{au}$)						
mcu	$number.y^{-1}$	454,424	427,084	390,000	295,823	187,735
bcu	$number.y^{-1}$	-	-	-	-	-
bcup	$number.y^{-1}$	142,932	-	158,701	272,522	507,400
Population	$persons.y^{-1}$	419,637	419,466	419,102	417,007	404,561

Table A8.5 Results of the single-period MGLP-model for the NAZ: policy view Environmental Protection. For explanation of codes see Tables 4.1 and 4.2.

Prices Agro-ecological coefficients		"average" "average"	"average" "optimistic"	"average" "pessimistic"	"high" "average"	"low" "average"
Objective function values						
ARM	ha.y^{-1}	20,315	19,159	22,298	14,735	32,188
BLM	y^{-1}	3	0	216	2	1
BUM	tonne a.i..y^{-1}	2	2	3	2	4
BUHA	kg.ha^{-1}.y^{-1}	0.12	0.12	0.12	0.12	0.12
NLM	tonne.y^{-1}	5,008	2,300	8,879	3,633	6,203
EMP	man years.y^{-1}	6,582	6,802	7,044	4,774	10,169
ESP	10^6 col.y^{-1}	4,294	3,831	4,483	3,640	4,621
INP	10^6 col.person^{-1}.y^{-1}	0.045	0.045	0.045	0.045	0.045
Land use allocation						
Forms of land use ($_j$)						
ma	ha.y^{-1}	-	-	-	-	-
ca	ha.y^{-1}	-	-	-	-	-
ba20	ha.y^{-1}	-	-	-	-	-
pa20	ha.y^{-1}	20,315	19,159	22,298	14,735	32,188
gi20	ha.y^{-1}	-	-	-	-	-
gl20	ha.y^{-1}	-	-	-	-	-
wt	ha.y^{-1}	-	-	-	-	-
Production techniques ($_c$)						
MBN	ha.y^{-1}	20,315	-	22,298	14,735	32,188
MbN	ha.y^{-1}	-	-	-	-	-
MBn	ha.y^{-1}	-	-	-	-	-
mBN	ha.y^{-1}	-	19,159	-	-	-
mbN	ha.y^{-1}	-	-	-	-	-
mBn	ha.y^{-1}	-	-	-	-	-
Terrain types ($_s$)						
s2	ha.y^{-1}	20,315	-	-	14,735	-
s3	ha.y^{-1}	-	-	-	-	-
s4	ha.y^{-1}	-	-	22,298	-	32,188
s5	ha.y^{-1}	-	19,159	-	-	-
s6	ha.y^{-1}	-	-	-	-	-
s7	ha.y^{-1}	-	-	-	-	-
Animal units ($_{au}$)						
mcu	number.y^{-1}	-	-	-	-	-
bcu	number.y^{-1}	-	-	-	-	-
bcup	number.y^{-1}	-	-	-	-	-
Population	persons.y^{-1}	275,418	275,418	275,418	275,418	275,418

Table A8.6 Results of the single-period MGLP-model for the NAZ: policy view Nature Conservation. For explanation of codes see Tables 4.1 and 4.2.

Prices		"average"	"average"	"average"	"high"	"low"
Agro-ecological coefficients		"average"	"optimistic"	"pessimistic"	"average"	"average"
Objective function values						
ARM	ha.y^{-1}	14,477	13,262	19,900	11,494	32,188
BLM	y^{-1}	153	0	2,365	121	1
BUM	tonne a.i..y^{-1}	67	68	12	54	4
BUHA	kg.ha^{-1}.y^{-1}	4.66	5.15	0.60	4.54	0.12
NLM	tonne.y^{-1}	2,717	918	6,459	2,147	6,203
EMP	man years.y^{-1}	6,733	6,599	8,156	5,338	10,169
ESP	10^6 col.y^{-1}	4,243	3,900	4,108	3,449	4,621
INP	10^6 col.$person^{-1}$.y^{-1}	0.045	0.045	0.045	0.045	0.045
Land use allocation						
Forms of land use ($_l$)						
ma	ha.y^{-1}	-	-	-	-	-
ca	ha.y^{-1}	14,477	13,262	15,445	11,494	-
ba20	ha.y^{-1}	-	-	-	-	-
pa20	ha.y^{-1}	-	-	4,455	-	32,188
gi20	ha.y^{-1}	-	-	-	-	-
gl20	ha.y^{-1}	-	-	-	-	-
wt	ha.y^{-1}	-	-	-	-	-
Production techniques ($_c$)						
MBN	ha.y^{-1}	-	-	4,455	-	32,188
MbN	ha.y^{-1}	-	-	-	-	-
MBn	ha.y^{-1}	-	-	-	-	-
mBN	ha.y^{-1}	12,865	13,262	-	10,208	-
mbN	ha.y^{-1}	1,612	-	15,445	1,286	-
mBn	ha.y^{-1}	-	-	-	-	-
Terrain types ($_s$)						
s2	ha.y^{-1}	1,612	-	15,445	-	-
s3	ha.y^{-1}	-	781	-	1,286	-
s4	ha.y^{-1}	-	-	4,455	-	32,188
s5	ha.y^{-1}	-	-	-	10,208	-
s6	ha.y^{-1}	12,865	12,481	-	-	-
s7	ha.y^{-1}	-	-	-	-	-
Animal units ($_{au}$)						
mcu	number.y^{-1}	-	-	-	-	-
bcu	number.y^{-1}	-	-	-	-	-
bcup	number.y^{-1}	-	-	-	-	-
Population	persons.y^{-1}	275,418	275,418	275,418	275,418	275,418

Table A8.7 Results of the multi-period MGLP-model for the NAZ: policy view Free Enterprise. For explanation of codes see Tables 4.2 and 6.1.

		Period *p1*	*p2*	*p3*	*p4*
Objective function values					
ARM	ha.y^{-1}	257,991	257,991	257,991	257,991
BLM	5 y^{-1}	43,488	42,876	43,821	44,305
BUM	tonne a.i..5 y^{-1}	8,327	8,268	8,469	8,577
BUHA	kg.ha^{-1}.y^{-1}	6.46	6.41	6.57	6.65
NLM	tonne.5 y^{-1}	278,248	257,919	265,948	272,353
EMP	man years.5 y^{-1}	397,105	376,823	387,980	397,105
ESP	10^6 col.5 y^{-1}	503,894	529,089	484,186	491,928
INP	10^6 col.$person^{-1}$.y^{-1}	0.302	0.311	0.292	0.297
Land use allocation					
Forms of land use ()					
ma	ha.y^{-1}	-	-	-	-
ca	ha.y^{-1}	60,000	60,000	60,000	60,000
ba1	ha.y^{-1}	11,811	23,382	22,915	-
bac	ha.y^{-1}	46,298	34,726	35,193	58,108
pa1	ha.y^{-1}	-	60,000	-	-
pac	ha.y^{-1}	60,000	-	60,000	60,000
gi1	ha.y^{-1}	-	-	19,883	-
gic	ha.y^{-1}	19,883	19,883	-	19,883
gl1	ha.y^{-1}	-	17,854	42,146	-
glc	ha.y^{-1}	60,000	42,146	17,854	60,000
wf	ha.y^{-1}	-	-	-	-
Production techniques ($_c$)					
MBN	ha.y^{-1}	114,557	114,170	11,4557	14,557
MbN	ha.y^{-1}	16,744	16,744	16,744	16,744
MBn	ha.y^{-1}	-	-	-	-
mBN	ha.y^{-1}	126,691	127,078	12,6691	126,691
mbN	ha.y^{-1}	-	-	-	-
mBn	ha.y^{-1}	-	-	-	-
Terrain types ($_s$)					
s2	ha.y^{-1}	63,257	63,257	63,257	63,257
s3	ha.y^{-1}	82,799	82,799	82,799	82,799
s4	ha.y^{-1}	45,245	45,245	45,245	45,245
s5	ha.y^{-1}	46,808	46,808	46,808	46,808
s6	ha.y^{-1}	17,874	17,874	17,874	17,874
s7	ha.y^{-1}	2,009	2,009	2,009	2,009
Animal units ($_{au}$)					
mcu	number.y^{-1}	467,290	471,520	430,121	453,271
bcu	number.y^{-1}	-	-	-	-
bcup	number.y^{-1}	168,969	175,728	150,551	163,900
Population	persons.y^{-1}	453,834	453,834	453,834	453,834

Table A8.8 Results of the multi-period MGLP-model for the NAZ: policy view National Development. For explanation of codes see Tables 4.2 and 6.1.

		Period			
		p1	*p2*	*p3*	*p4*
Objective function values					
ARM	ha.y^{-1}	210,311	210,311	210,311	210,311
BLM	5 y^{-1}	30,373	30,600	30,772	31,275
BUM	tonne a.i..5 y^{-1}	6,722	6,832	6,872	6,999
BUHA	kg.ha^{-1}.y^{-1}	6.39	6.50	6.54	6.66
NLM	tonne.5 y^{-1}	215,859	209,265	212,597	211,737
EMP	man years.5 y^{-1}	463,636	463,636	462,240	463,636
ESP	10^6 col.5 y^{-1}	398,813	418,754	389,050	391,962
INP	10^6 col.person^{-1}.y^{-1}	0.231	0.238	0.227	0.228
Land use allocation					
Forms of land use ()					
ma	ha.y^{-1}	27,975	27,975	28,211	27,975
ca	ha.y^{-1}	60,000	60,000	60,000	60,000
ba1	ha.y^{-1}	12,718	13,403	25,664	-
bac	ha.y^{-1}	39,067	38,382	26,121	51,785
pa1	ha.y^{-1}	7,555	35,603	6,747	10,095
pac	ha.y^{-1}	52,445	24,397	53,253	49,905
gi1	ha.y^{-1}	2,989	7,326	-	236
gic	ha.y^{-1}	7,562	3,226	10,316	10,316
gl1	ha.y^{-1}	-	-	-	-
glc	ha.y^{-1}	-	-	-	-
wt	ha.y^{-1}	-	-	-	-
Production techniques ($_c$)					
MBN	ha.y^{-1}	84,131	84,131	84,131	84,131
MbN	ha.y^{-1}	27,654	27,654	27,654	27,654
MBn	ha.y^{-1}	-	-	-	-
mBN	ha.y^{-1}	70,552	70,552	70,316	70,552
mbN	ha.y^{-1}	27,975	27,975	28,211	27,975
mBn	ha.y^{-1}	-	-	-	-
Terrain types ($_s$)					
s2	ha.y^{-1}	59,334	59,334	59,334	59,334
s3	ha.y^{-1}	72,071	72,071	72,071	72,071
s4	ha.y^{-1}	35,545	35,545	35,545	35,545
s5	ha.y^{-1}	27,503	27,503	27,503	27,503
s6	ha.y^{-1}	15,799	15,799	15,799	15,799
s7	ha.y^{-1}	60	60	60	60
Animal units ($_{au}$)					
mcu	number.y^{-1}	-	-	-	-
bcu	number.y^{-1}	139,784	141,859	141,859	141,859
bcup	number.y^{-1}	1,642	-	-	-
Population	persons.y^{-1}	529,870	529,870	529,870	529,870

Table A8.9 Results of the multi-period MGLP-model for the NAZ: policy view Regional Development. For explanation of codes see Tables 4.2 and 6.1.

		Period *p1*	*p2*	*p3*	*p4*
Objective function values					
ARM	ha.y^{-1}	210,311	207,622	210,311	210,311
BLM	5 y^{-1}	13,261	14,330	11,935	11,935
BUM	tonne a.i..5 y^{-1}	2,005	2,106	1,905	1,905
BUHA	kg.ha^{-1}.y^{-1}	1.91	2.03	1.81	1.81
NLM	tonne.5 y^{-1}	220,679	221,628	213,538	214,290
EMP	man years.5 y^{-1}	416,156	416,156	416,156	416,156
ESP	10^6 col.5 y^{-1}	368,779	396,779	342,599	356,589
INP	10^6 col.$person^{-1}$.y^{-1}	0.235	0.247	0.224	0.230
Land use allocation					
Forms of land use ()					
ma	ha.y^{-1}	27,495	24,102	29,448	28,199
ca	ha.y^{-1}	60,000	60,000	60,000	60,000
ba1	ha.y^{-1}	-	-	-	-
bac	ha.y^{-1}	-	-	-	-
pa1	ha.y^{-1}	14,881	11,610	23,019	10,490
pac	ha.y^{-1}	45,119	48,390	36,981	49,510
gi1	ha.y^{-1}	704	710	2,112	-
gic	ha.y^{-1}	2,112	2,810	-	2,112
gl1	ha.y^{-1}	-	45,564	-	14,436
glc	ha.y^{-1}	60,000	14,436	58,752	45,564
wt	ha.y^{-1}	-	-	-	-
Production techniques ($_c$)					
MBN	ha.y^{-1}	60,000	60,000	60,000	60,000
MbN	ha.y^{-1}	-	-	-	-
MBn	ha.y^{-1}	-	-	-	-
mBN	ha.y^{-1}	112,734	115,401	104,605	106,642
mbN	ha.y^{-1}	37,577	32,221	45,706	43,669
mBn	ha.y^{-1}	-	-	-	-
Terrain types ($_s$)					
s2	ha.y^{-1}	59,334	59,334	59,334	59,334
s3	ha.y^{-1}	72,071	72,071	72,071	72,071
s4	ha.y^{-1}	35,545	35,545	35,545	35,545
s5	ha.y^{-1}	27,503	27,503	27,503	27,503
s6	ha.y^{-1}	15,799	13,116	15,799	15,799
s7	ha.y^{-1}	60	54	60	60
Animal units ($_{au}$)					
mcu	number.y^{-1}	400,692	409,903	416,551	416,575
bcu	number.y^{-1}	-	-	-	-
bcup	number.y^{-1}	23,709	31,013	16,229	17,668
Population	persons.y^{-1}	475,607	475,607	475,607	475,607

Table A8.10 Results of the multi-period MGLP-model for the NAZ: policy view Environmental Protection. For explanation of codes see Tables 4.2 and 6.1.

		Period *p1*	*p2*	*p3*	*p4*
Objective function values					
ARM	ha.y^{-1}	20,561	20,561	20,561	20,561
BLM	5 y^{-1}	7	7	8	8
BUM	tonne a.i..5 y^{-1}	12	11	13	13
BUHA	kg.ha^{-1}.y^{-1}	0.12	0.11	0.12	0.12
NLM	tonne.5 y^{-1}	22,506	23,505	22,158	21,824
EMP	man years.5 y^{-1}	32,882	34,238	32,828	32,716
ESP	10^6 col.5 y^{-1}	20,930	20,473	20,949	20,986
INP	10^6 col.$person^{-1}$.y^{-1}	0.045	0.045	0.045	0.045
Land use allocation					
Forms of land use ($_j$)					
ma	ha.y^{-1}	-	-	-	-
ca	ha.y^{-1}	-	-	-	-
ba1	ha.y^{-1}	-	-	-	-
bac	ha.y^{-1}	-	-	-	-
pa1	ha.y^{-1}	5,076	4,803	5,335	5,346
pac	ha.y^{-1}	15,485	15,758	15,226	15,215
gi1	ha.y^{-1}	-	-	-	-
gic	ha.y^{-1}	-	-	-	-
gl1	ha.y^{-1}	-	-	-	-
glc	ha.y^{-1}	-	-	-	-
wt	ha.y^{-1}	-	-	-	-
Production techniques ($_c$)					
MBN	ha.y^{-1}	18,051	18,051	18,051	18,051
MbN	ha.y^{-1}	-	-	-	-
MBn	ha.y^{-1}	-	-	-	-
mBN	ha.y^{-1}	2,510	2,510	2,510	2,510
mbN	ha.y^{-1}	-	-	-	-
mBn	ha.y^{-1}	-	-	-	-
Terrain types ($_s$)					
s2	ha.y^{-1}	7,474	7,474	7,474	7,474
s3	ha.y^{-1}	-	-	-	-
s4	ha.y^{-1}	10,973	10,973	10,973	10,973
s5	ha.y^{-1}	2,114	2,114	2,114	2,114
s6	ha.y^{-1}	-	-	-	-
s7	ha.y^{-1}	-	-	-	-
Animal units ($_{au}$)					
mcu	number.y^{-1}	-	-	-	-
bcu	number.y^{-1}	-	-	-	-
bcup	number.y^{-1}	-	-	-	-
Population	persons.y^{-1}	275,418	275,418	275,418	275,418

Table A8.11 Results of the multi-period MGLP-model for the NAZ: policy view Nature Conservation. For explanation of codes see Tables 4.2 and 6.1.

		Period p1	p2	p3	p4
Objective function values					
ARM	ha.y^{-1}	14,603	13,950	14,775	15,091
BLM	5 y^{-1}	773	735	795	812
BUM	tonne a.i..5 y^{-1}	338	326	339	345
BUHA	kg.ha^{-1}.y^{-1}	4.58	4.80	4.52	4.43
NLM	tonne.5 y^{-1}	13,613	13,376	13,625	13,719
EMP	man years.5 y^{-1}	33,897	33,253	34,039	34,287
ESP	10^6 col.5 y^{-1}	21,139	21,356	21,091	21,007
INP	10^6 col.person^{-1}.y^{-1}	0.045	0.045	0.045	0.045
Land use allocation					
Forms of land use ($_j$)					
ma	ha.y^{-1}	-	-	-	-
ca	ha.y^{-1}	14,603	13,950	14,775	15,091
ba1	ha.y^{-1}	-	-	-	-
bac	ha.y^{-1}	-	-	-	-
pa1	ha.y^{-1}	-	-	-	-
pac	ha.y^{-1}	-	-	-	-
gi1	ha.y^{-1}	-	-	-	-
gic	ha.y^{-1}	-	-	-	-
gl1	ha.y^{-1}	-	-	-	-
glc	ha.y^{-1}	-	-	-	-
wt	ha.y^{-1}	-	-	-	-
Production techniques ($_c$)					
MBN	ha.y^{-1}	-	-	-	-
MbN	ha.y^{-1}	-	7	-	-
MBn	ha.y^{-1}	-	-	-	-
mBN	ha.y^{-1}	12,888	12,389	12,888	13,147
mbN	ha.y^{-1}	1,715	1,555	1,887	1,944
mBn	ha.y^{-1}	-	-	-	-
Terrain types ($_s$)					
s2	ha.y^{-1}	160	7	333	390
s3	ha.y^{-1}	1,555	1,555	1,555	1,555
s4	ha.y^{-1}	-	-	-	-
s5	ha.y^{-1}	12,888	12,389	12,888	13,147
s6	ha.y^{-1}	-	-	-	-
s7	ha.y^{-1}	-	-	-	-
Animal units ($_{au}$)					
mcu	number.y^{-1}	-	-	-	-
bcu	number.y^{-1}	-	-	-	-
bcup	number.y^{-1}	-	-	-	-
Population	persons.y^{-1}	275,418	275,418	275,418	275,418