Spatially explicit analysis of land use change: a case study for Ecuador

Free de Koning

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voormalig hoogleraar plantaardige productiesystemen met bijzondere aandacht voor de tropen, tevens hoogleraar externe betrekkingen

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Stellingen

1. Ruimtelijke variatie dient gebruikt te worden als een informatiebron bij het beschrijven van de sturende krachten van landgebruik.

   (dit proefschrift)

2. Empirische schaalafhankelijke analyses zijn een essentieel hulpmiddel in landgebruikmodellering, omdat het opschalen van procesmodellen vaak problematisch is.

   (dit proefschrift)

3. De resultaten van analyses van landgebruik hangen direct af van de resolutie en omvang van de studie met betrekking tot zowel tijd als ruimte. Hiermee moet rekening worden gehouden bij het vergelijken van de resultaten van verschillende studies.

   (dit proefschrift)

4. In plaats van het scheppen van statische eindbeelden, is het wetenschappelijk en praktisch van belang landgebruiktrajecten in de tijd te beschrijven.

   (dit proefschrift)

5. Het in toenemende mate beschikbaar komen van informatie van satellietbeelden mag niet leiden tot minder prioriteit voor het verzamelen, verspreiden en gebruiken van landbouwstatistieken, daar deze unieke gegevens voor landgebruikstudies bevatten.

6. De variatie in aardappelopbrengsten in de Ecuadoraanse Andes kan niet afdoende worden verklaard met de theoretische haalbare aardappelopbrengsten op basis van licht, temperatuur, water en gewaseigenschappen.

7. Duurzaamheidsindicatoren zoals nutriëntenbalansen kunnen zelden tot directe beleidsaanbevelingen leiden, maar zijn in de eerste plaats hulpmiddelen voor het debat tussen beleidsmakers, wetenschappers en boeren.

   Scoones, I., Toulmin, C., 1998. Soil nutrient balances: what use for policy? Agriculture, Ecosystems and Environment 71: 255-267.

8. Het Kyoto-protocol schiet tekort omdat het aanleiding kan geven tot het nemen van misleidende en soms ongewenste maatregelen voor het creëren van CO_2-*sinks*, zoals het vervangen van bestaand primair bos voor snelgroeiend productiebos.

   Kyoto-protocol to the United Nations Framework Convention on Climate Change, Kyoto, December 1997.

9. Bij discussies over toenemende aantallen slachtoffers als gevolg van natuurrampen, wordt de oorzaak te vaak gezocht bij een veranderend klimaat en te weinig bij veranderend landgebruik.

10. Wie enige tijd op grote hoogte boven zeeniveau heeft gewoond, brandt bij terugkomst in Nederland makkelijk de mond bij het drinken van het eerste kopje thee.

11. Het feit dat Gaudí geen opleverdatum had bij de constructie van de Sagrada Familia, heeft in belangrijke mate bijgedragen aan het succes van dit bouwwerk.

12. De toekomst komt niet naar ons toe, maar wij gaan er heen.

Stellingen bij het proefschrift:
Spatially explicit analysis of land use change: a case study for Ecuador.

Free de Koning, Wageningen, 16 april 1999

Preface

When applying for the job that has resulted in this thesis, my application letter was lost somewhere between the post-office and the Agronomy Department. Surely, I have never regretted that this was discovered just in time for a new letter to be sent. In this preface I would like to mention the people that have been important for the completion of this study.

To start with, I thank Louise Fresco. She was the person behind the ideas described in the initial project proposal that attracted my attention. Louise, I have very much appreciated your open approach in our numerous informal meetings and discussions, that were always very stimulating. You demonstrated your interest with a visit to Ecuador of which I keep good memories. Also after you left for Rome, you maintained the good habit of giving comments to manuscripts very rapidly.
Initially my roommate at Agronomy, Tom Veldkamp became later officially involved as a co-promotor. Thank you Tom, for your enthusiasm and for the large amounts of time we spent brainstorming. And of course your crash course geology in Ecuador.

Many thanks go to the other core-members of the "CLUE-group", Kasper Kok, Peter Verburg and Aldo Bergsma. Thanks Kasper and Peter, for the many fruitful discussions and creative ideas. Aldo, you were always ready with help on GIS and a variety of other matters; thank you very much.

An important part of the research was executed at the Centro Internacional de la Papa (CIP) in Quito, Ecuador. Initially completely focussing on Andean potato production, the study gradually took a somewhat different direction, aiming at an investigation of land use systems in the whole country. This was partly steered by data availability, and partly by the notion that for a proper understanding of changes in specific production systems, a wider view on land use would be very interesting. In spite of this change in direction, CIP proved to be a very good research environment. CIP generously offered research facilities and the working atmosphere was very pleasant. I would like to thank Hubert Zandstra, who was involved in the initial project plans, and Charles Crissman, who made me feel very welcome at the office in Quito and who was, with his large experience, an invaluable source of information. Charles, thanks a lot for your help. I would furthermore like to thank the support of Jukka Korva, Fabian Muñoz, Ricardo Rodríguez, Jorge Carillo, Paulina García, Leticia Herrera and Patricio Espinosa.

With respect to fieldwork that was executed with students, I acknowledge the support of FORTIPAPA, particularly Fausto Merino and Alberique Hibon, and the facilities offered by INIAP. I would especially like to thank the people of the villages of Santa Isabel and Guadalupe in the province of Chimborazo for their hospitality and generosity.

This study depended heavily on the large amount of data that was needed. I would like to thank all the people that were of invaluable help in collecting these data, especially Jaime Maldonado and Patricio Rodríguez (INEC), Hernán Velásquez (DINAREN), Carlos Larrea and Diego Jarrín (Frente Social), Tamara Noboa (CEPLAES) and José Espinosa (INPOFOS).

I keep good memories of 'my' students in Ecuador: Michelle Deugd, Joost Beuving and Petra van de Kop. You all turned out to be enthusiastic, motivated and pleasant to work with. Thank you very much for your contributions. I also thank Remco Roeland for his good company when we shared a house in Quito.

I would like to thank all my colleagues of what was called the Agronomy Department when I started this project, for the pleasant daily interactions. Especially I would like to mention the constructive discussions with Nico de Ridder and Tjeerd Jan Stomph and the professional support of Jan Wienk, Marieke Bosman, Wampie van Schouwenburg, Geke Visser and the TUPEA-team.

The C.T. de Wit Graduate School for Production Ecology is acknowledged for courses and support offered. I participated in the PhD-discussion group that was guided by Alfred Stein. I would like to thank Alfred and my fellow participants for the many interesting meetings.

Here I would also like to thank my parents. Their support has been unconditional and they have always followed my development with great interest. Many letters were written when I was abroad. Thank you very much!
I am also very grateful for the good care of Cecilia and Washington.

Verónica and Camila are related to this thesis in their own special way. Thanks Vero and Cami, for your love, support and good sense of humour.

Wageningen, February 1999

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1.1 Introduction

Within agricultural research increasing attention is being paid to the integrated study of agro-ecosystems in order to address issues related to sustainable food production at the eco-regional level (Fresco *et al.*, 1994; Bouma *et al.*, 1995). This has been stimulated by the awareness that the world-wide demand for food will continue to increase while at the same time there is a high pressure on natural resources needed for food production, such as suitable soils and available water (Alexandratos, 1995; IFPRI, 1995; Dyson, 1996). Also, the global change research community has stressed the crucial role human-driven land use change plays in the functioning of the global earth system, such as underlined in the science/research plan of the Land Use/Land Cover Change (LUCC) program of IGBP[1] and HDP[2] (Turner II *et al.*, 1995). Land use is relevant for global change because of its influence on sources and sinks of greenhouse gasses like CO_2, CH_4 and N_2O, and water and energy balances. Furthermore land use changes affect biodiversity. In the last decades the human factor has become more dominant in global land cover and land use change (Meyer and Turner II, 1994; Houghton, 1994; Ojima *et al.*, 1994; Turner II, 1994; Vitousek *et al.*, 1997).

These themes have confronted research with some major methodological challenges, such as the integration of biophysical and socio-economic disciplines over various spatio-temporal scales, and the development of modelling approaches for the exploration of future developments in land use and their effects.

This chapter serves as an introduction to some of these methodological issues within agro-ecosystem research and to the different types of approaches used for the integrated analysis of the spatial and temporal dynamics of agro-ecosystems and land use change. The formulation of the objective of the research of this thesis is then presented, followed by a short description of the study area, and, lastly, an outline of the thesis is given.

[1] IGBP: The International Geosphere-Biopspere Programme.

[2] HDP: The Human Dimensions of Global Environmental Change Programme.

1.2 Hierarchy and scale in complex systems

Hierarchy theory has been developed in general systems theory (e.g. Simon, 1962; Koestler, 1967) Later, hierarchy was introduced in ecology to describe the structure of ecological systems (Overton, 1974; Allen and Starr, 1982; O'Neill *et al.*, 1986). In complex systems different organisational levels can be distinguished. A certain level, say level 0, is bounded, constrained and controlled by a higher level where rates of change are slower. Level 0 can be divided into its interacting components at level -1, with which the level 0 phenomena can be explained. The rates of change at level -1 will be faster than at level 0. Hierarchy theory emphasises that a proper understanding of a phenomenon requires that references to the next higher and lower scales of resolution are made (Odum, 1994). Within hierarchy theory a phenomenon can be dissected from its complex spatio-temporal context (O'Neill, 1988).

While hierarchy and scale are related concepts, they have different implications (Allen and Hoekstra, 1990; Dumanski *et al.*, 1998). *Hierarchy* refers to levels of organisation. *Scale* refers to the spatial or temporal dimension considered (Turner and Gardner, 1991). Concepts related to scale are those of grain and extent. While *grain* refers to the size of the smallest units that can be distinguished (resolution), *extent* refers to the size of the study area. It is not possible to identify the whole entity unless the extent is large enough to include all parts. It is also impossible to detect a phenomenon that is finer than the grain of observations (Allen and Hoekstra, 1990). Because different ecological processes are dominant at different spatial and temporal scales, the interpretation of ecosystems will be highly dependent on the scale of observation employed (Allen and Starr, 1982; Holling, 1992; Kolasa and Pickett, 1991; Ehleringer and Field, 1993). This can for example be examined by applying different grains for the units for analysis and comparing the results (Baudry, 1995; Reed *et al.*, 1993; Walsh *et al.*, 1997). These methods can lead to a better understanding of which processes dominate at different spatial scales.

Concepts used in landscape ecology are those of *structure* (the spatial relationship between landscape elements and patches), *function* (the interaction between spatial elements) and *change* (the alteration in structure and function occurring through time) (Forman and Godron, 1986; Turner and Gardner, 1991). These concepts underline that a landscape is more than just the sum of all individual fields that can be observed, or, in other words, the total is more than the sum of its parts. This is sometimes referred to as the emerging properties of a system. In order to account for scale effects, a truly hierarchical approach has to be followed in the study of complex systems (Kolasa and Pickett, 1991). However, no *a priori* fundamental hierarchical levels are imposed upon us by nature, so that the used scales depend on the problem area (O'Neill, 1988).

Furthermore, hierarchies can change with time, due to the resilience and adaptability of natural systems (Dumanski *et al.*, 1998).

1.3 Agro-ecosystems

Agro-ecosystems are ecological systems modified by human beings to produce food, fibre or other agricultural products (Conway, 1987). This leads to more open systems because energy and mass flows enter and leave the system through human management (De Ridder, 1997). System approaches have been followed in order characterise agro-ecosystems by similar properties as those of natural ecosystems, such as their productivity, stability and resilience (Loucks, 1977; Conway, 1987; Marten, 1988; Okey, 1996). Also in agro-ecosystem research the importance of scale issues has been recognised (Fresco and Kroonenberg, 1992; Fresco, 1995; Rabbinge and Van Ittersum, 1994; Wolf and Allen, 1995). This has been especially stimulated by the need to study aggregation levels higher than fields and farms in order to address issues related to the management of natural resources (Barrett, 1992). From different disciplines hierarchies have been presented. Examples from soil science have been given by Wagenet (1998) and Bouma *et al.* (1998). Stomph *et al.* (1992) and Andriesse *et al.* (1994) have presented hierarchical levels in land use systems. Such studies emphasise that the integration of biogeophysical and socio-economic variables at the appropriate scale is still a major challenge. Some propose the identification of separate disciplinary hierarchies and finding the appropriate, coherent, levels at which these hierarchies can be linked (O'Neill, 1988; Dumanski *et al.*, 1998; Turner II *et al.*, 1995; Stomph, *et al.*, 1992). Others propose the complete integration of all information and then look for the most important processes at different nested artificial scales (Veldkamp and Fresco, 1997a). In order to link different disciplines, a spatially explicit approach is a prerequisite. This is also increasingly being recognised by economists (Bockstael, 1996; Antle *et al.*, 1996).

The multi-dimensional aspects of agro-ecosystems are intricately linked to the niche concept. In ecological sciences a *niche* can be defined as the functional position of an organism in its environment, comprising the habitat in which the organism lives, the periods of time during which it occurs and is active there and the resources it obtains there (Vandermeer, 1972; Odum, 1994; Allaby, 1994). An *agro-ecological niche* then, is the functional position of a crop or group of crops in their environment, which is a multi-dimensional space of variables resulting from the interaction between biophysical environment and human management. In an agro-ecosystem, management is the total of human actions directed at changing niche properties through changing flows of nutrients, water, energy and matter (related to the concept of function in landscape ecology). The goal of these human interventions is to obtain useful biomass output.

For agricultural crops a division can be made between potential and actual niches. A potential niche is a situation where a crop could be grown on the basis of the existing biophysical environment or after modification of this environment through management. This modification should then be warranted by the socio-economic conditions. By building a greenhouse for example, every place could be a potential niche, but this is in many cases not socio-economically feasible. An actual niche is a situation where a crop is really present, due to the actual interaction between the biophysical and socio-economic conditions. For example economic conditions like limited access to agricultural inputs may result in a crop not being grown.

According to these definitions, an agro-ecological niche can be very dynamic. Management by farmers and the physical and socio-economic environment are constantly changing. The rates of change will depend on the stability and resilience of the system (Holling, 1973). In order to describe niches, assumptions have to be made beforehand on the time scale that is going to be used. Under these assumptions the appearance and disappearance of niches and their suitability can be studied. The agro-ecological niche is also scale-dependent. At field level niche occurrence and performance are the result of local biophysical conditions and farmers decisions at field level. The farmers' decisions are governed by the perception of their fields, their biophysical environment in general and the socio-economic situation of their household (that is partly intrinsic for the household and partly impeded from higher hierarchical levels, for example regional markets and political decisions). At higher aggregation levels different niches will be observed because of bottom-up effects and the interaction between system components. This means that factors that best describe the multi-dimensional agro-ecological niche, depend on the hierarchical level. Sometimes these factors will be proxies of underlying processes that can not be directly observed at the level of analysis.

1.4 Land use studies and modelling approaches

Turner II *et al.* (1995) define *land cover* as the biophysical state of the earth's surface and immediate subsurface, and *land use* as involving both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation - the purpose for which the land is used.

In order to address relevant research and policy issues, land use studies are increasingly executed at regional to global levels. While much biophysical knowledge is available at detailed scales, new methodologies need to be developed for the analysis at higher aggregation levels and for the integration of information from different disciplines, requiring the use of hierarchical modelling frameworks (Easterling, 1997).

From different disciplines and perspectives, land use (change) models have been developed. Reviews have been given by Kaimowitz and Angelsen (1998), Lambin (1994) Riebsame *et al.* (1994a) and Sklar and Costanza (1991). A number of specific model approaches has been presented in the recent literature, for example the ones by Alcamo (1995), Bockstael *et al.* (1995), Engelen *et al.* (1995), Fischer *et al.* (1996), Hall *et al.* (1995), Mertens and Lambin (1997) and WRR (1992). While some models operate at global scales (Alcamo, 1995; Darwin *et al.*, 1996; Esser, 1989), others are directed at local scales (Dale *et al.*, 1993). Some originate mainly from (socio-) economic disciplines (e.g. Chomitz and Gray, 1996) while other emphasise biogeophysical processes (Penning de Vries *et al.*, 1995). It is beyond the scope of this introduction to give an exhaustive list of all approaches and their specific characteristics. Instead some general aspects of different approaches will be illustrated.

Bouma (1997) has illustrated a qualitative way to classify modelling approaches, mainly originating from the soil sciences, using a scheme of Hoosbeek and Bryant (1992). In this scheme different hierarchical levels from molecular interaction to world level are presented. The hierarchical levels are combined with different degrees of computation, from qualitative to quantitative, and degrees of complexity, from mechanistic to empirical. This way different types of know-how can be classified: user expertise, expert knowledge, generalised holistic models, complex holistic models and complex models for parts of the system.

A main motivation to use modelling approaches is their application for the assessment of possible future developments in order to address research and policy issues (Van Latesteijn, 1998; Van Ittersum *et al.* 1998; Costanza and Ruth, 1998). Such developments can be explored through scenario building. Using scenarios, probable outcomes under certain plausible assumptions are described. Van Ittersum *et al.* (1998) give a classification of studies on future land use on the basis of the level of uncertainty in data, model parameters and exogenous developments, and the level of causality within the model. However, in general land use change models contain different degrees of causality and uncertainty in their various components. For example, crop growth models as used in some explorative studies (Rabbinge *et al.*, 1994), may be considered to be process based, but important parts of such models can consist of empirical relations. Furthermore, model errors and uncertainties may increase when applying detailed level knowledge to more aggregated levels (Rastetter *et al.*, 1992). An important methodological issue that has to be addressed by all the models is the integration of different disciplines at various scales.

The critical question that decides the approach to be followed, is the goal of the study. One could be interested in the desired land use in order to obtain certain goals (e.g. of

individual land users or policy makers). A well-known method is the use of multiple goal programming techniques using objective functions and constraints (De Wit *et al.*, 1988). For use in these models, technical coefficients are generated for different production techniques (Van Ittersum and Rabbinge, 1997). Some recent examples are studies by Veeneklaas (1990), Schipper (1997) and Bessembinder (1997). Such models usually yield information on land use possibilities in the longer term. However, the question remains whether it is possible to change the system in the short term because land use systems are not easily changed towards certain directions due to their complex intrinsic structure.
This has stimulated modelling with a different goal, namely the understanding of actual land use systems and the exploration of their possible dynamics in the near future using scenarios. As Turner II *et al.* (1995) put it, for answering 'what if' questions, understanding of the past, 'what was', and present, 'what is', are essential. Statistical analysis can play an important role in the analysis of actual land use systems (Easterling, 1997; Wagenet, 1998). Veldkamp and Fresco (1997a) have proposed a multi-scale method for the integrated analysis of actual land use systems. In this empirical system analysis, biophysical and human drivers and their scale hierarchies are determined simultaneously. The resulting quantitative information was used in a multi-scale dynamic model for the exploration of land use change pathways under different scenarios, as demonstrated by Veldkamp and Fresco (1996b, 1997b) with the CLUE (Conversion of Land Use and its Effects) model. This approach offers scope for the spatially explicit description of land use changes, taking into account bottom-up and top-down effects over different hierarchical levels.

1.5 Research objective

The general objective of this thesis is the analysis of spatial variation and temporal dynamics of agricultural land use systems, in order to assess in a quantitative manner the interaction between land use and the natural resource base.
The main objective is addressed through three derived objectives:

- The spatial analysis of land use systems, taking into account their spatial scale dependence. The aim of this analysis is to detect the main biophysical and socio-economic drivers of actual land use systems at different spatial scales.
- The modelling of land use change dynamics in a spatially explicit way, taking into account the quantitative multi-scale structure of historical and actual land use and its drivers. The goal of this modelling approach is to explore possible future land use changes for different development scenarios.

- The quantification of possible effects of future land use change on the natural resource base.

1.6 The study area

The study area of this research is the South-American country Ecuador, located on the equator. Agriculture is important in this country, both for the production of subsistence crops and export crops. Broadly, the country can be divided in three eco-regions, the pacific coast, the Andean mountain range and the Amazon region. The strong altitude gradients result in a wide range of average annual temperatures, while precipitation regimes also vary strongly. The geology of the country is diverse and soil forming processes dynamic (Beinroth, 1985). For these reasons a high ecological diversity exists (Troll, 1968; Cañadas, 1983). Accordingly, agricultural land use is diverse, with respect to the crops that are grown as well as the technology levels that are used. Agricultural land use has in recent decades been dynamic due to resource degradation, changes in demand for agricultural products, migration, export and import developments, economic developments and sector policies (Scobie and Jardine, 1991; De Janvry *et al.*, 1991; Larrea, 1992; Whitaker *et al.*, 1990). A number of land use developments present serious threats to the natural resource base, such as erosion and loss of biodiversity (Southgate and Whitaker, 1992; Harden, 1991; Myers, 1988, 1993).

1.7 Outline of the thesis

Chapters 2, 3, 4, 5 and 6 have been written as separate articles for journals. Most of the text of these articles has remained unchanged in this thesis. Although this implies some overlap between chapters, it assures that the chapters can be read independently. Only the multiple use of some tables and figures has been avoided, through references to other chapters.

In Chapter 2 the spatial relations of land use in Ecuador for the reference year 1991 are examined. The reader is introduced to the type of data used, the geo-referencing of these data in a 5 by 5 minute geographical grid, and the way different aggregation levels are created. A multi-scale system analysis of land use through the use of multiple regression techniques at the different aggregation levels is presented. The obtained results offer an insight into the combinations of biogeophysical and socio-economic variables that best describe agricultural land use for the most important land use types at different

aggregation levels. The interpretation of these results reflects the historic and current processes that determine the Ecuadorian agro-ecological landscape.
Chapter 3 contains an explanation of how the results of the quantitative system description of Chapter 2 are used in a dynamic multi-scale land use change model for the spatially explicit exploration of near future land use changes. References to Chapter 2 are made with respect to the incorporation of the most important land use drivers in the model. Results of a base-line scenario are used to demonstrate the main features of the model, such as the multi-scale approach, the incorporation of top-down and bottom-up processes, the interconnectivity of land use over large distances and the competition between different land use types.
One of the objectives of this thesis is to find ways for the assessment of effects of land use change. The use of a nutrient balance model for the estimation of nitrogen, phosphorus and potassium fluxes in the main agro-ecosystems is illustrated in Chapter 4. A spatially explicit approach is followed, using the data collected for the 5 by 5 minute grid cells. This spatial structure allows a link with the land use change model that is demonstrated in Chapter 3.
In Chapter 5 the preceding chapters are integrated into a scenario study. Different national and sub-national developments related to food demand and land use limitations are evaluated with respect to their outcome in terms of spatially explicit land use changes. This offers insight in the areas with the highest dynamics and possible negative effects on the natural resource base as illustrated through the application of a nutrient balance model to the modelled land use changes.
Chapter 6 deals specifically with the spatial and temporal variation in Andean potato production systems. Again, a system analysis is followed, this time taking into account specific aspects of potato production, such as the spatial variation in yields and crop management. Results for two provinces are highlighted and it is shown how the results of the national land use change model can be used to address issues for a single crop in a specific eco-region.
The last chapter contains a summary of the most important results, followed by a discussion concerning the uses and limitations of the methodologies dealt with in the thesis. Finally the conclusions of the study are drawn and ideas for future research proposed.

Chapter 2

Land use in Ecuador: a statistical analysis at different aggregation levels

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Chapter 2

Land use in Ecuador: a statistical analysis at different aggregation levels

Abstract

Land use in Ecuador was investigated by means of statistical analysis with the purpose of deriving quantitative estimates of the relative areas of land use types on the basis of biogeophysical, socio-economic and infrastructural conditions. The smallest spatial units of investigation were 5 by 5 minute (9.25 x 9.25 km) cells of a homogenous geographical grid covering the whole country. Through aggregations of these cells, a total of six artificial aggregation levels was obtained with the aim of analysing spatial scale dependence of land use structure. For all aggregation levels independent multiple regression models were constructed for the estimation of areas within cells of the land use/cover types permanent crops, temporary crops, grassland and natural vegetation. The variables used in the models were selected from a total of 23 variables, that were considered proxies of biogeophysical, socio-economic and infrastructural conditions driving Ecuadorian land use. A spatial stratification was applied by dividing the country into three main eco-regions. The results showed that at higher aggregation levels, the independent variables explained more of the variance in areas of land use types. In most cases, biogeophysical, socio-economic as well as infrastructural variables were important for the explanation of land use, although the variables included in the models and their relative importance varied between land use types and eco-regions. Also within one eco-region, the model variables varied with aggregation level, indicating spatial scale effects. It is argued that these types of analyses can support the quantitative multi-scale understanding of land use, needed for the modelling of realistic future land use change scenarios that take into account local and regional conditions of actual land use.

2.1. Introduction

World-wide changes in land use and resulting land cover have caused important effects on natural resources through deterioration of soil and water quality, the loss of biodiversity, and by changing global climate systems (Turner II *et al.*, 1994; Ojima *et al.*, 1994). This has stimulated research aiming at a better understanding of the factors driving land use and cover change, and the effects of these changes on the environment. It is recognised that biogeophysical as well as human drivers have to be taken into account (Turner II *et al.*, 1995; Bilsborrow and Okoth Ogendo, 1992; Riebsame *et al.*, 1994a). In order to support explorative modelling of future land use and cover changes and their effects, quantitative information is needed about the way interacting driving forces relate to (changes in) land use/cover. Because of the complex nature of these relations, empirical statistical analysis of land use/cover and its drivers has been proposed (Turner II *et al.*, 1995; Bawa and Dayanandan, 1997; Walsh *et al.*, 1997; Veldkamp and Fresco, 1997a). Empirical models based on these statistical relations can complement process-based land use modelling. Process-based models aim at more explanatory power but have difficulties in linking biogeophysical and human drivers. Furthermore, scale problems may arise when applying point models to higher spatial scales (Veldkamp and Fresco, 1997b). Empirical explorative land use models based on the analysis of actual land use present possible scenarios that aim at a relatively limited future time scale (say 20 years), but are especially useful in situations where the actual production is still considerably below the biophysical potential, indicating strong limitations from socio-economic conditions.

It has been recognised that the type and effect of drivers of land use/cover may vary with spatial scale, because of the occurrence of patterns in land use/cover that disappear or emerge going from one scale to another (Walsh *et al.*, 1997; Veldkamp and Fresco, 1997a). In order to investigate these scale dependent patterns in land use, an analysis at different spatial scales is necessary. Veldkamp and Fresco (1997a) have analysed land use in Costa Rica at artificial spatial aggregation levels, created by aggregating uniformly sized cells of a geographical grid. They concluded that the contribution of biogeophysical and socio-economic factors to the explanation of land use/cover in Costa Rica shows a scale dependence.

In this chapter a statistical analyses is presented of current land use in Ecuador with the objective of finding quantitative estimates of (proxies of) land use/cover drivers. The methodology, a statistical analysis at different sub-national artificial spatial aggregation levels in order to investigate spatial scale effects, builds on the methodology proposed by Veldkamp and Fresco (1997a). However, some major adaptations were made in order to improve the methodology. A spatial stratification of land use through the definition of three

main eco-regions was applied. Furthermore, different sets of drivers were considered at the various aggregation levels.
Ecuador was chosen for this research because it is a country with a high agro-ecological diversity. It has a dynamic and expanding agricultural land use, which has major effects on the natural resources of the country and the sustainability of land use (Southgate and Whitaker, 1994; Bebbington, 1993). In many ways Ecuador can be considered indicative for the Andean countries in general.
Strictly, land use and land cover should be separated, land cover being the biophysical state of the earth's surface and immediate subsurface, and land use involving both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation - the purpose for which the land is used (Turner II *et al.*, 1995). However, land use and cover can often not be clearly separated. In this study only the term land use will be used.

2.2. Land use in Ecuador and its potential drivers

Ecuador is a country characterised by great agro-ecological diversity. Cañadas (1983) has identified 25 Holdridge lifezones within Ecuador. The country can be divided into three broad eco-regions. The Andean eco-region consists of the north-south orientated Andean mountain range, with peaks to around 6000 meters above sea level. West of this eco-region, the tropical lowlands bordering the pacific ocean comprise the coastal eco-region. East of the Andes, the Amazonian eco-region is located, still consisting mainly of tropical rainforest.
In the past, agriculture was mainly concentrated in the more densely populated Andean eco-region. Since 1900 the colonisation of the tropical lowlands has taken place especially in the coastal eco-region, first accelerated by the cocoa boom at the beginning of this century and later by the banana boom in the 1950s and 1960s (Bromley, 1981). Agricultural exploitation of the Amazonian eco-region has increased especially since the 1970s, coinciding with the discovery of oil (Southgate and Whitaker, 1994). Also during the agrarian reforms in the 1960s and early 1970s, colonisation of new land as a result of population pressure was area-wise more important than redistribution of land (Zevallos, 1989).
The land use data of the agricultural census of 1974 (INEC, 1974a) and data from 1991 (INEC, 1991) show that the area of agricultural land has increased in that period by approximately 2.1 million hectares, or 36% of the 1974 area. Figure 2.1 shows the land use changes for the three main administrative regions. A map of the administrative division of Ecuador into provinces is given in Figure 2.2.

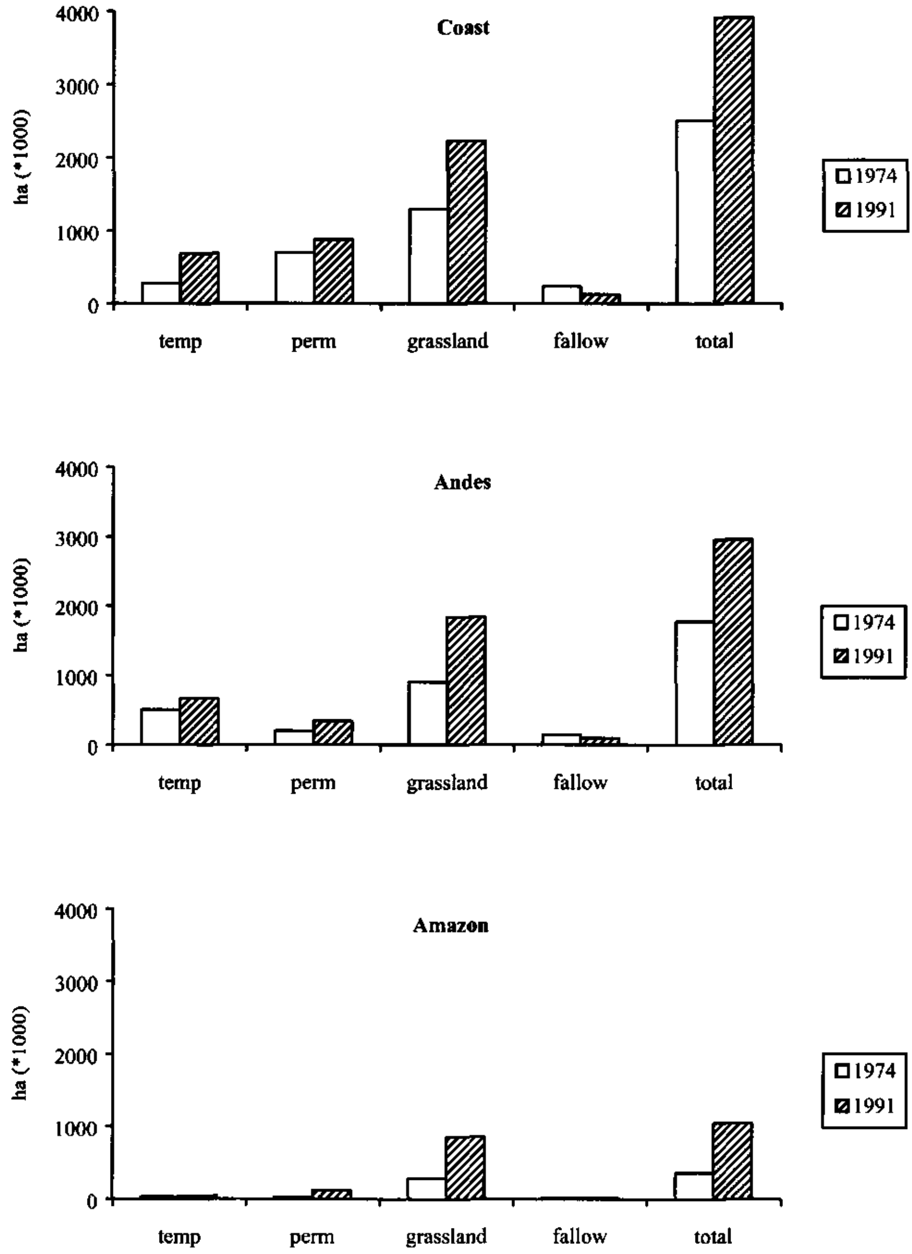

Figure 2.1. Land use in 1974 and 1991 in the main administrative regions Coast, Andes and Amazon. Sources: (INEC, 1974a, INEC, 1991). temp: temporary (annual) crops (including fallow less than one year); perm: permanent (perennial) crops; fallow: fallow between one to five years; total: total agricultural land. See Figure 2.2 for the administrative division of Ecuador.

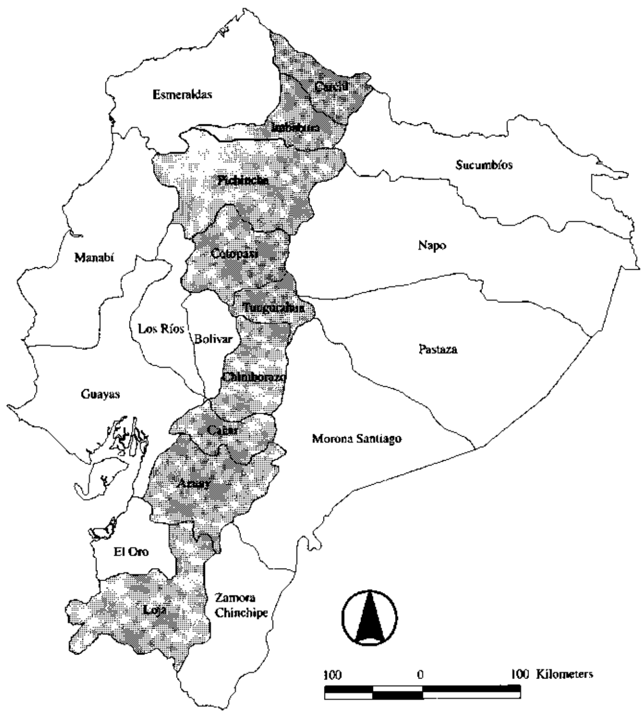

Figure 2.2. Provinces of Ecuador. The Andean provinces are indicated in grey. The Coastal provinces are located west of the Andean region, the Amazon provinces are located east of the Andean region.

In all regions important relative increases in agricultural land use for crops have taken place, whereas fallowing of agricultural land has decreased (Figure 2.1). Especially important is the increased area dedicated to grassland, which, among others, has been caused by the growing demand of the urban population for meat and milk (Zevallos, 1989; Commander and Peek, 1986).

Table 2.1 indicates per hectare yields of some important crops, averaged for the periods 1974-1982 and 1983-1991. Although some care has to be taken with respect to the reliability of yield data, it seems fairly safe to conclude that no significant increase in yields is occurring.

In almost the same period, Ecuador's population as reported in the censuses has risen from 6.5 million in 1974 (INEC, 1974b) to 9.7 million in 1990 (INEC, 1990), with the percentages of urban population being 41% in 1974 and 55% in 1990, respectively. It could be concluded therefore that, at a national scale, Ecuador's need for agricultural products has mainly caused the expansion of agricultural land. So far, a development where population pressure leads to intensification, such as higher per hectare yields (Boserup, 1965) seems less important.

Table 2.1. The 1974 and 1991 harvested area (x1000 ha) and average crop yields (ton/ha) over the periods 1974-1982 and 1983-1991 for Ecuador's 12 main crops (areawise in 1991). Sources: FAO (1998) and MAG/PRSA (1994).

Crop	Land use type	area 1974	area 1991	yield 1974-1982	yield 1983-1991
maize	temporary crops	271.6	474.2	1.05	1.16
coffee	permanent crops	231.8	403.9	0.30	0.31
cocoa	permanent crops	221.7	332.0	0.32	0.28
rice	temporary crops	102.7	283.9	3.69	3.20
banana	permanent crops	151.8	168.5	26.94	23.16
plantain	permanent crops	57.9	92.2	9.02	11.40
soybean	temporary crops	3.1	90.7	1.46	1.80
oil palm	permanent crops	10.6	58.6	7.08	13.80
barley	temporary crops	60.8	60.3	0.85	0.83
potato	temporary crops	39.1	52.2	11.67	8.60
bean	temporary crops	66.2	51.9	0.49	0.56
sugar cane	permanent crops	100.8	48.9	75.66	75.26

Actual land use in Ecuador is potentially related to a wide range of factors. Among the biogeophysical factors, obviously soil and climate have to be taken into account. General features derived from soil maps can serve as proxies for potential agricultural use. Soil texture and natural fertility indicators (including organic matter content, mineral composition and pH), yield information on workability, erosion risk, drainage and natural fertility. In Ecuador, climate characteristics are very complex with respect to their variability in time and space, with temperature regimes ranging from tropical to permanent frost, and precipitation regimes from desert-like to very humid. Annual mean temperature and annual total precipitation of climatic zones are examples of proxies for much more complex climate conditions at detailed scales. In the highly dissected Ecuadorian landscape slope steepness has importance, in combination with soil properties and climate, for soil workability and erosion risks.

Often, socio-economic data are collected and used in studies at the farm level. At higher aggregation levels (as in the present study), socio-economic variables have to be available for the total area of interest and should have the validity to serve as proxies for the much more differentiated underlying conditions. Among these proxies are demographic indicators, such as rural and urban population densities, which determine among others the availability of labour, the local need for food crops and animal products, and the pressure on land (Southgate *et al.*, 1991). The number of people working in agriculture and illiteracy levels further differentiates these broad demographic characteristics. Illiteracy can, for example, be considered an indicator of access to information and means. Poverty indicators can be of importance through their relation with investment opportunities and crop choice.

Distance to urban centres determines access to markets, relevant both for the selling of products, as well as for the access to means of production. This is further determined by proximity to infrastructure e.g. roads. Major rivers permit transportation and offer irrigation opportunities.

2.3. Methodology

2.3.1. Spatial resolution and aggregation levels

The lowest aggregation level used in this study was a homogeneous geographical grid with a grid cell size of 5 by 5 minutes (approximately 9.25 by 9.25 km), covering the Ecuadorian territory according to the protocol of Rio de Janeiro 1942, excluding the Galapagos islands. A cell was considered an Ecuadorian land cell when at least 50% of its surface was Ecuadorian territory excluding sea. The total number of Ecuadorian land cells was 2982. Biogeophysical and socio-economic data were collected and attributed to these cells. All attribute data for the cells of the base resolution were aggregated to higher artificial aggregation levels by averaging the data of 2 by 2 (= 4) cells, 3 by 3 (= 9) cells, 4 by 4 (= 16) cells, 5 by 5 (= 25) cells and 6 by 6 (=36) cells. Figure 2.3 presents the six aggregation levels created this way.

2.3.2. Biogeophysical data

Soil attribute data were derived from the 1:1 million soil map of Ecuador (González *et al.*, 1986). On this map 36 great groups are distinguished, which are further subdivided into 62 soil units, on the basis of parent material, climate, physiography, relief, soil texture, and chemical and mineralogical soil properties. The soil units on the soil map were matched with the base grid by assigning to each grid cell the two biggest occurring soil units with their respective surface fractions. Physical and chemical soil attribute data were linked to the soil units on the basis of map descriptions and related documentation. Three texture classes were defined on the basis of clay content (< 35%; 35-55%; > 55%) and for each cell the area fraction of each texture class was calculated. The same procedure was

followed for three slope classes (0-8%; 8-16%; >16%). Three natural soil fertility classes (low, medium and high fertility) were determined on the basis of the soil descriptions of Beinroth (1985).
Climate data were derived from the 1:1 million bio-climatic map of Cañadas (1983). He distinguished 29 climate zones, on basis of altitude/temperature and yearly total precipitation. The climate zones on the map were matched with the base grid by assigning to each grid cell the two dominant climate zones with their respective surface fractions. In this way annual total precipitation was calculated for each cell. Mean altitude per cell was taken from a 5 by 5 minute altitude database (W. Cramer, pers. comm., 1997).

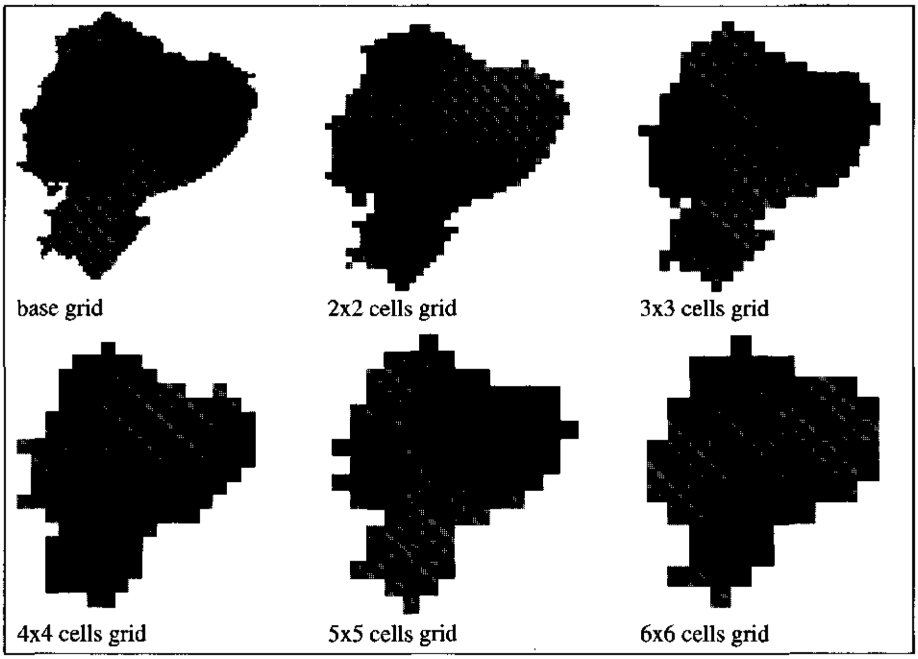

Figure 2.3. The six aggregation levels.

2.3.3. *Socio-economic data*

Ecuador's administrative division consists of provinces, subdivided into cantons which are further subdivided into parishes. In 1990 the number of provinces (excluding the Galapagos islands) amounted to 20 and the number of cantons 162. Ecuador's urban parishes are all located in the capitals of the cantons. The rural population is located in the periphery of these capitals and in rural parishes (738 rural parishes existed in 1990).

Population census data of 1990 at the parish level were used (INEC, 1990). On basis of 1:250.000 maps with administrative regions, each cell was allocated the (maximally) three main occurring rural parishes (or urban periphery) with their respective surface fractions. In this way the population of all rural parishes was allocated to the grid cells. The urban population of canton capitals was allocated to the cells where these capitals are located. Population data were corrected with the 1991 projections (INEC, 1993) in order to obtain the 1991 projected data at the level of cells.
Next to total numbers of rural and urban population, census data were used to determine the percentage of the economically active population working in agriculture, and the level of illiteracy. Furthermore, for 1990, data were available on the percentage of people living in poverty at the parish level in 1990 (Larrea *et al.*, 1996). The percentages of illiteracy, population working in agriculture and poverty of 1990, were considered to be representative for the 1991 situation.

2.3.4. Markets and infrastructure

In order to account for the accessibility to urban markets, the distance to the nearest urban centre was calculated through a standard distance operation in a geographical information system (GIS) using the centres of grid cells as reference points. Similarly, the distance to the nearest main roads and rivers was calculated with a GIS distance operation, using vector maps of the main roads and rivers.

2.3.5. Land use data

The current yearly agricultural statistics are collected by means of stratified sampling by the National System for Agricultural Statistics (SEAN). SEAN data for 1991 (INEC, 1991) were used, containing information on 65415 farmers in 3137 sample sites. Data of sample sites were related to grid cells, thus constructing a land use map. When more than one sample site was found within a grid cell, data from these sites were averaged. The four main land use types[1] were used: permanent (perennial) crops, temporary (annual) crops, grassland and natural vegetation. Instead of characterising land use in a cell by allocating the dominant land use type, for each cell the percentages of each of the land use types occurring in the cell was used for further analysis. Figure 2.4 shows the land use maps constructed this way.

[1] The term 'land use type' is here used to describe a category of agricultural crops, according to the census data used. Natural vegetation is also considered a land use type.

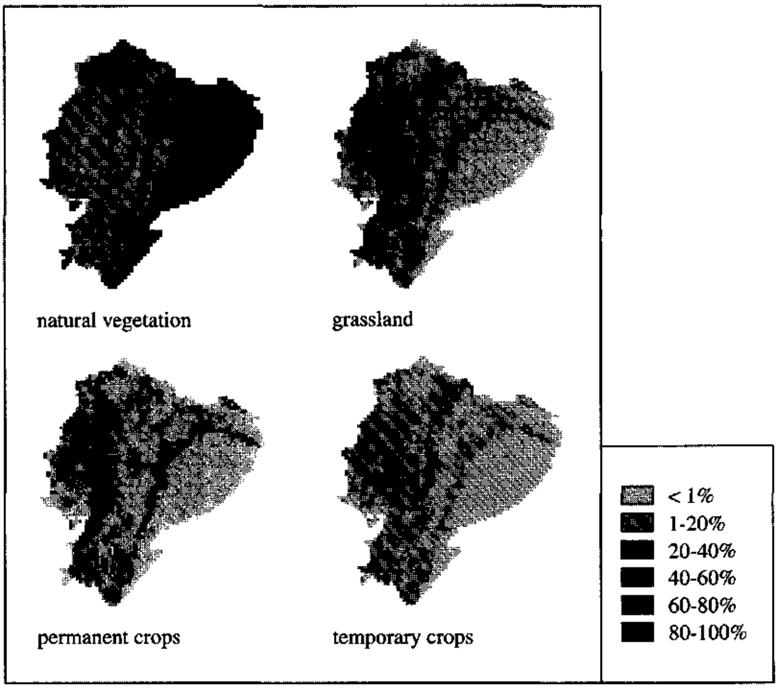

Figure 2.4. Area distribution of natural vegetation, grassland, permanent crops and temporary crops.

2.3.6. Stratification

A stratification was applied by dividing the country into three broad eco-regions. The eco-region Andes was defined as all cells above of an altitude of 1000 meters above sea level (m.a.s.l.), following the zonification of Frère *et al.* (1975). The remaining broad eco-regions are the Coast and Amazon (Figure 2.5). This division is slightly different than the one used in agricultural statistics, which is based on provinces (see Figure 2.2), but makes more ecological sense.

The stratification leads to a general division between typical highland crops like barley, broad bean, soft maize and potato, and crops cultivated at lower altitudes, like cocoa, rice, banana, plantain, soybean, hard maize and African palm. Also coffee is mainly cultivated below 1000 m.a.s.l. in Ecuador. Common beans are grown both below and above 1000 m.a.s.l. The number of cells at the six aggregation levels was for eco-region Coast 931, 248, 106, 60, 38 and 28, respectively, for eco-region Andes 1105, 279, 120, 70, 45 and 29, respectively, and for eco-region Amazon 946, 237, 107, 60, 39 and 30, respectively.

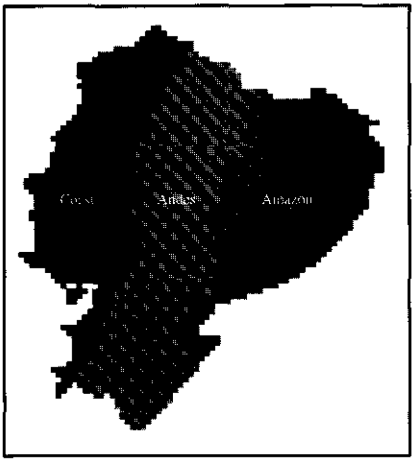

Figure 2.5. The stratification into three eco-regions.

2.3.7. Statistical analysis

The possible biogeophysical and socio-economic drivers of Ecuadorian land use in 1991 were investigated with multiple regression methods. Four main land use types were taken into account: permanent crops, temporary crops, grassland and natural vegetation. The analysis was done independently for the six aggregation levels and the three eco-regions.
The most important land use drivers (independent variables) for the four land use types (dependent variables) were selected by means of stepwise regression, using the 0.05 significance criterion for each independent variable. Table 2.2 lists the total set of variables that was included in the stepwise regression (temperature is not included because of its direct correlation with altitude in Ecuador). A maximum of seven variables was selected, because only slight improvements of model fits were obtained with more variables. At each aggregation level an independent set of variables was selected this way. This contrasts with the approach of Veldkamp and Fresco (1997a) for Costa Rica, who used the same set of six variables at each aggregation level.
The selected variables were then used in multiple regression models. Of these models the adjusted coefficient of determination (R^2) is a measure for the amount of variation in the percentage of the specific land use type in the spatial units that can be explained. The standardised betas indicate the number of standard deviation changes in the dependent variable associated with a standard deviation change in the independent variable if all other variables are held constant. They are therefore indicative for the relative importance of a variable for land use change in a given regression equation.

Table 2.2. Variables included in the stepwise regression analysis.

variable	explanation	unit
text1	Percentage soils with texture class 1 (< 35% clay)	-
text2	Percentage soils with texture class 2 (35-55% clay)	-
text3	Percentage soils with texture class 3 (> 55% clay	-
slope1	Percentage soils with slope class 1 (< 8%)	-
slope2	Percentage soils with slope class 2 (8-16%)	-
slope3	Percentage soils with slope class 3 (> 16%)	-
fert1	Percentage low fertility soils	-
fert2	Percentage medium fertility soils	-
fert3	Percentage high fertility soils	-
alt	Altitude	m.a.s.l.
prec	Total annual precipitation	mm
urbdis	Distance to nearest urban centre	km
roaddis	Distance to nearest road	km
riverdis	Distance to nearest river	km
totpop	total population per surface area	km^{-2}
rurpop	rural population per surface area	km^{-2}
urbpop	urban population per surface area	km^{-2}
pov-tot	percentage of total population living in poverty	-
pov-rur	percentage of rural population living in poverty	-
illit-tot	percentage of total population that is illiterate	-
illit-rur	percentage of rural population that is illiterate	-
agric-tot	percentage of total population working in agriculture	-
agric-rur	percentage of rural population working in agriculture	-

2.4. Results

Figure 2.6 presents graphically the adjusted coefficients of determination (R^2) of the multiple regression models for the four land use types and six aggregation levels, for the eco-regions Coast, Andes and Amazon. All models were significant at the 0.001 level. The general pattern in all three eco-regions is that of an increasing R^2 with higher aggregation levels, as expected given the reduction of extreme values.

In eco-region Coast, the model explains 24% to 46 % of the variance of the land use types at the 1x1 aggregation level, and this increases to 58% to 87 % at the 6x6 aggregation level. The best model fits are found for natural vegetation and temporary crops, except at the 6x6 level, where grassland is modelled slightly better than temporary crops. The shape of the curves is somewhat disturbed at the 5x5 and 6x6 aggregation levels, where (except for permanent crops) the models seem to become more unstable, probably because of the amount of values (cells) available for analysis which is becoming progressively lower. This is less the case in the eco-region Andes. Here, model fits range

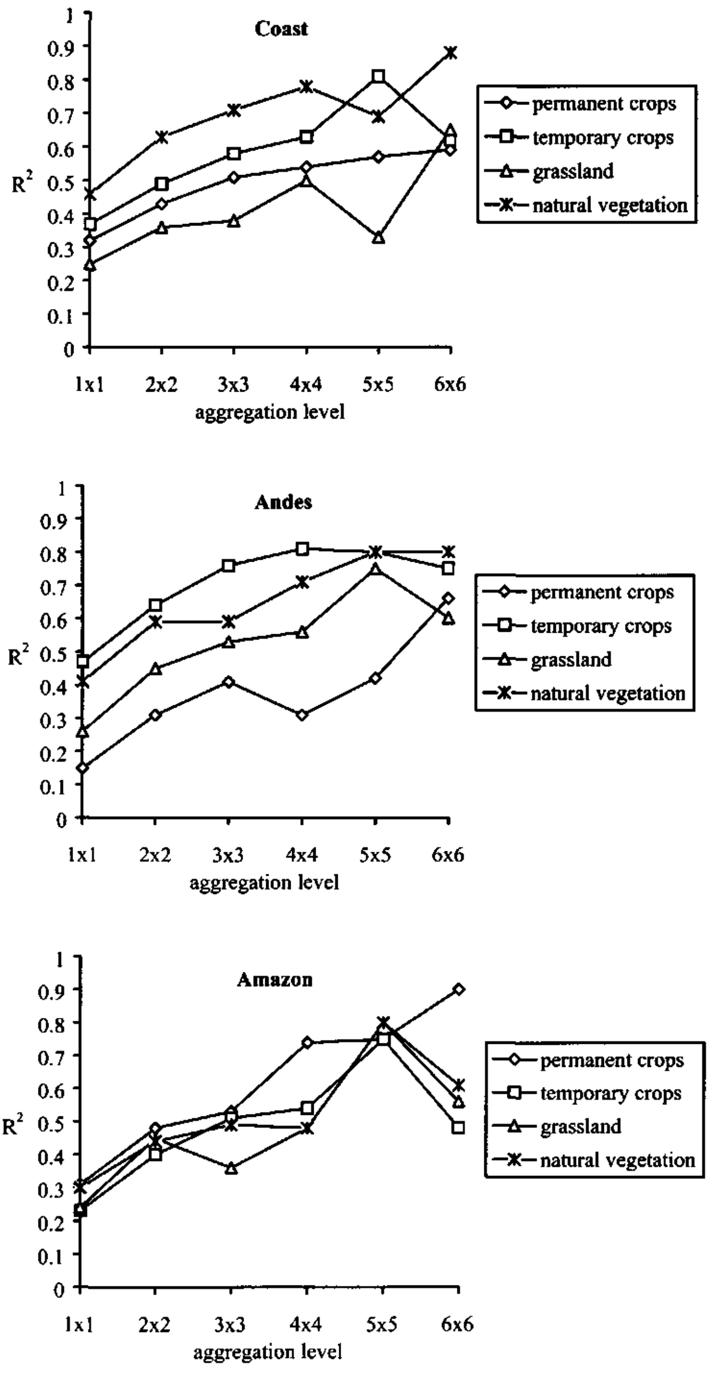

Figure 2.6. Coefficient of determination (R^2) of multiple regression models for four land use types at six aggregation levels for the eco-regions Coast, Andes and Amazon.

from 15% to 47% at the lowest aggregation level, to 60% to 80% at the highest aggregation level. In this eco-region temporary crops are explained best, followed by natural vegetation, grassland and permanent crops. In the Amazon, an increase of R^2 is seen up to the 5x5 aggregation levels where between 75% and 80% of the variance is explained. At the highest aggregation level model fits decrease quite strongly for all land use types except permanent crops.

Tables 2.3, 2.4 and 2.5 show for the three eco-regions the variables and their standardised betas (stb's) in the regression models. Table 2.2 gives the description of the variable names. The stb's can be considered a measure for the relative importance of a variable for changes in the dependent variable in a given equation. The stepwise regression procedure corrects for co-linearity, excluding variables that are strongly correlated with others. However, remaining weak correlation limits the interpretation of a single independent variable with respect to its one to one correlation with the dependent variable. Even the sign of the regression coefficient may be the opposite of the sign in a one to one correlation matrix. Cases where this occurs have been indicated with an asterisk. The results will be described in more detail for the three eco-regions independently.

2.4.1. Coast

Permanent crops

At the lower aggregation levels the area with permanent crops is mainly explained by the contributions of soil texture, distance to roads, altitude and slopes (Table 2.3). At the highest aggregation levels the number of included variables becomes smaller. The socio-economic variable agricultural labour force is the only one that is included in all models.

Interpreting the results, the association of permanent crops with light textured soils is likely to be related to the better drainage of these soils, which is especially beneficial in the low lying flat river plains (the direct correlation between permanent crops and both altitude and steep slopes is negative). Furthermore, cultivation of permanent crops (most of which are cash crops in this region) is associated with proximity to roads, a high share of people working in agriculture and low percentages of illiteracy.

Temporary crops

Socio-economic variables become increasingly important at higher aggregation levels (Table 2.3). Of these variables, the agricultural labour force is included only at the highest aggregation level. Of the biogeophysical variables, fertility and slope are contributing most to the model. Distance to rivers and roads both occur in the models but do not show a clear relation with aggregation level.

Table 2.3. Multiple regression models at 6 aggregation levels for areas permanent crops, temporary crops, grassland and natural vegetation in the eco-region **Coast**. stb: standardised regression coefficient. Asterisk: see text.

1x1 grid		2x2 grid		3x3 grid		4x4 grid		5x5 grid		6x6 grid	
variable	**stb**	**variable**	**stb**	**variable**	**stb**	**variable**	**stb**	**variable**	**stb**	**variable**	**stb**
permanent crops:											
text1	0.42	text1	0.52	text1	0.66	text1	0.57	fert1	-0.56	text2	-0.51
roaddis	-0.30	alt	-0.46	alt	-0.57	alt	-0.54	agric-rur	0.49	agric-rur	0.44
alt	-0.30	roaddis	-0.38	agric-tot	0.43	slope3	0.51*	slope2	-0.33	roaddis	-0.39
slope3	0.26*	slope3	0.36*	slope3	0.41*	roaddis	-0.45	illit-rur	-0.30		
agric-rur	0.22	agric-rur	0.26	urbdis	-0.38	agric-tot	0.43				
fert3	0.15	fert3	0.18	roaddis	-0.32	pov-tot	-0.38				
illit-rur	-0.11	illit-rur	-0.14	illit-tot	-0.26	fert3	0.32				
temporary crops:											
fert3	0.26	fert3	0.33	rurpop	0.60	rurpop	0.38	illit-rur	0.52	rurpop	0.68
illit-rur	0.23	slope3	-0.28	slope3	-0.31	fert3	0.38	rurpop	0.50	agric-rur	0.41
riverdis	-0.21	rurpop	0.28	fert2	-0.23	slope3	-0.23	fert2	-0.39		
slope3	-0.22	illit-rur	0.27	illit-rur	0.21	illit-rur	0.21	roaddis	-0.32		
rurpop	0.19	riverdis	-0.23	alt	0.19*	riverdis	-0.21	slope3	-0.30		
prec	-0.16	prec	-0.22								
roaddis	-0.08	alt	0.15*								
grassland:											
roaddis	-0.32	roaddis	-0.44	roaddis	-0.55	roaddis	-0.79	slope1	-0.43	agric-rur	0.80
slope3	0.26	slope3	0.32	text3	0.33	text1	-0.67	roaddis	-0.42	fert1	-0.76
fert1	-0.19	text3	0.25	riverdis	-0.31	prec	0.67*	fert1	-0.29	slope3	0.73
text3	0.16	riverdis	-0.25	slope3	0.24	fert2	0.52			alt	-0.70
riverdis	-0.15	fert1	0.25	fert2	0.22	agric-rur	0.52			illit-rur	-0.55*
totpop	-0.11										
urbdis	-0.10										
natural vegetation:											
roaddis	0.45	roaddis	0.49	roaddis	0.50	roaddis	0.55	roaddis	0.50	agric-rur	-0.68
fert1	0.26	fert1	0.31	fert1	0.25	agric-rur	-0.34	fert1	0.38	fert1	0.58
riverdis	0.16	riverdis	0.28	agric-rur	-0.20	fert1	0.34	agric-rur	-0.35	roaddis	0.43
agric-rur	-0.16	text3	-0.20	rurpop	-0.20	riverdis	0.22			alt	0.34
alt	0.13	rurpop	-0.12	riverdis	0.19	text3	-0.17			slope3	-0.34*
slope3	-0.12*	slope2	0.12*	text3	-0.12					illit-rur	0.20
urbdis	0.11										

In the eco-region coast, temporary crops are cultivated relatively more in areas with fertile soils, with few steeply sloping terrain and in proximity to rivers and roads. Furthermore, these crops are grown more in areas with high rural population densities and higher illiteracy. Fewer temporary crops are grown in wetter areas, which are especially found in the northern part of the Pacific coast.

Grassland

For grassland, aggregation level does not produce a very clear pattern (Table 2.3). At the highest aggregation level rural illiteracy and altitude are selected, variables that are not selected at the lower levels. Up to the 5x5 level, the distance to roads is a major variable in the models. Soil related variables also rank high. River distance is only included at the three lowest aggregation levels. As with permanent and temporary crops, the number of people working in agriculture is important at the highest aggregation level.

Grassland is related to dissected terrain, the likely reason being that steep slopes present more difficulties for the cultivation of permanent and temporary crops. Grassland is associated with medium and high fertility soils in the proximity of roads and, to a lesser extent, rivers.

Natural vegetation

In the models for the area natural vegetation, the number of people working in agriculture, distance to roads and soil fertility contribute strongly to the models, whereas the distance to rivers only contributes up to the 5x5 level (Table 2.3). The contributions of slope and altitude are very variable, and illiteracy is only selected at the highest aggregation level.

Natural vegetation is clearly associated with areas less favourable for agriculture: distant from roads, rivers and urban centres, and on low fertility soils. Furthermore, natural vegetation is related to low population densities, relatively few people working in agriculture, and higher illiteracy rates.

2.4.2. Andes

Permanent crops

The number of variables in the models for permanent crops decreases progressively with the aggregation level, leaving only three biogeophysical variables in the model for the highest aggregation level (Table 2.4). In all models, the variable contributing most dominantly is altitude. The highest-ranking socio-economic variable is total poverty, though it is not included in the 4x4 and 6x6 models. In most models soil fertility and texture is included, whereas the number of people working in agriculture is only included at the three lowest aggregation levels. The distance to urban centres contributes in just two models.

Table 2.4. Multiple regression models at 6 aggregation levels for areas permanent crops, temporary crops, grassland and natural vegetation in the eco-region **Andes**. stb: standardised regression coefficient. Asterisk: see text.

1x1 grid		2x2 grid		3x3 grid		4x4 grid		5x5 grid		6x6 grid	
variable	**stb**	**variable**	**stb**	**variable**	**stb**	**variable**	**stb**	**variable**	**stb**	**variable**	**stb**
permanent crops:											
alt	-0.32	alt	-0.44	alt	-0.66	alt	-0.49	alt	-0.84	alt	-0.73
pov-rur	-0.16	pov-tot	-0.27	pov-rur	-0.44	fert3	0.30	pov-tot	-0.58	fert3	0.68
fert3	0.12	fert3	0.24	slope2	0.28	urbdis	-0.26	illit-tot	0.38	text2	-0.25
slope2	0.11	slope2	0.17	text2	-0.20*						
agric-rur	0.11	agric-rur	0.17	agric-rur	0.20						
urbdis	-0.09										
text2	-0.06*										
temporary crops:											
illit-rur	0.52	rurpop	0.38	rurpop	0.49	text1	0.80	rurpop	0.56	rurpop	0.53
illit-tot	-0.34	illit-rur	0.21	illit-rur	0.28	rurpop	0.70	text2	0.55	illit-rur	0.39
rurpop	0.29	urbdis	-0.15	slope2	0.23	fert2	-0.49	text1	0.36	urbdis	-0.26
prec	-0.13	slope3	-0.13	urbdis	-0.15	text2	0.45	illit-rur	0.33		
fert3	0.13	fert3	0.13	text2	0.11	urbpop	-0.28*				
slope3	-0.12	prec	-0.12			illit-rur	0.22				
urbdis	-0.12										
grassland:											
alt	-0.29	pov-tot	-0.34	alt	-0.48	fert3	0.38	pov-tot	-0.47	fert3	0.73
pov-rur	-0.22	fert3	0.34	pov-tot	-0.42	alt	-0.33	fert3	0.47	alt	-0.43
fert3	0.16	alt	-0.26	fert3	0.31	pov-tot	-0.32	alt	-0.35		
urbdis	-0.15	urbdis	-0.24	prec	-0.21	prec	-0.28	text2	0.34		
prec	-0.12	slope3	0.19*	riverdis	0.12	illit-tot	-0.23	slope3	0.26*		
roaddis	-0.08	text2	0.13					roaddis	-0.23		
riverdis	0.08	riverdis	0.12								
natural vegetation:											
pov-tot	0.21	illit-rur	-0.22	pov-tot	0.29	pov-tot	0.28	text2	-0.40	fert3	-0.50
illit-tot	-0.20	roaddis	0.18	roaddis	0.25	roaddis	0.28	fert3	-0.36	slope2	-0.38
roaddis	0.16	prec	0.16	fert3	-0.23	prec	0.26	text1	-0.32	illit-rur	-0.21
urbdis	0.15	fert3	-0.16	prec	0.19	fert3	-0.24	roaddis	0.27		
prec	0.13	urbdis	0.15	illit-tot	-0.18	riverdis	-0.15	illit-rur	-0.23		
fert3	-0.12	riverdis	-0.13	riverdis	-0.15			pov-rur	0.21		
riverdis	-0.09							riverdis	-0.19		

Permanent crops in the Andes are mostly cultivated at lower elevations because of climatic requirements. Next to coffee, the majority of permanent crops are fruit trees. These crops are associated with relatively well endowed areas with less poverty, fertile soils and, though less clear, close to urban centres. A relation is found with a relatively high percentage of the rural population working in agriculture.

Temporary crops

The socio-economic variables in the models for temporary crops are population density and illiteracy (Table 2.4). At the highest level no biogeophysical variables are included in the model. At the lower levels soil texture and fertility as well as slope class are selected. Precipitation is only included at the lowest two levels and distance to urban centres only at the lowest three and highest aggregation level.

Temporary crops in this eco-region are mostly subsistence crops, associated with high rural population densities and high illiteracy. This land use type is related with light-textured and medium-textured soils.

Grassland

As for permanent and temporary crops in this eco-region, there is a tendency towards models with fewer variables at higher aggregation levels (Table 2.4). Altitude, poverty, and soil fertility are the most important variables at the first five levels. As for permanent crops in this eco-region, only biogeophysical variables are included at the highest aggregation level.

Grassland in this mountainous eco-region is associated with lower altitude and relatively fertile soils, in areas with relatively less poverty not far from roads and urban centres.

Natural vegetation

Also for natural vegetation, the number of variables decreases with aggregation level (Table 2.4). At the highest level, only three (biogeophysical) variables are left but the model still has a rather high R^2 (Figure 2.6). The percentage of the total population living in poverty is a high ranking variable at the first four aggregation levels. The other variables and their relative stb's vary quite strongly among the six models.

As expected, natural vegetation is more dominant in economically poor areas, on poor soils and further away from roads and cities. Contrary to the eco-region coast, more natural vegetation is found close to rivers. The positive relation with precipitation is probably the result of the natural areas along the outer slopes of the Andes receiving higher rainfalls.

2.4.3. Amazon

Permanent crops

Population density (rural or total) and soil fertility rank high in all models (Table 2.5). Distance variables are included at the lowest two levels and at the 4x4 level. Agricultural labour force of the rural population is only included in the 5x5 model.

Permanent crops are associated with places with higher population densities and medium fertility soils. As expected in this region, more permanent crops are grown close to rivers, roads and cities, although this is not found in all models.

Temporary crops

For temporary crops in all models except one, rural population density and precipitation are the highest-ranking variables (Table 2.5). At the lower aggregation levels slope and agricultural labour force are included but river distance is only selected in the 1x1 model.

As with permanent crops, temporary crops are related to higher population densities and precipitation. Temporary crops are negatively related with poor soils. For small areas a positive relation is found with agricultural labour force and proximity to rivers.

Grassland

For grassland, soil fertility, precipitation and slope are included in most models (Table 2.5). At least one of the socio-economic variables related with population densities, poverty or illiteracy is included in the models but there is not a clear pattern with aggregation level. Distance variables are included in the 1x1 and 4x4 models.

Relatively more grassland is grown in the Amazon on medium fertility soils under relatively high precipitation, and in areas with relatively high population densities and relatively little poverty and illiteracy rates.

Natural vegetation

Variables selected in all models are soil fertility and precipitation (Table 2.5). Urban distance was only selected for the 1x1 model. In most models slope is also included and at the highest three aggregation levels the agricultural labour force. Of the socio-economic variables, rural population density and illiteracy are included at the lower aggregation levels and poverty is included in most models.

Natural vegetation is associated with low fertility soils and low population densities in areas with relatively less high precipitation and with relatively more illiteracy and poverty.

Table 2.5. Multiple regression models at 6 aggregation levels for areas permanent crops, temporary crops, grassland and natural vegetation in the eco-region **Amazon**. stb: standardised regression coefficient. Asterisk: see text.

1x1 grid		2x2 grid		3x3 grid		4x4 grid		5x5 grid		6x6 grid	
variable	**stb**	**variable**	**stb**	**variable**	**stb**	**variable**	**stb**	**variable**	**stb**	**variable**	**stb**
permanent crops:											
fert1	-0.32	totpop	0.49	totpop	0.62	totpop	0.59	totpop	0.78	rurpop	0.93
rurpop	0.23	fert2	0.25	fert2	-0.27	alt	-0.26*	fert1	-0.28	slope2	-0.19
fert3	-0.22*	urbdis	-0.12	prec	0.18	fert2	0.21	agric-rur	0.18	fert1	-0.16
totpop	0.21	alt	-0.11*			urbdis	-0.19			alt	-0.13*
urbdis	-0.15	fert3	0.11			riverdis	-0.14				
alt	-0.11*	prec	0.10								
riverdis	-0.08										
temporary crops:											
rurpop	0.29	rurpop	0.41	prec	0.49	rurpop	0.52	fert2	0.73	rurpop	0.58
prec	0.23	prec	0.35	rurpop	0.48	prec	0.42	urbdis	-0.25	prec	0.34
fert1	-0.17	fert1	-0.29	fert1	-0.48	fert1	-0.33				
slope3	0.11*	slope3	0.18*	slope3	0.30	slope3	0.28				
agric-rur	0.09	agric-rur	0.14	text3	0.21*						
riverdis	-0.08										
totpop	0.08										
grassland:											
rurpop	0.21	fert2	0.53	fert2	0.38	prec	0.39	fert2	0.56	fert2	0.41
urbdis	-0.20	prec	0.38	prec	0.33	text2	-0.38	urbpop	0.34	prec	0.41
fert1	-0.18	fert1	-0.34	illit-tot	-0.30	pov-tot	-0.36	alt	0.19	pov-tot	-0.38
illit-rur	0.18*	text1	-0.26*					riverdis	-0.15		
alt	0.17	pov-tot	-0.22								
prec	0.13	slope1	-0.20								
pov-rur	-0.12	alt	0.12								
natural vegetation:											
rurpop	-0.30	prec	-0.45	prec	-0.52	prec	-0.42	urbpop	-0.56	prec	-0.50
fert1	0.24	fert1	0.36	fert1	0.39	fert2	-0.35	prec	-0.47	pov-tot	0.40
illit-rur	-0.24*	slope3	-0.29	rurpop	-0.27	pov-tot	0.32	slope1	0.38	fert2	-0.35
urbdis	0.22	rurpop	-0.24	slope3	-0.22			fert1	0.33		
prec	-0.18	fert2	-0.18	pov-tot	0.21						
alt	-0.15	pov-tot	0.16								
slope3	-0.15	illit-rur	-0.14*								

2.5. Discussion

The statistical analysis of Ecuadorian land use has resulted in significant multiple regression models for all combinations of land use type, eco-region and aggregation level. In most cases the models give rather satisfying fits, taking into account the highly complex nature of agro-ecosystems and the limited number of variables used. Not only the R^2 and the variables selected in the multiple regression models vary with the aggregation level, but also the standardised betas of the variables. In most models, biogeophysical as well as socio-economic or infra-structural variables are selected. Clear differences exist between land use types within each eco-region and between eco-regions.

The results quantify the structure of Ecuadorian land use. In the eco-region Coast large areas of export crops (banana, coffee and cocoa) are grown. For most of the permanent crops (especially banana) proximity to infrastructure and good soil conditions are important. Generally (though less so for coffee) they are associated with better socio-economic conditions (Larrea *et al.*, 1988). Irrigation is widely practised in order to overcome the dry conditions in the south. Important temporary crops in the Pacific coast are rice, soybean and hard maize. These last two crops are closely related to the agro-industry (Cuvi and Urriola, 1988). Soybean cultivation is rather concentrated, with hard maize grown in a more dispersed way. Remaining natural vegetation is mainly located in the north (Esmeraldas) and along the Andean footslopes. The results of statistical analysis for the eco-region Coast confirm the occurrence of permanent crops in the areas where the biogeophysical conditions are favourable. However, in these areas competition exists with temporary crops. The results illustrate the association of permanent crops with relatively better socio-economic conditions, through the negatively relation with illiteracy. Grassland is mainly different in its association with dissected terrain, because of a relative advantage compared to crop cultivation in those areas.

In the eco-region Andes, permanent crops are mainly fruit crops grown in the warmer valley bottoms and some coffee at the outer slopes of the Andes. Export crops are relatively unimportant compared to the Pacific Coast, and most temporary crops are traditional food crops (potato, beans, soft corn and barley) and vegetables, produced for on-farm consumption and the internal market. Especially after the agrarian reforms, the cultivation of these traditional food crops has in large parts of the Andes moved to the marginal areas, being grown at small farms (Bebbington, 1993). An exception is for example the northern province of Carchi where potato is grown under relatively good conditions and with the highest yields of the country. Increasing demands for meat and milk have caused an important increase in grassland at relatively large holdings in the valley bottoms and in newly colonised areas (Schodt, 1991; Commander and Peek, 1986). The statistical relation of permanent crops with low altitudes (warmer), fertile soils, and lower poverty levels, accords with expectations. The cultivation of temporary crops in marginal areas is not clearly reflected in the biogeophysical variables but might be illustrated by the association with rural illiteracy. Especially strong is the relation of these crops with high rural population densities, which probably reflects the small farm sizes.

The Amazon region is being affected by agricultural colonisation as a result of high pressure on agricultural land in the Andes and Pacific Coast, a process that has been stimulated by oil exploitation (Southgate and Whitaker, 1994). Especially affected by land clearing is the North-eastern part of the Amazon. A wide diversity of land-use patterns exists and many farms still contain significant areas of natural forest (Pichón, 1997). Although the most predominant agricultural land use type is grassland, a range of permanent and temporary crops is grown. Rural settlement is attracted by roads and populated areas, as well as by the presence of good soils (Southgate *et al.*, 1991; Pichón, 1997). This is confirmed by the statistical analysis at the lowest aggregation level where permanent crops, temporary crops and grassland are negatively associated with poor soils and positively by high population densities. Furthermore, proximity to rivers and urban centres is important. At the highest aggregation levels other patterns appear, where distances to urban centres, roads and rivers are less decisive.

In comparison with results for Costa Rica (Veldkamp and Fresco, 1997a) it can be concluded that the R^2 values obtained for comparable land use types, were higher for Ecuador. This is related to the fact that for Ecuador models with different independent variables were considered at the six aggregation levels. The use of different variables in the models has the disadvantage that comparison between models is more difficult. The advantages are that the inclusion of other variables further illustrates the effects of aggregation and gives better model fits.

Some caution has to be taken when interpreting the results of such a statistical analysis. The models should in the first place be appreciated for their multi-variable descriptive and predictive power. In the explanation of the models causality is not always easy to verify, though case studies can support the interpretation of the results. Although multiple regression models are more commonly applied at household and national levels, this technique has been much less applied for the analysis of agro-ecosystems at intermediate aggregation levels. Furthermore, research has often focused on either the biogeophysical or socio-economic characteristics of agro-ecosystems. In order to further enforce the theoretical frameworks for the description and explanation of biogeophysical and socio-economic drivers of land use at different aggregation levels, more research in different geographical regions will be necessary. This is especially necessary as the nature of the studied system prevents intervention studies being carried out. A reproducible quantitative method such as presented here allows for comparative studies.

Care is needed with a direct comparison between land use types and single independent variables. The multi-dimensional space made up by all the independent variables can, in analogy with ecosystems theory (Odum, 1994), be considered the niche for certain agro-ecosystems. It is the specific combination of all these variables that create the conditions for agro-ecosystems to express themselves. These niches do not only depend on spatial scales, but are also dynamic in time. In this study only one year was investigated because of limitations in data availability. Time series can be a valuable extension of the current study.

With regards to data quality further improvements can be expected with the rapid progress in availability of large data bases and standardisation of censuses. Especially data obtained from remote sensing can complement data from censuses (Skole and Tucker, 1993). In the case of Ecuador, a new analysis should be done after the publication of a new complete agricultural census, which will be available in a few years. This could especially improve data for the Amazon region where land use is highly dynamic and current data quality is probably poor as a result of problems of access and the difficulties in clearly classifying land use because of the complex combination of agricultural land use and natural vegetation.

A quantitative analysis of land use as was presented in this chapter offers scope for implementation of its results in a dynamic multi-scale land use change model (Veldkamp and Fresco, 1996a; 1996b). The development of such a model for Ecuador is described in the next chapter.

Chapter 3

Multi-scale modelling of land use change dynamics in Ecuador.

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Chapter 3

Multi-scale modelling of land use change dynamics in Ecuador

Abstract

A spatially explicit multi-scale approach to land use change modelling is explained and demonstrated. It is based on the empirical description of the biogeophysical and socio-economic drivers of land use at different aggregation levels, using a system analytical approach for the characterisation of agro-ecosystems. Sub-national changes in land use following changes in the national demand for agricultural commodities are modelled on the basis of complex interactions in time and space and the competition between alternative land uses. In a multi-scale allocation procedure, land use changes are calculated for cells of a geographical grid. The model was applied to Ecuador. Land use change allocation in the model was validated with historical data. A hypothetical future base-line scenario of increasing demands for agricultural commodities was used to demonstrate how dynamics of land use are modelled. The results may be used to detect so-called "hot-spots". These are dynamic areas where impacts on land use change on the natural resource base can be expected. The model offers scope for comparison of different scenarios in which alternative development paths can be defined, for example with respect to changes in food demands, technology levels, infrastructure, soil suitability or the protection of natural areas.

3.1. Introduction

Changes in land cover and land use have important consequences for natural resources through their impacts on soil and water quality, biodiversity, and global climate systems (Houghton, 1994; Houghton *et al.*, 1991; Turner II *et al.*, 1995). Land cover modification and conversion is driven by the interaction in space and time between biophysical and human dimensions (Turner II *et al.*, 1993; Turner II *et al.*, 1995; Skole *et al.*, 1994). The need for better understanding of land use change has stimulated research in its causes and effects, and the development of conceptual models of land transformation (Riebsame *et al.*, 1994a, 1994b; Sklar and Costanza, 1991). A number of approaches have been described in the literature, for example by Mertens and Lambin (1997), Hall *et al.* (1995), Alcamo (1995), Fisher *et al.* (1996), Bockstael *et al.* (1995) and Engelen *et al.* (1995). While some models operate at global scales (Alcamo, 1995; Darwin *et al.*, 1996), others are directed at local scales (Dale *et al.*, 1993).

In this chapter the CLUE (Conversion of Land Use and its Effects) modelling framework is used for the quantitative multi-scale description of land use dynamics. CLUE was initially developed for, and applied to, Costa-Rica (Veldkamp and Fresco 1996b, 1997a, 1997b). The aim of the modelling framework is the description and analysis of actual land use and the comparison of spatial patterns of land use change under different agricultural development scenarios.

The objective of this chapter is to describe further model developments and to illustrate these with an investigation in land use dynamics in Ecuador. Ecuador has a high ecological diversity (Cañadas, 1983) and dynamic land use. Its total area of agricultural land has significantly increased during the last two decades (Whitaker and Alzamora, 1990), causing threats to natural resources through land degradation and loss of biodiversity (Southgate and Whitaker, 1992; Myers, 1988, 1993).

3.2. Characteristics of the CLUE modelling approach

Actual land use in the study area is the starting point for the analysis and exploration of land use change, presented in this study. This approach is distinct from optimisation oriented approaches in which land use options are calculated with the aim to define optimal land use configurations under certain boundary conditions and goals. Our approach assumes that optimal situations are in practice hard to realise in the short term due to the complex (historical) interactions of socio-economic and biogeophysical driving factors that determine actual land use systems. In other words, agro-ecosystems are not easy to "design". This is particularly relevant under constraining socio-economic conditions. For short term explorations (15 to 20 years) the spatial and temporal dynamics of the actual land use systems are highly relevant for the understanding of near future agro-ecosystem behaviour (Veldkamp and Fresco, 1997b).

For the analysis and description of land use a systems approach is being followed. In analogy to ecosystems theory (Odum, 1994; Vandermeer, 1972), niches for agro-ecosystems are considered multidimensional. Next to time and space they are determined by the complex interactions made up by a range of biophysical and socio-economic factors, determining agro-ecosystem properties like productivity, stability, resilience and sustainability (Conway, 1987; Marten, 1988). For an integrated description of these agro-ecological conditions, an empirical method is followed. As such we try to assess the relative importance of socio-economic and biogeophysical factors simultaneously. In comparison with process based modelling it may offer less explanatory power, but it avoids problems of using causal relations at scales other than for which these relations were established.

Agro-ecosystems are determined by processes that operate at coarse scales, as well as by processes that operate at fine scales (Fresco and Kroonenberg, 1992). While at detailed scales local variability in land use drivers can be observed, landscape patterns remain hidden, and vice versa. Furthermore, factors determining land use can operate at large distances from the area affected (Skole *et al.*, 1994). Thus, when describing the dynamics of these agro-ecosystems, this aspect is explicitly taken into account by using a multi-scale approach that identifies and quantifies land use drivers and their interrelationships at various spatial scales (Veldkamp and Fresco, 1997a).

Land use modelling should be sufficiently spatially explicit. Analyses at highly aggregated spatial scales do not allow proper evaluation of local driving forces of land use change. Such local information is important to adequately address the impacts of land use change at these scales and determine areas of special interest, so-called hot spots, which are of concern for further research or policy measures.

3.3 Methodology

3.3.1. Multi-scale statistical analysis of land-use drivers

The first part of the methodology consists of a statistical multi-scale analysis of land use drivers. Because of the multi-dimensional character of the factors that determine the spatial organisation of agro-ecosystems, a multivariate technique was applied.

The basic spatial organisation in the analysis was a geographical grid with a cell size of 5 by 5 minutes (approximately 9.25 by 9.25 km), covering the Ecuadorian territory according to the protocol of Rio de Janeiro 1942, excluding the Galápagos Islands. A cell was included when it covered Ecuadorian land for at least 50% of its surface. The total number of these basis cells equalled 2982. Biophysical and socio-economic data derived from maps and censuses were attributed to these cells. Although a grid approach uses imposed boundaries that have no biophysical or administrative meaning, they are a way to link data that are normally related to units that do not spatially match. The grid cells offer convenient uniform units for analysis, which can be aggregated to a series of higher artificial aggregation levels, considered proxies for different spatial scales. By averaging data of 2 by 2 (= 4) basis cells, 3 by 3 (= 9) basis cells, 4 by 4 (= 16) basis cells, 5 by 5 (= 25) basis cells and 6 by 6 (=36) basis cells, 6 aggregation levels (nested scales) were created. The geo-referenced data used were (proxies of) factors considered important for land use in Ecuador. Data were collected at a resolution that was in correspondence with the resolution of the basis grid and stored in a geographical information system. Altitude data were taken from a 5 by 5 minutes altitude database, while soil and climate data were derived from maps (González *et al.*, 1986; Cañadas, 1983) and related databases. Markets and infrastructure were accounted for by calculating distances between the centres of grid cells and the nearest main road, river, and urban centre. Socio-economic data were obtained from the 1990 population census at parish level (INEC, 1990) and derived data (Larrea *et al.*, 1996). In 1990, 738 rural and 162 urban parishes existed (excluding the Galápagos Islands). The 1990 socio-economic data were considered representative for 1991, the year for which land use was analysed. The total set of independent variables used in the analysis is listed in Table 2.2.

A land use map was constructed based on the disaggregated 1991 data of the National System for Agricultural Statistics (INEC, 1991) containing information on 65415 farmers in 3137 sample sites. Three main agricultural land use types were included: permanent crops, temporary crops and grassland. Fallow of less than one year is included in the land use type temporary crops. Grassland comprises the categories cultivated and natural grassland, but páramo, the Andean high altitude alpine grassland, is excluded. Grid cells were not treated as homogenous units, but the surface fraction within cells for each land use type was used. For example, a cell could consist of 10% grassland, 35% permanent crops, 20% temporary crops and 35% natural vegetation.

The hypothetical biogeophysical and socio-economic drivers of actual land were investigated with multiple regression methods. To take scale dependencies into account, this analysis was performed independently at the different artificial aggregation levels and stratified for three eco-regions: Pacific Coast, Andes and Amazon. The criterion used for this stratification was altitude, the Andean eco-region being defined as cells with an average altitude above 1000 m above sea level. In the statistical procedure, the most important land use drivers (independent variables) for different land use types (dependent variables) were selected from the total set of hypothetically important variables by means of stepwise regression for each aggregation level and eco-region. The selected significant variables were then used to construct multiple regression models. The biogeophysical, socio-economic and infrastructural variables selected in the multiple regression models depended on land use type and eco-region. Furthermore, the selected variables and their relative contribution varied with the aggregation level, a result in line with an earlier study of Veldkamp and Fresco (1997a) for Costa Rica. A complete description of the statistical analysis and its results is given in Chapter 2.

3.3.2. General model framework

In the model, demands for agricultural products are calculated at the aggregated national level (Figure 3.1).

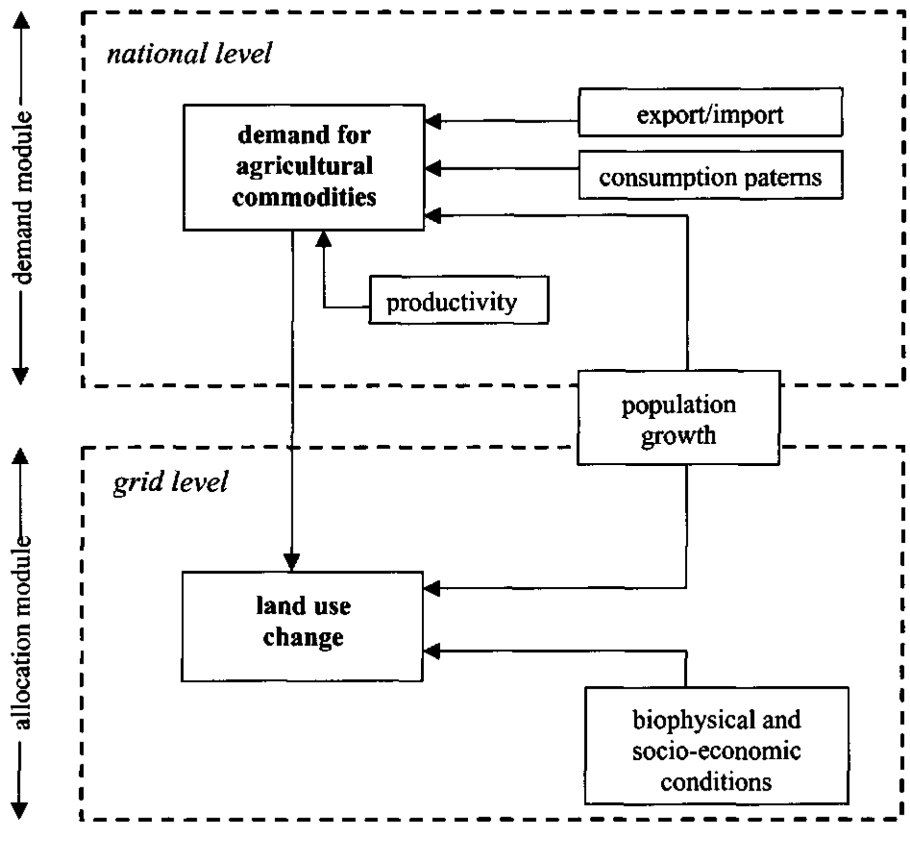

Figure 3.1. General concept of the CLUE modelling framework.

It is assumed that these national demands determine the final total amount of land used for all commodities (after correcting for imports and exports). An increasing demand for certain commodities will internally drive market and structural incentives that push the supply of those commodities through expansion of the area used for production and/or through technological changes leading to higher per hectare yields (Bilsborrow and Okoth Ogendo, 1992). In other words, in the model land use is directed at meeting the national demand. This simplified model was considered appropriate as an approximation of the yearly response to changing demands, although in reality imperfections in market structure and prices will cause a less direct match between demand and offer (Tschirley and Riley, 1990). At sub-national levels, actual land use changes are determined by changes in national demand, and by changes in the socio-economic and biogeophysical conditions at these levels.

Scenarios of future development are based on possible future changes in the national demand and changes in the sub-national socio-economic and biophysical conditions. For the calculation of land use changes in these scenarios, a time step of one year is used. The model is broadly divided into two main modules: the demand and the allocation module.

3.3.3. The demand module

In the CLUE demand module, the total area needed for different land use types is calculated on basis of national demands for separate commodities. The demands for these commodities are the sum of domestic consumption volumes and export volumes.

Export volumes can be related to international prices and national tariffs and subsidies. Domestic intake is a function of population size, population composition and consumption patterns. Historic data can be used to calibrate the commodity volume demand functions. Future developments are hard to predict, and therefore different possible development scenarios are to be formulated, taking into account varying projections of future developments. Crop commodity demands calculated as production volumes are translated into areas sown through crop yields, taking into account estimated harvest and transportation losses, quantities used for seed and amounts used for animal feed, according to data of FAO (1998). Industrial animal production is included through crop products used for feed. Bovine milk and meat production is related to the area grassland, taking into account average production per animal and stocking densities.

On the basis of the calculated areas needed for separate crops, the areas for broader land use types (in this study permanent crops, temporary crops and grassland) are calculated by lumping crops together.

3.3.4. The allocation module

The spatially explicit modelling of land use changes is based upon the assumption that land use at each place is determined by a combination of biogeophysical, socio-economic and infra-structural factors. They determine the feasibility of land uses under the given conditions. A comparison with actual land use indicates potential land use change. In the CLUE allocation module, this basic assumption is further elaborated for the calculation of actual land use changes, taking into account competition between alternative land use types and using a nested scale approach. Different scales are included because local land use change is determined by local biophysical and socio-economic conditions, as well as by conditions at higher scales. Decisions at the local level are determined by local processes, but also by processes that operate over large distances.

In the allocation module the multi-dimensional space made up by land use drivers is described by the regression equations for individual land use types. The expected surface area of each land use type is calculated for individual cells using the regression equation for the specific land use type, aggregation level and eco-region. The total cover calculated this way is called the "regression cover" of a land use type (representing the feasible land use). This "regression cover" is calculated firstly at a coarse allocation scale for which, in the case of Ecuador, the aggregation level of 4 by 4 averaged basis cells was used (Figure 3.2).

Differences between the regression cover and the actual cover are considered indicative for land use changes under changing national demands. If a cell has less area of a certain land use type than expected on basis of the regression equation, area increase of that land use type is considered feasible over time, and vice versa. When national demand is increasing, change will take place in cells where the difference between the regression cover and the actual cover is positive. In case of a decreasing demand, change will take place in cells where this difference is negative. The fraction of change within cells is gradually adapted in an iteration loop in which the total allocated area for each land use type is compared with the demand (Figure 3.3.).

An important feature of the allocation procedure is that not only the dominant land use type in a cell is being considered but that for all land use types their relative proportions are being calculated. Therefore, the iteration is done simultaneously for all land use types. Within cells, competition between individual land use types is taken into account by using the relative pressure on the land in order to equalise total land use area with the cell size. After equilibrium is reached at the coarse allocation scale (total demand is then allocated) the comparative advantages between the coarse cells, representing artificial regions, are used in the second iteration loop at the fine allocation scale. In this loop local changes of all land use types in the basis cells are calculated on basis of their locally specific

biogeophysical and socio-economic conditions, but taking into account the conditions in the larger cells in which these cells are nested. In basis cells that are nested in fastly changing coarse scale cells, a relatively larger proportion of their local change is allocated, provided that the fine scale change is in the same direction as the coarse scale change. To some extent, autonomous development can take place in the basis cells. This means that change can be opposite to the change at the coarse scale, due to the local conditions in those cells. A more extensive description of the characteristics and functioning of the allocation module has been given by Verburg *et al.* (1999).
In the multi-scale allocation procedure top-down and bottom-up effects are modelled. The demand is allocated from national to intermediate and local levels, but local conditions may constrain increases in areas of certain land use types, thereby forcing other areas to grow or even prohibit the national demand to be allocated.

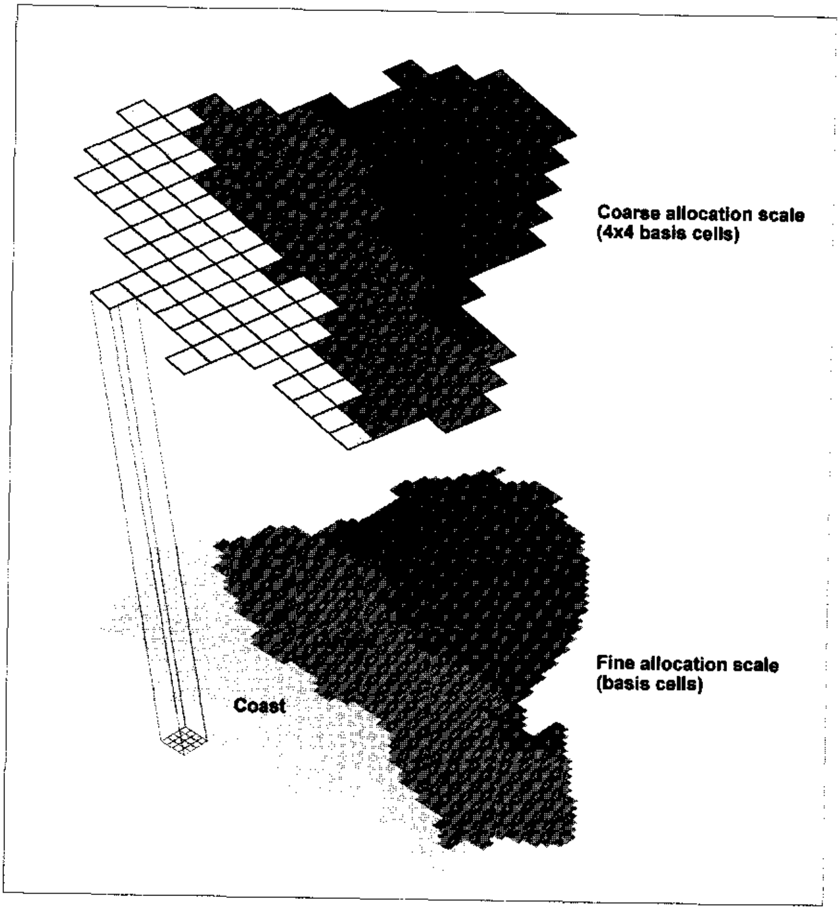

Figure 3.2. Allocation at a coarse scale and at a fine scale.

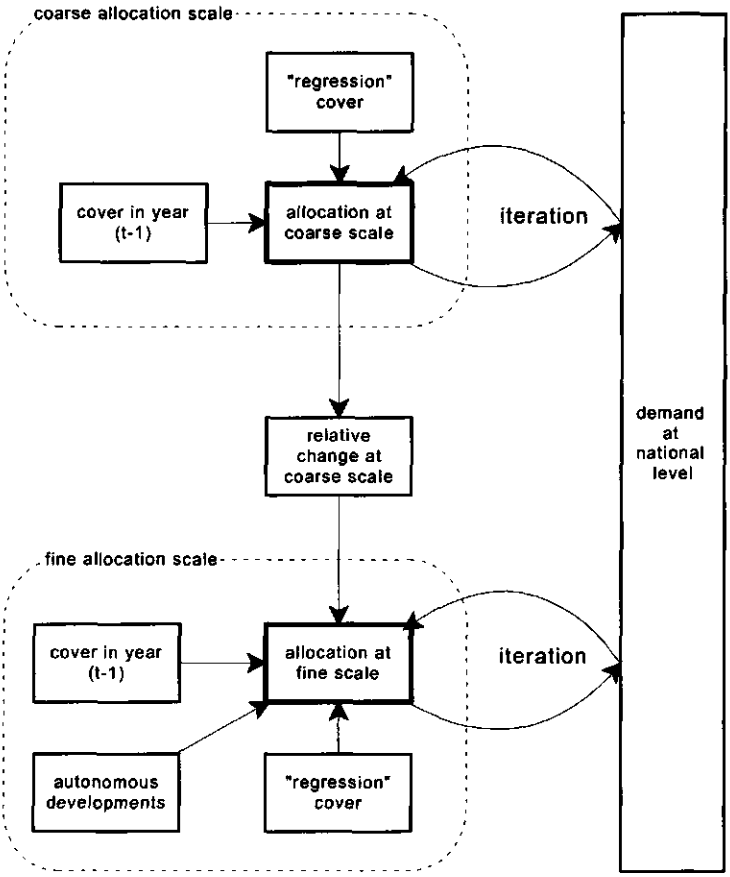

Figure 3.3. Schematic representation of the allocation module (source: Verburg *et al.*, 1999).

In the model, local effects like the protection of areas through national parks, or areas becoming unsuitable through deterioration of biophysical resources can be included as different scenarios (Veldkamp and Fresco, 1997b). Changes of biophysical and socio-economic drivers are taken into account as well, thereby changing the multi-dimensional space within which land use is situated and calculated. For example, changes in local population densities are included. The drivers taken into account for the two scales and the three eco-regions are listed in Table 3.1.

The Amazon region was treated somewhat differently from the other two eco-regions. Whereas in the eco-regions Coast and Andes current agricultural land use is the result of a long period of gradual land use changes, large scale colonisation of the Amazon region is of a relatively recent and particular nature. Major areas are still predominantly natural forest and although disperse agriculture is being practised by various small groups, the focus in this study is on colonisation agriculture that takes place along the borders of existing areas with significant agricultural land use. For that reason only the distances to urban centres, rivers and roads were taken into account as main drivers for land use change in the Amazon region.

Table 3.1. Variables selected for the regression equations for 4 land use types in 3 eco-regions.

	permanent crops						temporary crops						grassland						rest					
	Coast		Andes		Amazon		Coast		Andes		Amazon		Coast		Andes		Amazon		Coast		Andes		Amazon	
	1	4	1	4	1	4	1	4	1	4	1	4	1	4	1	4	1	4	1	4	1	4	1	4
text1	x	x								x				x										
text2			x							x														
text3													x							x				
slope1																								
slope2			x																					
slope3	x	x					x	x	x				x						x					
fert1													x						x	x				
fert2										x				x										
fert3	x	x	x	x			x	x	x						x	x					x	x		
alt	x	x	x	x											x	x			x					
prec							x		x					x	x	x					x	x		
urbdis			x	x	x	x			x		x	x	x		x		x	x	x		x		x	x
roaddis	x	x			x	x	x				x	x	x	x	x		x	x	x	x	x	x	x	x
riverdis					x	x	x	x			x	x	x		x		x	x	x	x	x	x	x	x
totpop													x											
rurpop							x	x	x	x														
urbpop										x														
pov-tot		x														x					x	x		
pov-rur			x												x									
illit-tot									x							x					x			
illit-rur	x						x	x	x	x														
agric-tot		x																						
agric-rur	x		x											x					x	x				

Notes: 1) Two scale levels are indicated; 1=basis cells; 4=aggregation of 4 by 4 basis cells
2) x: included in regression, blank: not included in regression.

3.3.5. Backward validation

The allocation module was tested by means of a backward calculation of land use changes from the reference year 1991 until the year 1974, a year in which a full agricultural census was executed (INEC, 1974a). The reason for doing a backward instead of a forward validation was that for 1991 data with more spatial detail were available. The empirical statistical relations derived for 1991 were therefore used as the starting point and these were applied within the allocation module for the period 1991-1974. The actual changes at the national level in the areas of permanent crops, temporary crops and grassland were used directly, this way replacing the demand module. Changes in urban and rural population numbers (INEC, 1974b), urban markets and road density were taken into account at the sub-national levels. The final model results for 1974 at the level of basis cells were aggregated to the levels of the 1974 cantons and provinces, in order to compare them with published census data.

3.3.6. Future baseline scenario

To study basic model behaviour for Ecuador, a baseline scenario was defined for the period 1991 to 2010. In this baseline scenario only population growth was taken into account, while consumption patterns and crop yields, as well as the biophysical conditions were kept constant.

Estimates of changes in rural and urban population densities were obtained from projections of INEC (1993) with estimated changes in population until the year 2000 at the level of cantons. The rates of change at canton level where extrapolated until the year 2010. The rates of change of the canton were applied to the parishes within the cantons. The estimated population for parishes was allocated to the basis grid cells, thus constructing estimated population maps until the year 2010. The total projected population for 1991 and 2010 was 10.5 million and 14.6 million, respectively. This national increase in total population is almost exclusively an increase of the urban population, living in the canton capitals.

Three main agricultural land use types were considered: permanent crops, temporary crops and grassland. All remaining area was lumped together as a rest group, predominantly consisting of natural vegetation.

3.4. Results

3.4.1. Backward validation

The total area of all three agricultural land use types increased over the period 1974-1991. The 1974 national areas of permanent crops, temporary crops and grassland amounted to 63%, 65% and 50% of their 1991 national areas, respectively. In Figure 3.4, the 1974 areas of permanent crops, temporary crops and grassland calculated by the allocation module are plotted against the areas reported in the 1974 census. Two aggregation levels are illustrated: canton level and province level.

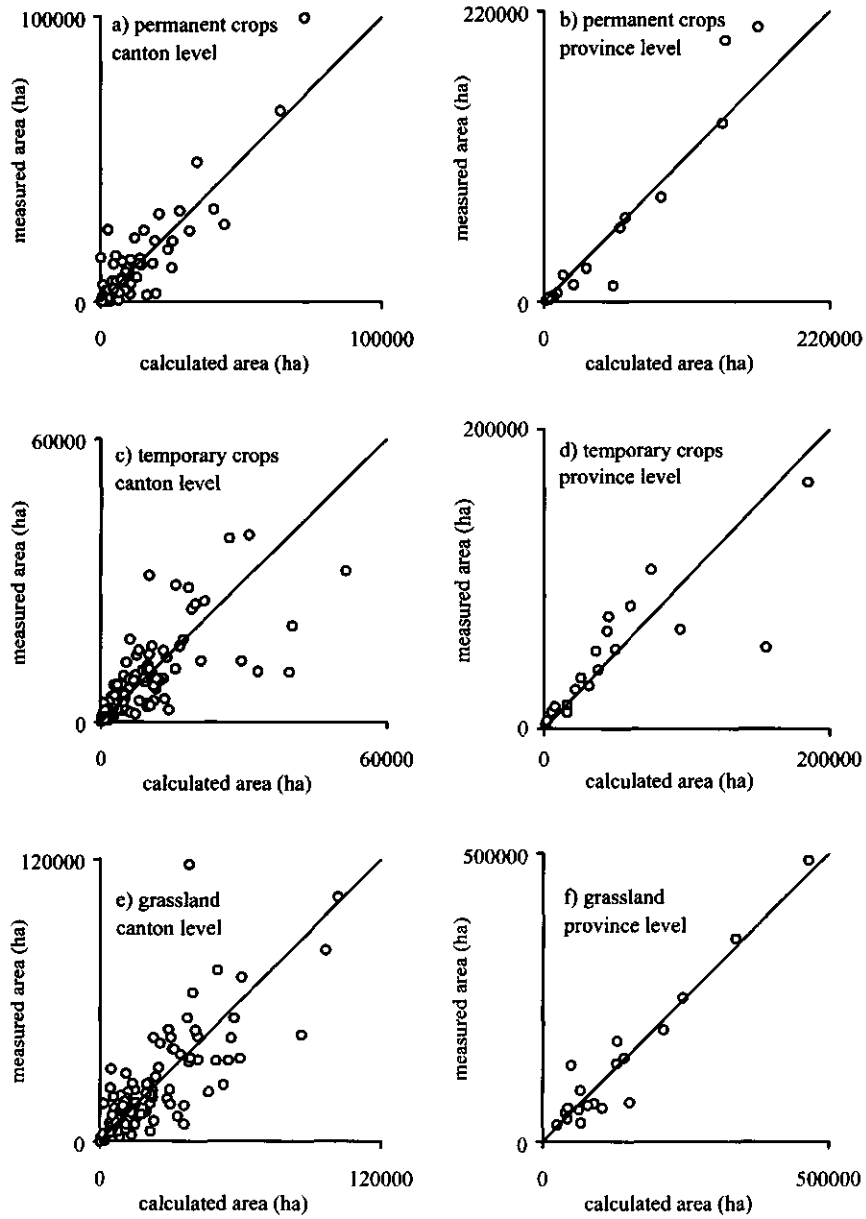

Figure 3.4. Areas (ha) reported in the agricultural census (indicated as measured area) and calculated by the model for 1974 for the three agricultural land use types at canton level and province level. Lines indicate the hypothetical one to one relation between calculated and measured areas. Correlation coefficients between calculated and measured area: a): 0.90; b): 0.96; c): 0.71; d): 0.82; e): 0.85; f): 0.91. All correlation coefficients are significant at the 0.05 level.

The calculated areas for permanent crops at the canton level deviate relatively more from the measured areas in cantons with small areas of permanent crops. A rather high correlation coefficient of 0.9 is obtained. At the province level, the correlation coefficient is still higher, and for most provinces the calculated areas for permanent crops are close to the measured areas.

The three provinces for which the absolute differences between calculated and measured areas of permanent crops are biggest, are, in order of calculated area, Napo, Manabí and Los Ríos (province boundaries of continental Ecuador are indicated in Figure 2.2). In Napo, located in the north-eastern part of eco-region Amazon, the actual change between 1974 and 1991 was bigger than calculated by the model. For the provinces Manabí and Los Ríos the opposite is the case. Here the high areas of permanent crops have been more constant than calculated by the model.

For temporary crops the relation between calculated and measured areas at the canton level is not as good as for permanent crops, which is illustrated by the lower correlation coefficients. The absolute differences between measured and calculated areas increase with higher calculated absolute areas. Differences level out at the province level. The highest absolute difference is found for the province of Los Ríos, where the calculated area is clearly higher than the measured area. The actual change between 1974 and 1991 for this province was higher than the calculated change. Problems in banana production systems in this province have initiated government supported programs to stimulate the production of maize, soybean and rice, making Los Ríos the most dynamic province of the country in terms of absolute land use changes in this period (Cuvi and Urriola, 1988). These strong changes are not completely captured by the model.

For grassland areas at the level of cantons, the correlation coefficient is close to that of permanent crops. Except for one clear outlier, absolute differences between measured and calculated areas do not increase with the total area of grassland present in a canton. At the level of provinces, the correlation further increases. Especially in provinces with large areas of grassland, the calculated areas are close to the measured areas.

Instead of comparing absolute calculated and measured area, measured and calculated changes can be compared. This comparison still gives satisfying results, even though correlation coefficients are lower. For the canton level and province level, respectively, the correlation coefficients are 0.66 and 0.67 for permanent crops, 0.76 and 0.84 for temporary crops, and 0.87 and 0.92 for grassland.

3.4.2. Baseline scenario

Figure 3.5 shows the total land use changes calculated with the demand module for separate land use types under the assumptions for the base-line scenario. In this scenario the areas for grassland and temporary crops show the highest relative increases. In absolute terms, the area increase of grassland is very important. Due to the growing total population, the domestic intake of basic food crops and animal products, under a constant per capita intake, increases. Increasing demand for animal products results in an indirect increase in the demand for annual crops like hard maize and soybean, used as feed in intensive animal production, and furthermore in an increase of grassland for bovine meat and milk production. The most important export crops are permanent crops (banana, coffee and cocoa). The increase of the area for permanent crops is not as strong as that of the other land use types, because in the baseline scenario export was assumed to remain stable at the 1991 level.

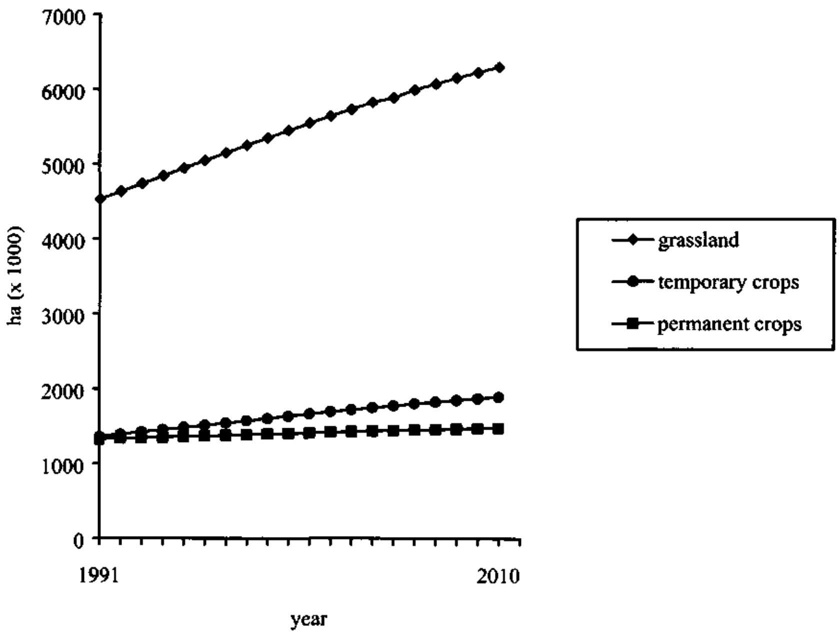

Figure 3.5. Land use type areas calculated with the demand module for the base-line scenario.

The estimated percentage of cell areas dedicated to different land use types in the year 1991, is given in Figure 3.6. For permanent crops, temporary crops and grassland, the cells are indicated with a positive difference between the cell areas in the regression cover for 1991 and the cell areas in 1991. These areas, here called regression hot-spots, indicate where in the model under growing demand, area increase is considered most likely for an individual land use type. The finally modelled changes in relative cell areas depend also on the national increase in demand for a land use type and the competition with other land use types. The modelled increases and decreases over the period 1991-2010 are also illustrated in Figure 3.6.

For permanent crops, the pattern of modelled increases is related to the regression hot-spots, but because of the relatively small total national area increase of permanent crops in this scenario, a significant increase was not calculated for all these cells. Modelled increase is mainly significant in the eco-regions Coast and Amazon. In the coastal region, major increases are located in the north-west, along the borders of the remaining humid tropical forest in the province of Esmeraldas. Other increases are indicated slightly west and east of the already existing north-south orientated strip with relatively high concentrations of permanent crops, and in some new areas along the Pacific ocean in the provinces of Manabí and Guayas. Increases of permanent crops in the Amazon are mainly found in the north-eastern provinces of Sucumbíos and Napo, and along the Andean footslopes further south. Decreases are the result of competition with temporary crops and grassland. These decreases are mainly located in areas where the 1991 relative area for permanent crops was high, in the provinces of Los Ríos, Guayas and El Oro.

Increases in temporary crops show a more disperse pattern, with important changes in all three eco-regions. As with permanent crops, the modelled growth occurs mainly in regression hot spots, but due to the larger total increase of the area temporary crops some other areas also show an increase. This change is also the result of competition, especially with the fast growing grassland area. In the Coast, allocation of temporary crops occurs mainly in the north-west, in the provinces of Esmeraldas and Manabí, and in the south. Temporary crops in the Andes increase quite evenly over the whole eco-region. Here expansion takes place from the inter-Andean valley upwards, and along the outer slopes of the Andean *cordilleras*. In the Amazon, the same pattern is followed as for permanent crops. Decrease through competition occurs mainly in the central coastal region.

The strongest changes occur in cell areas allocated to grassland, especially around the areas where high cell fractions of grassland were present in 1991, such as the grassland area in the north-western province of Manabí, indicated by the regression hot spots. In the Andean region, competition occurs with temporary crops (see decreases of temporary crops) and expansion takes place from the existing areas, especially along the eastern slopes. The agricultural frontier in the Amazon region is mainly pushed by grassland, progressing along infrastructure, and from populated centres, above all in the north-east.

The land use type defined as rest in Figure 3.6 is the direct complement of the other three land-use types and consists mainly of natural vegetation. It also includes Andean alpine grassland (páramo). Because areas of all agricultural land use types increase, the rest cover decreases accordingly. This decrease takes especially place along the eastern slopes of the Andes, the northeastern part of the Amazon, and the northwestern part of the Coast.

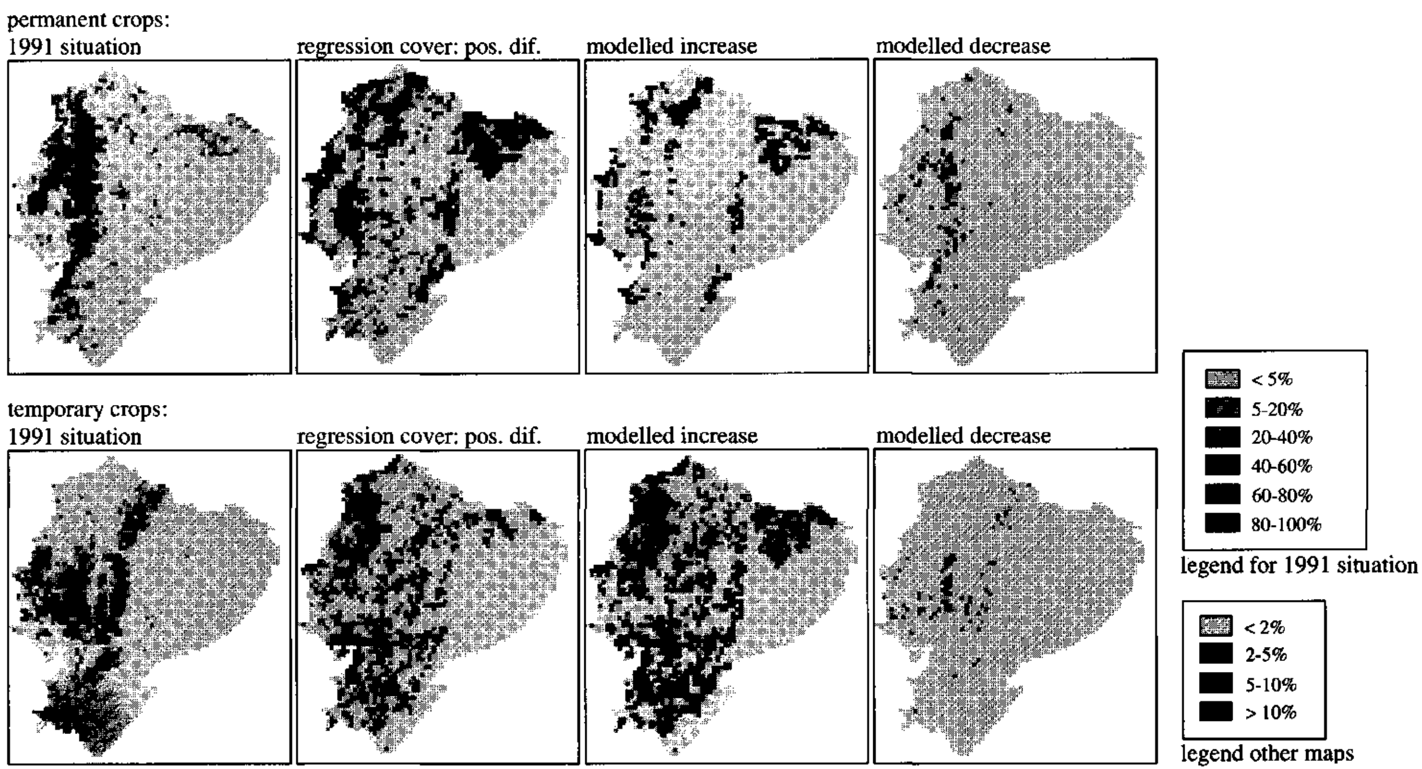

Figure 3.6a. Modelled land use dynamics. For permanent crops and temporary crops the estimated areas in 1991 are given in the maps "1991 situation". The maps "regression cover: pos. dif." indicate cells with a positive difference between the calculated regression cover for 1991 and the estimated areas in 1991. The maps "modelled increase" and "modelled decrease" indicate the modelled changes for the period 1991 to 2010. The regression cover differences and the modelled increases and decreases are expressed as the difference in percentage cell area compared with the 1991 percentage.

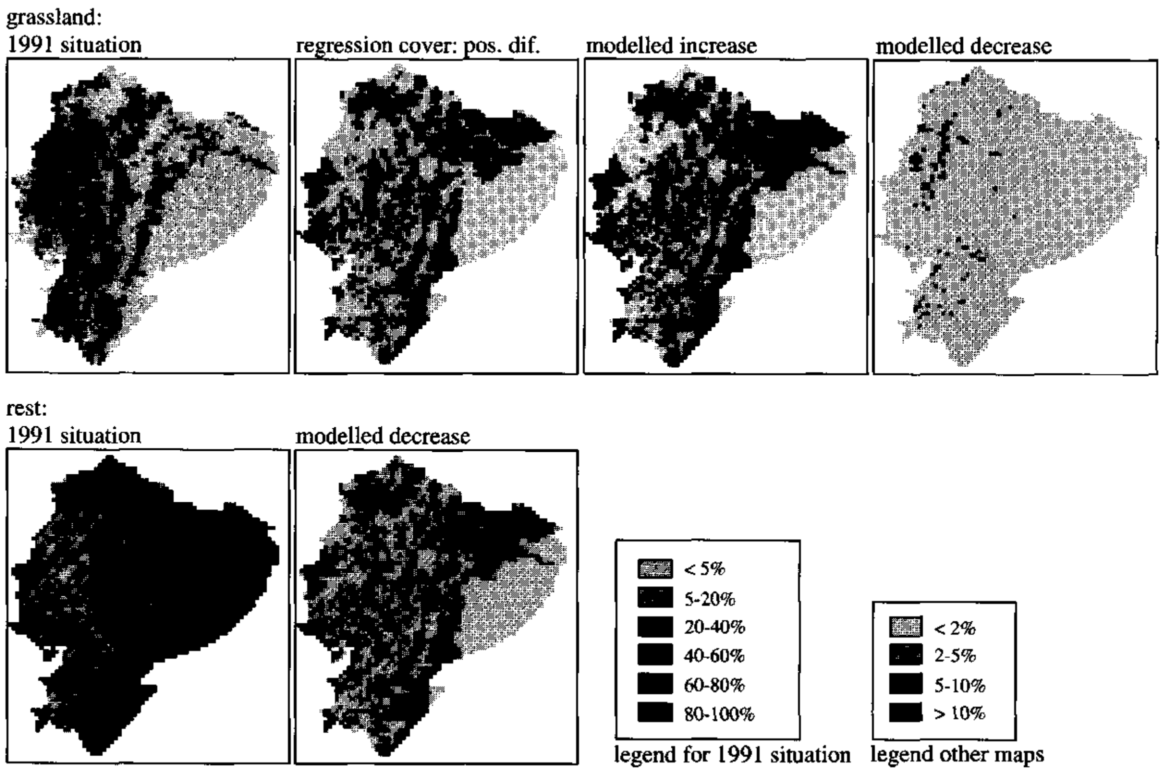

Figure 3.6b. Modelled land use dynamics. For grassland, the estimated areas in 1991 are given in the maps "1991 situation". The maps "regression cover: pos. dif." indicate cells with a positive difference between the calculated regression cover for 1991 and the estimated areas in 1991. The maps "modelled increase" and "modelled decrease" indicate the modelled changes for the period 1991 to 2010. For the rest area only the situation in 1991 and the modelled decreases are given. The regression cover differences and the modelled increases and decreases are expressed as the difference in percentage cell area compared with the 1991 percentage.

The complex spatial relations captured by the model are demonstrated by excluding part of the available area for agricultural land use. Figure 3.7 demonstrates model results for the same increase in national demands, but for a situation where nature parks are fully protected. Different outcomes can be observed in places spatially distant from the protected areas. In most cases these are increases of modelled areas, though in some cases even decreases are modelled due to interactions between land use types.

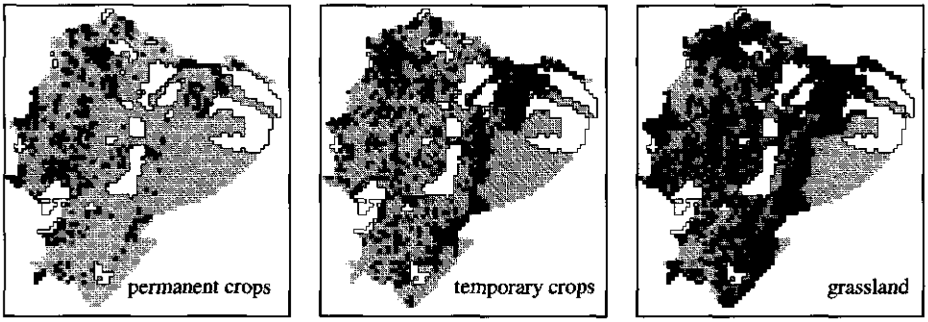

Figure 3.7. Differences in final model outcome for three agricultural land use types due to the exclusion of areas dedicated to nature parks. Light grey: no difference; dark grey: decrease of area; black: increase of area; delineated white areas: nature parks.

In Table 3.2 the total modelled regional changes in the area of individual land use types between 1991 and 2010 are given for the baseline scenario without protection of nature parks. Absolute change is given, as well as the relative change of the area within a region, and the contribution of the regional change to the national change. Absolute increases in the area permanent crops are mainly modelled for the eco-regions Coast and Amazon. In these eco-regions more than 90% of the total national change is allocated. Permanent crops are mainly grown at lower altitudes. For the Amazon region the increase means almost a doubling of the 1991 permanent crop area. Absolute increase in temporary crops is very similar in the eco-regions Coast and Andes, while that of the Amazon is about one third of the area change in the other regions. However, this means for the Amazon region an area temporary crops which is five times that of 1991. The highest absolute increase in grassland area is allocated in the Andes, followed by the Coast and Amazon. Again for the Amazon this means the highest relative increase in the regional area, more than twice the 1991 area.

The rest group complements the balance of land use change. The changes in the eco-regions Coast and Andes each contribute to slightly less than 40 percent of the national change. The decrease in this rest area can not be directly interpreted as deforestation rates. Apart from the fact that this rest area does not only include natural forest, the demand for forestry products is not explicitly modelled. Logging for timber or for the exploitation of oil, such as in the Amazon, is therefore not represented and the changes are the mere results of expanding agriculture. The area of virgin forest affected by expansion is larger that just the increase of land for crops or grassland, because especially in the Amazon agriculture is combined with significant on-farm areas of natural vegetation (Pichón, 1997).

Table 3.2. Calculated absolute change (x1000 ha), relative regional change as percentage of the 1991 area in the region, and relative regional change as percentage of national change, for different land use types in the three eco-regions.

land use type	Coast			Andes			Amazon		
	change	% of region	% of country	change	% of region	% of country	change	% of region	% of country
permanent crops	+67	6	47	+14	8	9	+62	85	44
temporary crops	+237	33	45	+210	33	40	+79	576	15
grassland	+646	26	35	+788	43	41	+449	220	24
rest	-948	26	38	-1017	15	39	-577	8	23

3.5. Discussion

The CLUE modelling framework analyses the spatial and temporal dynamics of agro-ecosystems by describing the behaviour of the system as a whole. While the spatial dynamics are captured by taking multi-scale variability into account between cells of a geographical grid that covers the entire study area, temporal dynamics are the result of changing national demands for agricultural commodities, and sub-national changes in socio-economic and biophysical drivers of land use. In reality, land use is in the first place the direct result of the decisions of individual land users. However, these decisions are related to decisions made by other land users and by policy makers at regional and national levels. Land use is not only based on local conditions for land use, but also by phenomena that operate over larger distances like the presence of urban centres, the proximity to infrastructure and the broad ecological setting. The model assumption that demand is determined at the national levels, is a top down approach to total land use change. However, because of the spatially explicit local changes bottom-up effects are also included. The self-organising system that emerges is one where spatially distant places are still interconnected. Deforestation of the Ecuadorian Amazon region, for example, cannot be properly understood without taking into account what is happening in the rest of the country.

This interconnection is illustrated with the base-line scenario of increasing national demands for agricultural commodities. Regression hot spots indicate places where individual land use changes are feasible. However, for a complete system description, alternative uses are considered simultaneously in the model. When national demand for a certain land use type increases, still decreases can be modelled in some areas due to competition with other land uses for which local conditions are more favourable. In the scenario presented, increases in grassland areas dominate the spatial pattern of land use changes. These increases do not only take place in areas where agriculture is already present, but also expansion occurs into new areas such as the coastal tropical forest, the Andean footslopes and the Amazon. This new land is often less suitable, because the best land is already in use.

The influence local changes can have over long distances is demonstrated with a theoretical full protection of natural parks, resulting in increases as well as decreases of land use in spatially distant areas. This indicates that for a proper understanding of future developments in Ecuadorian agro-ecosystems, changes at local, regional and national levels have to be taken into account.

The base-line scenario that is used to model land use dynamics is a rather moderate one, because only population growth is considered while no increases in per capita consumption and increasing export are taken into account. However, even under these conditions land use changes can be quite significant if per hectare crop yields do not increase. The model results are not meant as predictions of future land use change. Instead, possible plausible future developments can be explored with scenarios in which different assumptions are made for national developments in demand and sub-national changes in biogeophysical and socio-economic conditions. The model can serve as a way to compare these scenarios with respect to their outcomes and obtain more insight in possible land use dynamics. This approach allows for the identification of hot-spots of special interest in Ecuador, where changes potentially affect the natural resource base through impacts on soils (erosion, declining fertility), water (availability of irrigation water) and nature (loss of biodiversity). Methods that give indications of the sustainability of agro-ecosystems under specific conditions can be used to assess these potential impacts. Though deforestation is not explicitly modelled, areas of special concern because of expanding agricultural land use can be identified.

Parameterisation of the model is relatively simple, because the quantitative relations between land use drivers and land use are directly based on an empirical multiple regression analysis executed for a reference year. These quantitative relations are considered to have validity for the near future, while changes in the actual values of the drivers in the relations (for example population density) are taken into account. Because of this empirical approach, the model is valid for relatively short time spans (15 to 20 years). Full validation of the model is complicated because time series of land use developments at sufficiently high spatial detail are often lacking. For Ecuador, only one year with data of sufficient spatial detail was available. Starting with this reference year, the backward validation results in rather high correlation coefficients, especially considering the complexity of the land use systems. This validation indicates that under known national changes in demand, the patterns of change are well described for this period. Capturing these patterns is the aim of the model, not evaluating the outcome of each individual basis cell. The highest deviations in the backward allocation can be attributed to important structural incentives that have taken place, such as in the province of Los Ríos. For the allocation of possible future changes the situation can be somewhat different, because under conditions of increasing demand the allocation of agricultural land might be increasingly difficult to realise and competition between crops can therefore become more important. It has to be evaluated if all these dynamics fall within the domain of the allocation module. In a previous study of Veldkamp and Fresco (1996b), a validation of an earlier version of the model was performed for Costa Rica, for which 2 sample years were available. This validation lead to the conclusion that the empirical relations describing the factors driving land use were stable over the period 1973-1984.

The data demand for the presented modelling approach is rather high. Most data are taken from biophysical maps with their related databases, and from socio-economic and agricultural censuses. Sufficient spatial detail is necessary and the data should cover the complete study area. Expected future standardisation of the collection and storage of data will greatly facilitate the approach.

The methodology presented can be complementary to other approaches, such as optimisation techniques. Our approach does not intend to come up with an optimal land use configuration or land use plan. Instead, possible land use changes under different conditions are quantified and visualised. The model can be used to explore different possible development scenarios of changing technology levels, national demand and socio-economic and biogeophysical conditions in the near future, with special reference to the impacts on natural resources. Comparison of the outcomes of such model exercises can give valuable information to address issues of sustainable food production.

Chapter 4

Estimates of sub-national nutrient balances as sustainability indicators for agro-ecosystems in Ecuador

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Chapter 4

Estimates of sub-national nutrient balances as sustainability indicators for agro-ecosystems in Ecuador

Abstract

Using a model, inputs and outputs of nitrogen, phosphorus and potassium were calculated for Ecuadorian agro-ecosystems, in order to assess sustainability of different land use types in terms of a soil fertility balance. For 5 by 5 minute cells of a geographical grid covering the Ecuadorian territory, the nutrient balance was calculated on the basis of the separate contributions of the inputs and outputs: mineral fertiliser, organic fertiliser, atmospheric deposition, biological N-fixation, sedimentation, harvested product, removed crop residues, leaching, gaseous losses and erosion. The estimates were aggregated to sub-national and national level.

In general, the estimates show a depletion of the soil nutrient stock in Ecuadorian agro-ecosystems. At a national scale for the land use type temporary crops there is mainly a deficit of nitrogen (42 kg ha^{-1} yr^{-1}), while for permanent crops both nitrogen and potassium balances are clearly negative (40 and 25 kg ha^{-1} yr^{-1}, respectively). For grassland overall, losses are smaller. Erosion is a major cause of nitrogen loss, but leaching and denitrification also contribute significantly. In permanent crops relatively large amounts of potassium leave the agro-ecosystem through harvested products, due to high potassium concentrations in these products and high yields.

At sub-national scale, nutrient depletion under current land use is more severe in the Andean region than the coastal region, mainly as a result of higher erosion losses. In the Andean region, this situation is likely to worsen due to the exploitation of marginal lands under the high pressure on the land. The Amazon region is still largely unexploited but this study suggests that the current conversion of forest to agricultural land, may cause serious nutrient balance problems at a local level.

The presented approach allows the sub-national assessment of soil nutrient balances as sustainability indicator. It appears a useful tool to indicate areas of interest for more detailed follow-up studies. Furthermore it may assist in the exploration of the effects of land use changes.

4.1. Introduction

In recent years, and especially since the 1992 United Nations Conference of Environment and Development, there has been a growing awareness of the need for sustainable development in order to prevent the exhaustion of earth's natural resources in an alarmingly high rate. In agricultural research, this has lead to the need for indicators to assess sustainability of agro-ecosystems systems.

An indicator proposed by Smaling (1993) is the soil nutrient balance, that takes into account inputs and outputs of the main nutrients in the production process. A highly positive balance can result in pollution of ground and surface water, while a negative balance may lead to mining of the soil nutrient stock with subsequent loss of soil fertility, diminishing crop yields and finally the abandoning of previously suitable agricultural land. The main nutrient inputs and outputs that should be quantified when monitoring nutrient balances under agricultural land use are shown in Table 4.1. These were combined into the so-called NUTMON model by Smaling and Fresco (1993).

Table 4.1. Components of a nutrient balance (after Smaling, 1993).

Inputs	Outputs
IN1 mineral fertiliser	OUT1 harvested product
IN2 organic fertiliser	OUT2 removed crop residues
IN3 atmospheric deposition	OUT3 leaching
IN4 biological N-fixation	OUT4 gaseous losses
IN5 sedimentation	OUT5 erosion

This concept was used to assess nutrient flows and budgets for Sub-Saharan Africa at a supra-national scale (Stoorvogel *et al.*, 1993), using the FAO 1:5 million soil map and FAO land/water classes. They concluded that nutrient losses are high in most Sub-Saharan countries and, according to current trends, are likely to exacerbate in the future.

Next to this broad continental approach, the model has been applied to district level. Studies for a well inventorized Kenian district, using data at a much larger scale and replacing estimates being made at the supra-national scale with primary data from inventories, indicated that nutrient depletion was also severe at the district scale (Smaling *et al.*, 1993). Similarly, in a study covering a section of the Atlantic Zone of Costa Rica, Stoorvogel (1993) calibrated the nutrient balance model as used for the Kenian district scale, in order to optimise the distribution of land utilisation towards a minimum of nutrient depletion, using linear programming techniques. The NUTMON approach is now elaborated to include farm level management variables.

However, thus far there has been no effort to use nutrient balances at national level with explicit attention to spatial distribution. The study of Stoorvogel *et al.* (1993) used very broad land water-classes and aggregated national statistics for selected crops.
The study presented here takes the NUTMON approach one step further and calculates regional nutrient balances on the basis of a standard geographical grid with uniformly sized cells in which all data are geo-referenced and linked. For separate land use types and total land use, nutrient balances are assessed per grid cell, and aggregated to different spatial units. Such an approach provides better geo-referencing and thus more scope to explore the effects of changes in land use on nutrient balances. Furthermore, to estimate outcomes at aggregated (sub-national) level calculations are performed at a much lower aggregation level in order to account for spatial variability.
As a test case, Ecuador was selected, a country with a high agro-ecological diversity, that is characterised by an increasing pressure on land use, over-exploitation of natural resources, low productivity and threats to biodiversity (Quiroz *et al.*, 1995).

4.2. Data

4.2.1. Spatial resolution

The basis for the analysis was a geographical grid with a grid cell size of 5 by 5 minutes (approximately 9.25 by 9.25 km), covering the Ecuadorian territory according to the protocol of Rio de Janeiro 1942. A cell was considered an Ecuadorian land cell when at least 50% of its surface existed of Ecuadorian territory excluding sea. The total number of Ecuadorian land cells that was created this way was 2981. The grid approach and the chosen resolution are chosen in order to allow for a link with the dynamic land use change model described in Chapter 3.

4.2.2. Soil data

The 1: 1 million soil map of Ecuador (González *et al.*, 1986) was used. This map has been constructed on basis of detailed soil maps (varying from 1:50.000 to 1:200.000) of the PRONAREG/ORSTOM program of the Ecuadorian Ministry of Agriculture, applying the USDA Soil Taxonomy classification system. On this map 36 great groups are distinguished, which are further subdivided into 62 soil units, on the basis of parent material, climate, physiography, relief, soil texture, and chemical and mineralogical soil properties. The soil units on the soil map were matched with the base grid by assigning to each grid cell the two biggest occurring soil units with their respective surface fractions.

These two soil units were maintained as separate units without averaging their physical and chemical properties.

Soil attribute data required for calculation of the nutrient balance (Table 4.2) were derived from different sources. Texture and slope classes of the 62 soil units were derived directly from the soil map. Texture classes on the soil map correspond with the texture classes from the USDA soil texture triangle. These texture classes were converted to three clay percentage classes. Slope classes vary from (almost) plane (less than 2%), undulating (2 to 8%), substantially undulating (8 to 16%), hilly (16 to 30%), to steeply dissected mountainous (more than 30%) (González *et al.*, 1986).

Table 4.2. Attributes of soil units, their specification and information source as used in the model.

Soil attribute	Specification	Source
texture	clay % classes: 1) < 35%; 2) 35 - 55%; 3) > 55%	soil map
slope	slope % classes: 1) <2%; 2) 2-8%; 3) 8-16%; 4)16-30%; 5) >30%	soil map
total N	g/100 g	reference profiles
exchangeable K	mmol/100 g	reference profiles
bulk density	g/cm^3	reference profiles
pH		reference profiles
erodibility	erodibility classes: 1) low; 2) medium; 3) high; 4) very high	literature

In order to assign chemical soil attributes (total N, exchangeable K, bulk density and pH), the soil units were re-classified into 16 groups, on basis of parent material, climate and clay mineralogy using soil descriptions of Beinroth *et al.* (1985). For these 16 groups, soil attribute data were determined on basis of descriptions of 139 reference soil profiles for Ecuador. Furthermore erodibility classes were established for each soil unit, as will be explained later.

4.2.3 Climate data

Climate data were derived from the 1:1 million bio-climatic map of Cañadas (1983). He distinguished 29 climate zones, on basis of altitude/temperature and yearly total precipitation.

This zonation, together with the estimated areas of the zones, is given in Table 4.3. The climate zones on the map were matched with the base grid by assigning to each grid cell the two dominant climate zones with their respective surface fractions. Similar to the assignment of the soil units, the two dominant climate units were maintained as separate units without averaging.

Table 4.3. Climatic zonation of Ecuador (after Cañadas, 1983). Temperature is the average day temperature. *Páramo: alpine natural grasslands.

Climatic zone	Estimated area (1000 ha)	Altitude (m.a.s.l.)	Temperature (°C)	Rainfall (mm yr^{-1})
desertical tropical	187	0 - 300	23 - 26	< 200
sub-desertical tropical	980	0 - 300	23 - 26	200 - 500
very dry tropical	1368	0 - 300	23 - 26	500 - 1000
dry tropical	1104	0 - 300	23 - 26	1000 - 1500
sub-humid tropical	912	0 - 300	23 - 26	1500 - 2000
humid tropical	6738	0 - 300	23 - 26	2000 - 3000
very humid tropical	1848	0 - 300	23 - 26	> 3000
very dry sub-tropical	491	300 - 1800	18 - 23	200 - 500
dry sub-tropical	1014	300 - 1800	18 - 23	500 - 1000
sub-humid sub-tropical	943	300 - 1800	18 - 23	1000 - 1500
humid sub-tropical	1004	300 - 1800	18 - 23	1500 - 2000
very humid sub-tropical	2001	300 - 1800	18 - 23	2000 - 3000
rainy sub-tropical	1580	300 - 1800	18 - 23	> 3000
dry temperate	117	1800 - 3000	12 - 18	200 - 500
sub-humid temperate	814	1800 - 3000	12 - 18	500 - 1000
humid temperate	881	1800 - 3000	12 - 18	1000 - 1500
very humid temperate	488	1800 - 3000	12 - 18	1500 - 2000
rainy temperate	490	1800 - 3000	12 - 18	2000 - 3000
very rainy temperate	66	1800 - 3000	12 - 18	> 3000
sub-humid sub-temperate	110	3000 - 4000	6 - 12	200 - 500
humid sub-temperate	975	3000 - 4000	6 - 12	500 - 1000
very humid sub-temperate	835	3000 - 4000	6 - 12	1000 - 1500
rainy sub-temperate	263	3000 - 4000	6 - 12	1500 - 2000
very rainy sub-temperate	100	3000 - 4000	6 - 12	2000 - 3000
pluvial sub-temperate	5	3000 - 4000	6 - 12	> 3000
humid páramo *	26	4000 - 5000	3 - 6	200 - 500
very humid páramo *	208	4000 - 5000	3 - 6	500 - 1000
rainy páramo *	161	4000 - 5000	3 - 6	1000 - 1500
very rainy páramo *	52	4000 - 5000	3 - 6	> 1500

4.2.4. Land use/cover data

In Ecuador, yearly agricultural statistics are collected by means of stratified sampling by the National System for Agricultural Statistics (SEAN). SEAN data for 1991 (INEC, 1991) were used, containing information on 65415 farmers in 3137 sample sites. Data of sample sites were related to grid cells, thus constructing a land use map. When more than one sample site was found within a grid cell, data of these sites were averaged. The data can be categorised in general land use types, individual crops and animal husbandry. Table 4.4 shows the items in each category and the data available.

Table 4.4. SEAN-91 Land use items and data. * Páramo: alpine natural grasslands.

	Land use types	Individual crops		Animal husbandry
Items	temporary crops	Temporary:	Permanent:	cattle
	permanent crops	rice	banana	sheep
	cultivated grassland	barley	plantain	goats
	natural grassland	maize	cocoa	horses
	páramo *	wheat	coffee	donkeys
	short fallow (< 1 year)	potato	sugar cane	mules
	long fallow (1-5 years)	bean		pigs
	mountains/forests	broad bean		
	other land use	soybean		
Data	area	area sown		number of heads
		yield		
		area with organic fertiliser		
		area with mineral fertiliser		
		area with organic and mineral fertiliser		
		area irrigated		

Ecuador can broadly be divided in the administrative regions Coast, Andes and Amazon (Figure. 2.2). A summary of land use for these adminstrative regions Coast, Andes and Amazon is given in Table 4.5 (INEC, 1991). The area of agricultural land as percentage of total land in 1991 was 59 % in the coast, 46 % in the Andes and 8 % in the Amazon

Table 4.5. SEAN-91 land use data: area (x 1000 ha) of different land use types (calculated from INEC, 1991).

land use type	Coast	Andes	Amazon
temporary crops + short fallow	686	667	46
permanent crops	874	348	129
total grassland	2227	1838	854
long fallow (1-5 years)	128	102	17
non-agricultural land	2726	3440	11997
total land	6641	6394	13042

4.3. The nutrient balance model

4.3.1. Calculation of the nutrient balance

All model calculations were executed per grid cell, the smallest spatial unit. Only the three most important nutrients were considered: nitrogen (N), phosphorus (P) and potassium (K). Per cell the individual inputs and outputs of the nutrient balance were estimated for the land use types temporary crops (including the area short fallow), permanent crops, cultivated and natural grassland, and páramo. For the land use types temporary and permanent crops, specific inputs and outputs (IN1, IN2, IN4, IN5, OUT1, OUT2, OUT4 and OUT5) were assessed for the individual crops and attributed to the total area of temporary and permanent crops. Deposition (IN3) and leaching (OUT3) were directly attributed to the total area of temporary and permanent crops.

It was assumed that organic manure is not entering or leaving a grid cell. However, within a cell nutrients in organic manure do flow from one land use type to another.

For the land use types long fallow, mountains and forest, the inputs and outputs were not assessed separately, but a balanced system was assumed. Other land use was not taken into account.

4.3.2. Model inputs and outputs

The model will be described on basis of the separate inputs and outputs listed in Table 4.1.

IN1 : mineral fertiliser

All mineral fertilisers used in Ecuador are imported. In 1991 total fertiliser imports amounted to 45000 tonnes N, 16815 tonnes P_2O_5 and 24100 tonnes K_2O (FAO, 1995). On basis of these total importations for 1991 and the fertilised area per crop in 1991 (SEAN-91 data) the nutrient application rates as estimated by Hammond and Hill (1984) were corrected to obtain the Ecuadorian 1991 application rates for the fertilised area of each crop.

IN2: organic fertiliser

Within each cell cattle was allocated to cultivated grassland up to a maximum stocking rate of 2.5 animals ha^{-1}. Remaining cattle was supposed to graze on natural grassland up to 1.5 animal ha^{-1}. Sheep and goats were allocated to natural grassland and páramo, with maximum stocking rates of 4 animals ha^{-1}. Cattle, sheep and goat manure was assumed to be collected at night, when animals are gathered in stables. Amounts of nutrients in collected manure are calculated using average grazing hours, dry matter intake, digestibility of herbage, and nutrient concentrations of manure from literature (Knapp, 1991; Landon, 1991). This amount of nutrients was evenly applied to the area of temporary and permanent crops fertilised with organic manure, taking into account a physical limit to manure application of 5 ton ha^{-1} fresh weight.

Horses, donkeys, mules and pigs graze near the farm house on crop residues, and their manure production was not taken into account, assuming that the nutrients consumed remain in the same land use type, with minor losses.

Nutrients in supplementary feedstuffs like soybean meal and cotton seed cake for cattle were regarded as organic manure on grassland (after removal of part of the manure as organic fertiliser, calculated in OUT1)

IN3: Atmospheric deposition

No specific data were available on wet and dry deposition for Ecuador. Therefore, the equations of Stoorvogel *et al.* (1993) were used, relating deposition with the square root of average annual rainfall. For the different Ecuadorian rainfall classes calculated depositions are given in Table 4.6.

Table 4.6. Estimated deposition of N, P and K (kg ha^{-1} yr^{-1}) per rainfall class (mm yr^{-1}). After: Stoorvogel *et al.* (1993).

Rainfall class	N	P	K
< 200	1.4	0.2	0.9
200 - 500	2.6	0.4	1.7
500 - 1000	3.8	0.6	2.5
1000 - 1500	5.0	0.8	3.3
1500 - 2000	5.9	1.0	3.9
2000 - 3000	7.0	1.2	4.6
> 3000	8.6	1.4	5.7

IN4: biological N-fixation

Smaling *et al.* (1993) have estimated that symbiotic N-fixation by leguminous crops can supply up to 75% of their nitrogen demand. In Ecuador, P-availability in soils is generally low, which limits N-fixation. The supply percentage was set at 50%. On basis of this percentage, symbiotic N-fixation of bean, soybean and broad bean was calculated, taking into account the harvested areas and yields of these crops.

For non-symbiotic N-fixation by *Azotobacter*, *Beyerinckia* and *Clostridium spp*, a small rainfall dependent contribution (3, 4 and 5 kg ha^{-1} yr^{-1} for the rainfall classes < 500 mm, 500-1000 mm, and > 1000 mm, respectively) was taken into account, as derived from Stoorvogel *et al.* (1993).

Chemo-autotrophic N-fixation (*Azolla* and other algae) was assumed to supply up to a maximum of 30 kg ha^{-1} yr^{-1} in wetland rice.

IN5: sedimentation

Sediment input through irrigation water for irrigated land was calculated from the 1:1,000,000 map with average annual hydrological deficits (average annual hydrological deficit calculated from monthly differences between precipitation and potential evapotranspiration) determined by Peralta *et al.* (1978), and average sediment loads of irrigation water on the basis of data from INECEL (1992). Nutrient concentrations in the sediment were assumed to be equal to the average nutrient concentrations in the top 20 cm of the soils in the grid cell. Sedimentation was calculated for the irrigated surface given by SEAN-91.

OUT1: harvested product; OUT2: removed crop residues

Nutrient losses through removal of harvested crop products were calculated from the SEAN-91 data on harvested area and yields, using crop specific data on nutrient concentrations. Most crop residues remain on the field, where they decompose or are grazed on by pigs and mules. Only the straw of cereals was supposed to leave the system through external use.

OUT3: leaching

Leaching of phosphorous was not taken into account because of its minor importance in Ecuadorian soils.

Leaching of nitrogen and potassium was determined with transfer functions from Smaling *et al.* (1993). With these functions nitrogen leaching is calculated as percentage of total mineral soil-N and crop dependent fertiliser-N. Potassium leaching is calculated as percentage of exchangeable K and crop dependent fertiliser-K. The percentage leaching is calculated separately for nitrogen and potassium, and for each texture class, using regression equations where rainfall is the independent variable. Total mineral soil N was calculated for the 0-20 cm soil layer, from total soil N, bulk density and a fixed, annual temperature dependent, mineralization rate.

OUT4: gaseous losses

Denitrification of nitrogen was calculated on basis transfer functions of Stoorvogel *et al.* (1993). A rainfall dependent base denitrification was estimated, that amounts to up to 8 kg ha^{-1} yr^{-1} under the wettest climatic conditions. Additional denitrification was calculated through multiple regression using inherent soil fertility, mineral fertiliser and organic fertiliser as the independent variables.

OUT5: erosion

To estimate soil and nutrient loss by erosion a semi-quantitative approach was used, taking into account rainfall intensity, land use, slope angle and soil type. For each of these factors a

rating of 0 (no erosion risk) to 1 (maximum erosion risk) was given on basis of various literature sources. Multiplication of these factors resulted in the total erosion risk.
Rain intensity ratings ranging from 0.5 to 1 were derived from a rain intensity map (De Noni and Trujillo, 1986) reflecting the maximum rainfall during 30 minutes that is expected to occur once every two years. Land use ratings of 1 for bare land, 0.55 for temporary crops, 0.25 for permanent crops and 0.05 for grassland were used, on basis of data from INECEL (1992). Slope ratings were, for a standard slope length, derived from Wischmeier and Smith (1978). Finally soil type specific erodibility ratings were established by grouping the soil units in erodibility rating classes of low, moderate, high and very high erodibility using literature (Restrepo *et al.*, 1993; Custode and Viennot, 1986; González *et al.*, 1986; FAO, 1979)
The maximum soil loss was established on basis of literature on soil loss measurements on Wischmeier plots by Dehn (1995), De Noni *et al.* (1986), Harden (1988, 1991, 1993) and additional unpublished data. The average maximum soil loss for bare land at field level was estimated at 150 ton ha^{-1} yr^{-1}.
Finally, nutrient loss due to erosion per land use type within a grid, was calculated by multiplying the erosion total risk factor, maximum soil loss, and N and K concentrations in the soil material. As the finest nutrient rich soil particles are eroded most easy, eroded soil has higher nutrients contents than the average top-soil. This was being accounted for by an enrichment factor of 1.5, based on Stoorvogel (1993). Of this amount of nutrients lost, 80% is assumed to actually enter the water streams, and leave grid cells (INECEL, 1992).
As data on soil P were not available for Ecuador, it was not possible to calculate P loss by erosion.

4.4. Results

The separate inputs and outputs of the nutrient balance for the land use types temporary crops, permanent crops and permanent grassland at a national scale are given in Figures 4.1, 4.2 and 4.3.
The contribution of erosion (OUT5) to the total balance of nitrogen is to be noted, especially for temporary crops and permanent crops. This finding is strongly related to the land use ratings in the erosion assessment. Also, leaching (OUT3) and gaseous losses (OUT4) contribute significantly to total N output. The output of N through harvested product (OUT1) as well as the mineral fertiliser input is for temporary crops very similar to that of permanent crops, but in temporary crops organic fertiliser (IN2) is more important.

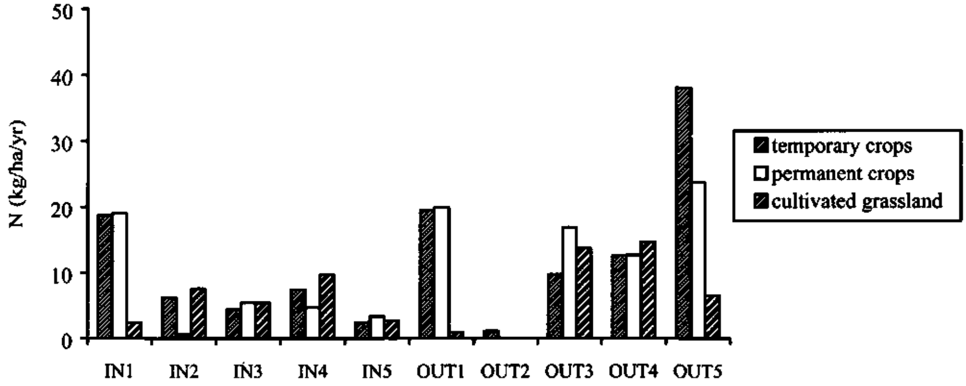

Figure 4.1. Average inputs and outputs of N for land use types at a national scale.

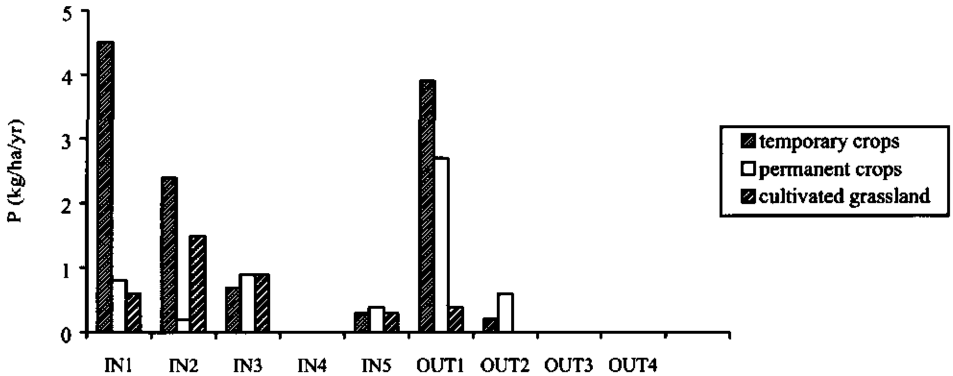

Figure 4.2. Average inputs and outputs of P for land use types at a national scale.

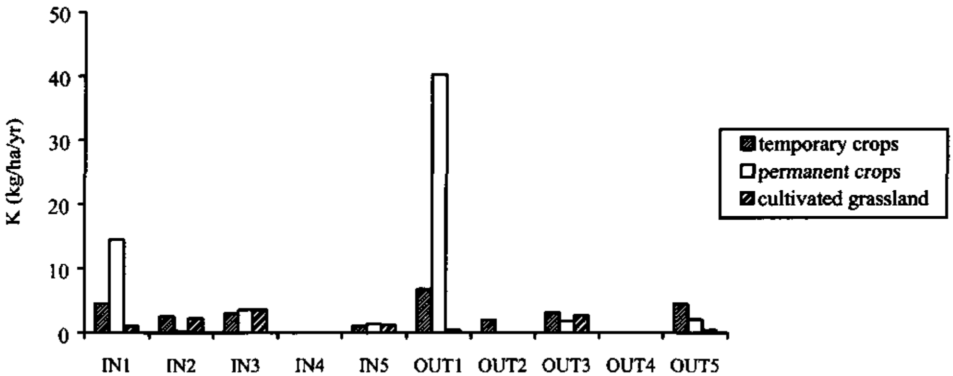

Figure 4.3. Average inputs and outputs of K for land use types at a national scale.

As P loss by erosion was not calculated, the total P balance was not assessed. However, individual inputs and outputs are presented, in order to make comparison between the land use types temporary crops, permanent crops and cultivated grassland possible. Both mineral and organic P fertiliser inputs are notably higher for temporary crops than for permanent crops. Output of P through harvest crop product and residues is slightly higher in temporary crops.

As a combined result of high K concentrations in permanent crops and intensive cultivation systems, K removal in harvested product (OUT1) is relatively high for the land use type permanent crops and is the main output of the balance. Due to lower K concentrations in the soil, losses of K through leaching and erosion are much lower than losses of N.

National nitrogen and potassium balances were obtained by averaging inputs and outputs calculated per grid cell for the land use types temporary crops, permanent crops and cultivated grassland. Furthermore these balances were calculated for total land use, taking into account the fractions of the land use types temporary crops, permanent crops, cultivated grassland, natural grassland, páramo, fallow, and mountains and forests (Table 4.7). With the exception of potassium in cultivated grassland, negative total balances were found indicating a depletion of the soil nutrient stock.

Table 4.7. Total national nitrogen and potassium balance (kg ha^{-1} yr^{-1}) for different land use types and total land.

Land use type	Nitrogen	Potassium
temporary crops	-42	-5
permanent crops	-40	-25
cultivated grassland	-8	+4
natural grassland	-10	-2
total land	-8	-2

Tables 4.8, 4.9 and 4.10 present inputs, outputs and total nutrient balances for separate land use types and total land use in the 3 regions Coast, Andes and Amazon. The proportion of agricultural land to total area (Table 4.5) explains why nitrogen and potassium balances for total land use in the Amazon are close to zero, though nitrogen balances for separate land use types, and the potassium balance for permanent crops is strongly negative.

The data in Table 4.8 indicate that the nitrogen balance for total land is most negative in the Andes. Erosion is an important component of the nitrogen balance, especially for temporary and permanent crops. In the Andes erosion losses are higher then in the coast, but erosion risk is highest in the Amazon region. This is mainly caused by agriculture on the low Eastern footslopes of the Andes where steep slopes, susceptible soils and high rainfall intensity cause unfavourable conditions. Leaching of nitrogen is for most

Table 4.8. Nitrogen inputs and outputs and total balance (kg ha^{-1} yr^{-1}) for different land use types and total land, in three regions. The meaning of in1-out5 is explained in Table 4.1. The number of grid cells is for each land use type indicated with *n*.

Region	Land use type	*n*	in1	in2	in3	in4	in5	out1	out2	out3	out4	out5	balance
Coast	temporary crops	544	25.5	0.3	4.9	11.2	3.7	29.6	1.5	11.2	11.2	19.8	-27.7
	permanent crops	535	21.9	0.3	5.4	4.7	3.3	15.5	0.0	15.9	13.3	20.0	-29.1
	cultivated grassland	554	2.4	8.0	5.2	9.7	3.4	0.3	0.0	10.5	14.5	5.9	-2.5
	natural grassland	297	0.0	0.0	4.1	9.1	0.0	0.1	0.0	4.2	7.4	1.9	-0.4
	total land												-9.9
Andes	temporary crops	550	12.8	11.5	4.2	4.3	1.5	10.8	0.8	8.8	13.7	53.4	-53.2
	permanent crops	385	11.8	1.3	5.9	4.7	3.1	31.4	0.2	23.1	11.3	30.4	-69.6
	cultivated grassland	485	2.4	7.7	5.9	9.7	1.4	2.8	0.0	20.6	15.3	6.7	-18.3
	natural grassland	472	0.0	0.0	4.3	9.4	0.0	4.6	0.0	7.0	8.0	6.8	-12.7
	páramo	259	0.0	0.0	4.5	9.4	0.0	1.2	0.0	5.1	10.1	8.0	-10.5
	total land												-20.1
Amazon	temporary crops	126	0.5	0.3	6.9	5.0	0.0	10.8	0.0	20.1	11.8	112.4	-142.4
	permanent crops	138	0.8	0.8	7.2	5.0	0.0	24.9	0.0	21.3	10.7	38.5	-81.6
	cultivated grassland	144	2.4	2.2	6.9	10.0	0.3	0.1	0.0	20.1	13.9	10.9	-23.3
	natural grassland	16	0.0	0.0	6.4	10.0	0.0	0.0	0.0	12.7	11.8	4.7	-12.8
	total land												-0.6

Table 4.9. Phosphorous inputs and outputs (kg ha^{-1} yr^{-1}) for different land use types in three regions. The meaning of in1-out5 is explained in Table 4.1. The number of grid cells is for each land use type indicated with *n*.

Region	Land use type	*n*	in1	in2	in3	in4	in5	out1	out2	out3	out4	out5
Coast	temporary crops	554	3.9	0.1	0.8	0.0	0.5	5.7	0.3	0.0	0.0	-
	permanent crops	535	0.8	0.1	0.9	0.0	0.4	1.9	0.2	0.0	0.0	-
	cultivated grassland	554	0.6	1.6	0.9	0.0	0.4	0.1	0.0	0.0	0.0	-
	natural grassland	297	0.0	0.0	0.6	0.0	0.0	0.1	0.0	0.0	0.0	-
Andes	temporary crops	550	5.0	4.5	0.7	0.0	0.2	2.3	0.2	0.0	0.0	-
	permanent crops	385	0.9	0.5	1.0	0.0	0.4	4.8	1.7	0.0	0.0	-
	cultivated grassland	485	0.6	1.5	1.0	0.0	0.2	1.1	0.0	0.0	0.0	-
	natural grassland	472	0.7	0.0	0.7	0.0	0.0	2.4	0.0	0.0	0.0	-
	páramo	259	0.0	0.0	0.7	0.0	0.0	0.9	0.0	0.0	0.0	-
Amazon	temporary crops	126	0.2	0.1	1.2	0.0	0.0	3.1	0.0	0.0	0.0	-
	permanent crops	138	0.1	0.3	1.2	0.0	0.0	3.4	0.1	0.0	0.0	-
	cultivated grassland	144	0.6	0.4	1.2	0.0	0.0	0.1	0.0	0.0	0.0	-
	natural grassland	16	0.0	0.0	1.1	0.0	0.0	0.0	0.0	0.0	0.0	-

Table 4.10. Potassium inputs and outputs and total balance (kg ha^{-1} yr^{-1}) for different land use types and total land, in three regions. The meaning of in1-out5 is explained in Table 4.1. The number of grid cells is for each land use type indicated with *n*.

Region	Land use type	*n*	in1	in2	in3	in4	in5	out1	out2	out3	out4	out5	balance
Coast	temporary crops	544	5.5	0.1	3.2	0.0	1.6	8.2	2.1	3.8	0.0	2.6	-6.3
	permanent crops	535	16.9	0.2	3.6	0.0	1.4	36.3	0.0	2.0	0.0	1.9	-18.1
	cultivated grassland	554	1.0	2.4	3.4	0.0	1.5	0.1	0.0	2.8	0.0	0.6	4.8
	natural grassland	297	0.0	0.0	2.7	0.0	0.0	0.1	0.0	2.3	0.0	0.2	0.1
	total land												-2.4
Andes	temporary crops	550	3.7	4.8	2.8	0.0	0.6	5.6	2.0	2.5	0.0	6.2	-4.3
	permanent crops	385	8.2	0.6	3.9	0.0	1.3	49.6	0.2	1.5	0.0	2.7	-40.0
	cultivated grassland	485	1.0	2.3	3.9	0.0	0.6	1.3	0.0	2.8	0.0	0.5	3.9
	natural grassland	472	0.0	0.0	2.8	0.0	0.0	2.7	0.0	2.2	0.0	0.6	-2.7
	páramo	259	0.0	0	2.9	0.0	0	3.2	0	2.4	0.0	0.4	-3.2
	total land												-3.3
Amazon	temporary crops	126	0.1	0.2	4.5	0.0	0.0	2.9	0.1	0.9	0.0	2.2	-1.2
	permanent crops	138	0.4	0.4	4.7	0.0	0.0	43.3	0.0	0.5	0.0	0.8	-39.1
	cultivated grassland	144	1.0	0.7	4.5	0.0	0.1	0.1	0.0	0.9	0.0	0.2	5.1
	natural grassland	16	0.0	0.0	4.2	0.0	0.0	0.0	0.0	0.7	0.0	0.1	3.4
	total land												0.0

land use types highest in the Andes, reflecting the characteristics of soil types in this region. In the coastal region relatively more mineral fertiliser is used than in the Andes, above all the result of high application rates in banana plantations and rice. The importance of organic manure in the Andes compared to the Coast and the Amazon is remarkable. In the Andes relatively more grazing cattle, sheep and goats are present, and a higher percentage of (mainly temporary) crops is fertilised with organic manure. Under the assumption of the collection of part of the animal manure, this leads to relative high inputs of organic nitrogen, phosphorus and potassium, particularly for temporary crops, at the expense of cultivated and natural grassland and páramo. Furthermore, gaseous losses constitute significantly to the loss of nitrogen in all three regions.

In the potassium balance, the output through harvested products of permanent crops is high, due to high potassium concentrations and high yields of especially banana and to a lesser extent plantain. It seems that especially for permanent crops, fertiliser application is not sufficient to supply the amount of nutrients that is taken up by the crop.

4.5. Discussion and conclusions

The NUTMON model suggests that, overall, Ecuadorian land use systems display a net depletion of nutrients. The actual degree of depletion depends on the combination of land use, soils, rainfall, fertiliser application, crop yields and animal husbandry.

Current fertiliser application rates appear generally hardly sufficient to supply the nutrients that leave the production system through harvested products and do not compensate additional nutrient losses.

Erosion is an important factor in a negative nutrient balance as it was also in the previous studies by Stoorvogel *et al.* (1993) and Smaling *et al.* (1993). This is in line with Quiroz *et al.* (1995) who used the EPIC model to estimate soil loss through erosion in Peru. They state that "current management of most cultivable land in the Andes threatens the sustainability of the agricultural systems and thus jeopardises the future of the region's inhabitants, because of excessive soil erosion". Our results suggest that not only in the Andes, but also in the coastal zone and the Amazon, serious threats occur due to erosion and leaching. However, in the Amazon this does not yet lead to problems at the regional scale due to the spatial predominance of undisturbed forest. Intensive logging and introduction of agriculture leads to local impoverishment of soils.

In Ecuador, population growth has caused high pressure on the land. This leads to shorter fallow periods and the conversion of non-agricultural land into land for agricultural crops and grassland, often in marginal areas (Southgate and Whitaker, 1994), resulting in stronger nutrient depletion.

In this study the yearly rates of changing nutrient stock are assessed, based on the 1991 land use data. It is obvious that a negative balance does not necessarily lead to problems in the short term. On some deep volcanic soils of the Andes even soil losses of 100 ton ha^{-1} yr^{-1} do not cause immediate problems. However, if after several years of soil losses the infertile subsoil (often with poor hydraulic properties) is reached, the process is irreversible on a human time scale. The strength of the nutrient balance approach lies in its use as a sustainability indicator that is regularly monitored.

Further improvement of the assessment of soil nutrient balances requires a reduction of data uncertainty. Specific data needs for the Ecuadorian situation first of all relate to erosion, which is a key factor. More information on soil loss under different conditions of land use, soils and climate is desirable. Simultaneous studies at field and watershed level will contribute to better estimates of the amount of soil and nutrients lost at field level, that actually enter the river systems. Some of this material is redistributed to lower areas and is therefore not a loss at national level. Furthermore more detailed data on the spatial variability in fertiliser application rates is desirable. The role of the fallow in nutrient

replenishment also needs further consideration, as it has hitherto been treated as a balanced system ignoring grazing of fallow land. The positive contribution of the fallow depends on climate and altitude as well as soils.
The grid approach proved to be suitable for linking input data and performing calculations at a spatial aggregation level that is related to the detail of the input data. By treating different land use types separately, effects of changing land use can be explored. This is especially interesting when the monitoring of nutrient balances will be linked with models that explore possible land use changes under influence of changing land use drivers such as technical improvements, population growth and market changes.
Moving between different hierarchical spatial levels allows the detection of broad zones that seem interesting with regards to sustainability issues. Zooming in to these zones is possible to a level where still enough spatial units (grid cells) contain relevant data. For further detail in areas of interest, a combination with field studies that investigate the relation between land use and nutrient flows at the level of small watersheds is recommendable. An example of such a study has been presented by De Ridder *et al.* (1996) for West Africa.
We conclude that the monitoring of nutrient regional balances seems to be a useful tool for the support of research and policy measures aiming at sustainable developments in (changing) agricultural land use. In Ecuador, recommendations with respect to erosion control and fertiliser policy are corroborated by this study.

Chapter 5

Exploring changes in Ecuadorian land use for food production and their effects on natural resources

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Chapter 5

Exploring changes in Ecuadorian land use for food production and their effects on natural resources

Abstract

A model was used for the dynamic and spatially explicit exploration of near future agricultural land use changes. In a case study for Ecuador, different plausible scenarios were formulated, taking into account possible developments in national food demand until the year 2010. The protection of nature parks and restrictions due to land degradation were evaluated with respect to their possible spatial impacts on the land use change dynamics within the country. Under the assumptions of the demand scenarios, agricultural land use expanded significantly, resulting in more use of land in existing agricultural areas and frontier-type expansion into rather undisturbed natural areas. The patterns of change depended on the increase in demand, competition between land use types, changes in drivers of land use, and the area and characteristics of land that was excluded from agricultural use. The modelled land use dynamics were being related to their possible impacts on the natural resource base, specifically soil fertility. The results indicated potential negative effects of land use changes on the soil nutrient balance and biodiversity. It is argued that quantification of land use dynamics at the landscape level can support research and policy aimed at understanding the drivers of land use change and the behaviour of complex agro-ecosystems under changing conditions at different spatial scales. This way, issues dealing with sustainable food production and the management of the natural resource base can be addressed in a more integrated and quantitative manner.

5.1. Introduction

Human induced land use change is an important factor in environmental change because of its impacts on biogeochemical cycles, sustainability and biodiversity (Turner II *et al.*, 1995). This has stimulated research aiming at understanding the dynamics of land use change through modelling Reviews of modelling approaches have among others been given by Kaimowitz and Angelsen (1998), Lambin (1994), Riebsame *et al.* (1994a) and Sklar and Costanza (1991).

In this chapter a case study for Ecuador is presented. The objective of this study is to explore possible future land use changes and their effects on natural resources in a spatially explicit and dynamic way. Plausible scenarios, taking into account different national developments in food demand and changing sub-national conditions for food production, are compared with respect to their outcome for the dynamics of the agro-ecological landscape. These dynamics are evaluated concerning their possible impacts on the natural resource base, especially soil fertility.

For the multi-scale modelling of Ecuadorian land use change the CLUE (Conversion of Land Use and its Effects) model was used (see Chapter 3). This model is an adapted version of the model developed by Veldkamp and Fresco (1996b, 1997b) for Costa Rica.

Ecuador is endowed with a high diversity in biophysical resources. Its location on the equator and strong vertical gradients in the Andean mountains, make that climatic conditions range from tropical to alpine (Parsons, 1982). Precipitation regimes vary from desert-like in the south-western arid coastal plains to very humid in the tropical rainforest in the northern coastal area and the Amazon (Southgate, 1990). The climatic diversity makes that within Ecuador 25 Holdridge lifezones can be found (Cañadas, 1983). Soils can broadly be grouped into alluvial soils, soils over volcanic ejects and soils over ancient materials. They vary widely in their chemical and physical properties (Beinroth *et al.*, 1985; González *et al.*, 1986).

Land use in Ecuador in the last decades has been dynamic as the result of population growth, changing consumption patterns, internal migration, land reforms and increasing export of agricultural commodities (Commander and Peek, 1986; Larrea, 1992; Zevallos, 1989; Southgate, 1990). Stagnating productivity per hectare has lead to expansion of the total agricultural land area, causing pressure on the natural resource base (Southgate and Whitaker, 1992, 1994). Soil degradation threatens the sustainability of agricultural production (Harden, 1991) while the conversion of natural vegetation into agricultural land endangers biodiversity (Myers, 1988; Sarmiento, 1997).

5.2. Methodology

The CLUE model was used to describe and analyse land use change dynamics. It can be classified as a dynamic, spatially explicit model, based on empirical analysis of land use. The model uses time steps of one year, and consists of a demand module and allocation module. In the demand module the national demands for agricultural products are calculated. Yearly changes in national demands drive sub-national land use changes, assuming that total land use meets the demand. Sub-national changes are modelled in the allocation module for cells of 9.25 by 9.25 kilometres. These cells are not treated as homogenous units, but within cells the relative surface fractions of each of the studied land use types are distinguished. Land use changes in the cells are calculated on the basis of the factors within cells that determine land use, the so-called land use drivers (Turner II *et al.*, 1995). These are biogeophysical factors (e.g. physical and chemical soil characteristics, climate characteristics, slope), socio-economic factors (e.g. demography, income levels, occupation) and infrastructural factors (e.g. distance to roads and markets). Before using the model, the quantitative relations between land use drivers and the relative areas of different land use types within cells are determined on the basis of a multiple regression analysis. This analysis is done for a reference year, using a complete data set with detailed actual land use data, taken from a national agricultural census. The results of the analysis are used in the allocation module. For scenarios of changing national demands and changing local conditions driving land use, land use changes in each cell are modelled in the allocation module (Verburg *et al.*, 1999) on the basis of:

- the comparative advantage within a cell for a certain land use type compared to all other cells within the country.
- the comparative advantage of a certain land use type within a cell compared to the other land use types within that same cell.

Increasing national demand for areas of certain land use types will generally lead to an increase of their area within selected cells. However, also area decrease can take place due to competition effects between land use types, or due to adverse local conditions. Yearly, spatially explicit changes in the drivers of land use are taken into account.

The CLUE model describes multi-scale land use change dynamics under certain assumptions of possible future developments, defined as scenarios. Therefore "what if" situations are described. Results of CLUE are not meant to be predictions, but possible spatial outcomes of feasible land-use developments. This offers information that can be used to evaluate the range of possible outcomes for land use changes and their effects on the natural resource base.

For Ecuador the reference year 1991 was used to quantitatively determine the drivers for the land use types permanent crops, temporary crops (annuals), grassland and natural vegetation (see Chapter 2). These land use types were chosen because of their distinctive characteristics (life cycle, purpose, and biophysical and socio-economic setting). An extensive description of the operational model for the Ecuadorian situation was given in Chapter 3, together with its partial validation for the period 1974 -1991. In this chapter the model will be applied for different scenarios for the period 1991 until the year 2010.

5.3. Scenario formulation

A wide range of aspects can be taken into account when evaluating possible future developments in land use in Ecuador. On basis of current developments and issues considered important for the debate on the relation between agricultural land use and natural resources, four aspects were examined in more detail. At *national* level, different agricultural demands were determined on the basis of developments in consumption patterns and total export volumes. At *sub-national* level, restrictions related to land degradation and nature protection were taken into account. For the scenarios used in this study, different combinations of developments in national demands and sub-national restrictions where formulated.

For all scenarios the same population growth projection was used. This projection was based on the projections until 2000 at canton level published by INEC (1993). The rates of change at canton level were extrapolated until the year 2010. The total projected population was 10.5 million for the year 1991 and 14.6 million for the year 2010. The rates of change at canton level were also applied to the parishes within the cantons, this way constructing detailed population maps for each year at cell level. These estimated changes in local population densities were used in the allocation module because population density is among the drivers of local land use.

5.3.1. Changes in national demand

Consumption patterns

The national domestic consumption volume is determined by the size of the population and the food consumption per capita. Food consumption patterns have undergone major changes over the last two decades. In Figure 5.1, the total per capita intake of vegetable products and animal products, expressed as kcal/day are given for Ecuador for the period 1974-1995 (source: FAO, 1998). Also data for Colombia and Brazil are given, two countries that had comparable per capita intakes of animal products in 1974 but with faster increasing intakes over the period 1974-1995.

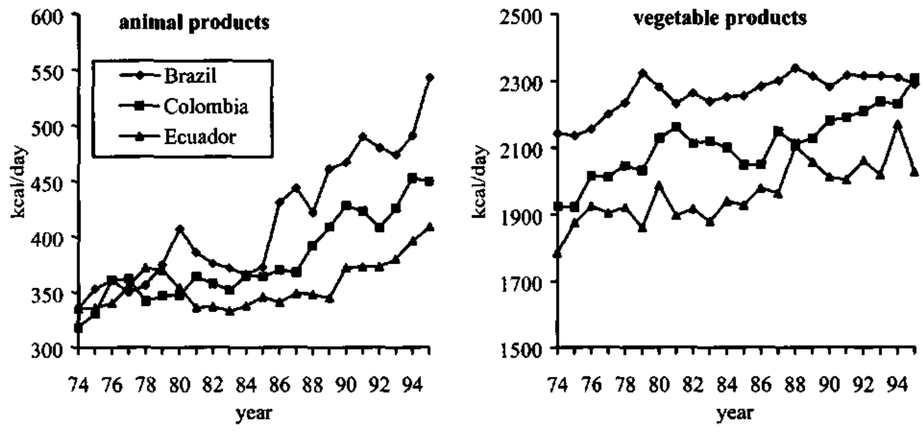

Figure 5.1. Per capita consumption of vegetable and animal products (kcal/day) in the period 1974-1995 for Ecuador, Brazil and Colombia (source: FAO, 1998). Vegetable products are all products originating from plants (not to be confused with vegetables).

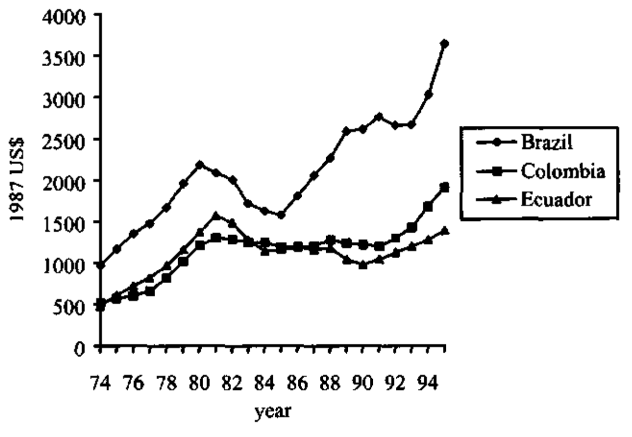

Figure 5.2. Per capita GNP (in 1987 US$) in the period 1974-1995 for Ecuador, Brazil and Colombia (source: World Bank, 1998).

For all three countries a general pattern of increasing intakes can be observed. For animal products this increase has been especially strong since the end of the eighties. Per capita consumption of animal products is highest in Brazil. For this country, the per capita intake of animal products shows the strongest relation with the per capita Gross National Product (GNP) (Figure 5.2), with a correlation coefficient of 0.89. For all countries the macro-economic crisis of the beginning of the eighties seems to have influenced consumption. However, over the whole period, for Ecuador the relation with GNP is not as clear as for Brazil. In Ecuador, the consumption of animal products in the 90's was higher than consumption in the 70's with comparable GNP's. This can be due to economic factors such as relative purchasing power, income distribution, relative prices of food products, and price and income elasticities. Furthermore, consumption patterns could have changed due to cultural factors, for example related to an increasing urban population. Data for a complete analysis of these separate factors are lacking.

The consumption of vegetable products does not show a strong relation with per capita GNP. In Brazil the consumption of vegetable products appears to have reached a plateau at 2300 kcal/day, while in Colombia recently the same intake was realised. In Ecuador intake has been rising, the correlation coefficient between time and intake equals 0.68. However, the intake still lags clearly behind that of Colombia. On the basis of these figures it seems realistic to assume that further increase of per capita consumption of both vegetable and animal products is probable in Ecuador.

The possible consequences of increasing consumption for the total areas of permanent crops, temporary crops and grassland are assessed under the assumption that yields will remain constant. Over the period 1974 to 1991, yields of most major crops were rather stable (Chapter 2). An increase in domestic intake will especially affect the land use types temporary crops and grassland, because a relative large share of the area permanent crops (an estimated 60%) is dedicated to export.

Under the assumption of stable per hectare yields (not only in kilos product per hectare but also in caloric value), increasing per capita caloric intake can be directly translated into increasing per capita surface areas. Two situations were taken into account: constant per capita consumption, and increasing per capita consumption. For increasing per capita consumption, it was assumed that caloric intake of vegetable products in 2010 is 13% higher than in 1991 and the intake of animal products 20% higher. For 2010 that would mean a caloric intake of these products similar to that of Colombia in the beginning of the nineties.

Table 5.1. Per capita consumption of vegetable and animal products and per capita areas of different land use types. Data for 1991 are taken from FAO (1998) (consumption) and from INEC (1991) (land use types). For 2010 data are given assuming a 13% rise in vegetable product consumption and a 20% rise in animal product consumption, under constant (caloric) yield per ha. *: Estimated.

	1991 (data)	**2010 (scenario)**
intake vegetable products (kcal/capita/day)	2003	2263 (+13%)
intake animal products (kcal/capita/day)	373	448 (+20%)
area temporary crops (ha/cap)	0.133	0.151
area permanent crops for domestic use (ha/cap)*	0.050	0.057
area grassland (ha/cap)	0.432	0.518

Data for 1991 and the assumptions for 2010 for increasing per capita intake are demonstrated in Table 5.1. For permanent crops only production for domestic consumption is given, export is treated separately. Within the area temporary crops, the area fallow shorter than 1 year as defined by INEC (1991) is included. It is assumed that the increase in per capita intake of animal and vegetable products from the 1991 situation to the 2010 situation as described in Table 5.1, takes place linearly. For temporary crops an increase of 16% is used order to account for the estimated proportion of these crops used for animal feed. The demand for these feed crops is directly related to the human consumption of animal products.

Export developments

Import of agricultural crops is rather limited in Ecuador, the main exception being wheat (Peltre-Wurz, 1988). The most important export crops in Ecuador are banana, coffee and cocoa. The exported volumes of banana, cocoa and coffee over the period 1974-1995 are given in Figure 5.3.

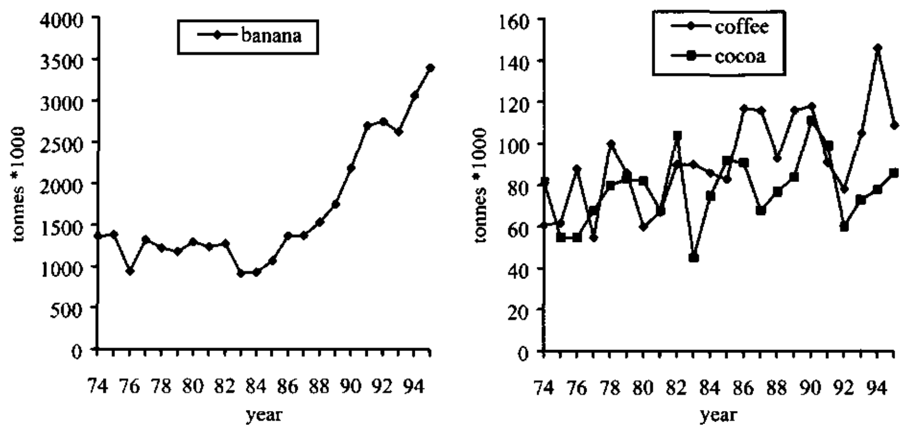

Figure 5.3. Total Ecuadorian export volumes of banana, coffee and cocoa over the period 1974 and 1991 (source: FAO, 1998).

Especially the increase of banana exports since the beginning of the eighties is steep. Because of the rather stable banana yields over this period, this has lead to direct increases in the area used for banana cultivation. Exports of cocoa and coffee fluctuate strongly in between years, but especially exports of coffee have on average slightly increased. Yields per hectare of coffee and cocoa are low, and total volume changes have strong impacts on cultivated areas. Future developments of exports are difficult to

estimate, because of the direct relations with world market prices, international regulations and production volumes of other exporting countries. For example in the case of banana production, there has historically been a clear relation between banana production in Ecuador and Central-America (Larrea *et al.*, 1988).
The effect of increasing export on the total area of land used for cultivation of export crops depends on the crop yields. Under the assumption that yields of exported products of a crop are equal to the domestically consumed product of that crop, an estimation of the areas used for export of the major export crops results in roughly 770000 ha. Two situations with respect to export volumes were taken into account: stable export volumes and increasing volumes. For increasing export we assumed that over the period 1991-2010 export volumes increase with a percentage of the 1991 volumes amounting to 60% for banana, 30% for coffee and 10% for cocoa. Assuming constant yields, this results in an estimated total increase of 220000 ha. In the model, this increase was assumed to proceed linearly over the years.

Total national demand
Figure 5.4 illustrates the combined effect of increasing population growth and consumption pattern on total demand of agricultural land. For permanent crops a situation with increasing export is added. The combination of population size and per capita consumption patterns results in non-linear developments over time. The decreasing annual increase that can be noted in the stable consumption pattern is caused by the decreasing population growth rate. However, in the scenarios with increasing per capita intake (and for permanent crops increasing export), the decreasing yearly area increase does not take place. For permanent crops, increasing export is more important than consumption increase because of the large relative area dedicated to export. No yearly fluctuations and changes in buffer stocks were taken into account.

5.3.2. Sub-national conditions for agricultural land use

Land degradation
Land degradation in Ecuador is a matter of serious concern (Harden, 1991; Southgate and Whitaker, 1994). De Noni and Trujillo (1986) have estimated that around half of the Ecuadorian territory is affected by erosion. Although erosion is especially widespread in the Andean region, areas in the coast are also affected, as well as areas in the Amazon (Custode and Viennot, 1986). Actual erosion is strongly determined by actual and past land use. Potential erosion risk on the basis of only biophysical conditions can be used as an indicator of areas susceptible for erosion. Potential erosion risk for each grid cell was

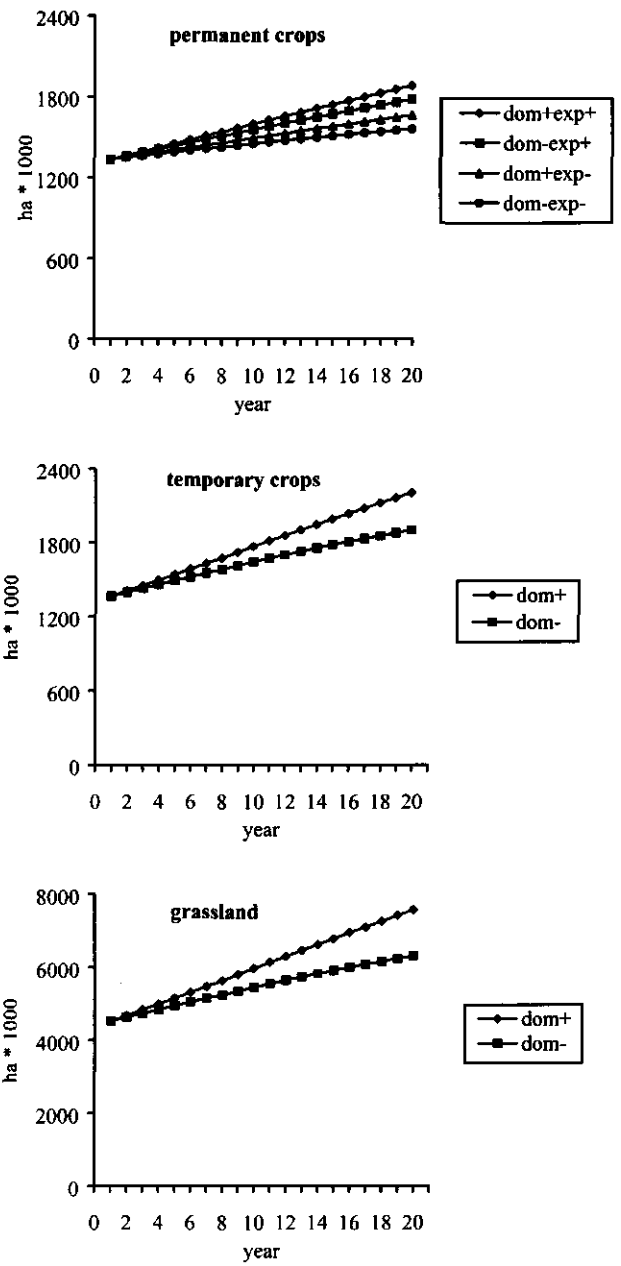

Figure 5.4. Developments of total national demand for land for the land use types permanent crops, temporary crops and grassland under different assumptions of consumption patterns and export developments (scenarios). Year 1 represents 1991, year 20 represents 2010. dom-: no increasing per capita consumption; dom+: increasing per capita consumption; exp-: no increasing export; exp+: increasing export. The total land area of Ecuador amounts to around 26 million ha.

estimated on basis of ratings for rainfall intensity, slope and soil erodibility (Chapter 4). The resulting soil erosion risk map is given in Figure 5.5.

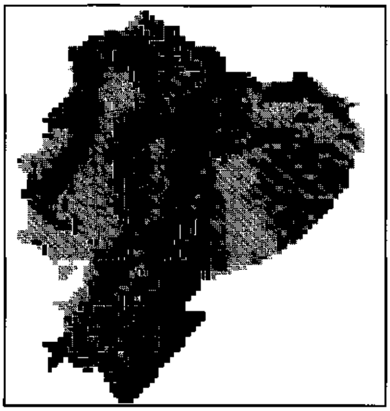

Figure 5.5. Erosion risk. Darker tones indicate higher risk. The delineated darkest areas are excluded in the land degradation scenario.

According to this classification, risks are high along the footslopes of the Andean *cordilleras*, especially the outer slopes due to higher rainfall intensities. In the southern Andes erosion is aggravated by susceptible soils and highly dissected terrain along the outer slopes of the eastern *cordillera*. In the coastal region, erosion risk is especially high in the coastal hills and in the north, where rainfall is high and soils are susceptible. In the scenarios taking into account erosion problems, it was assumed that the cells with the highest erosion risk are excluded from further allocation of new agricultural land, effectively halting land use expansion in these cells. These areas are delineated in Figure 5.5. Although such scenarios might not be realistic from the point of view that people will not stop cultivating land in the short term because of land degradation (Bebbington, 1993; Stadel, 1989), it illustrates the implications continuous land degradation in certain areas can have on other parts of the country. For Ecuador, it has for example been reported that drought and land degradation problems, especially in the southern Andes but also elsewhere, have forced farmers to look for other opportunities. While some leave agriculture and migrate to urban centres, others look for new agricultural land, for example in the Amazon region (Harden, 1996; Bilsborrow, 1992; Hicks *et al.*, 1990; Brown *et al.*, 1992; Pichón, 1997; Commander and Peek, 1986).

Protection of natural areas
A relatively large part of Ecuador's national territory is destined protected area (Southgate and Whitaker, 1994). In practice very little legal power and institutional means exists to reinforce the protection of these areas against invasions of dwellers searching for agricultural land. The national system of protected areas (INEFAN, 1996) includes the categories national parks, biological reserves, ecological reserves, geobotanic reserves, faunistic production reserves, and national recreation areas, together comprising an estimated 3.6 million hectares. These categories have different legal statuses with respect to land use, but in the scenarios taking into account nature protection, no agricultural land is allocated within these areas. In Figure 5.6 all cells are indicated of which at least 50% of the area falls within of one of the categories protected area. All mangrove areas were also considered protected.

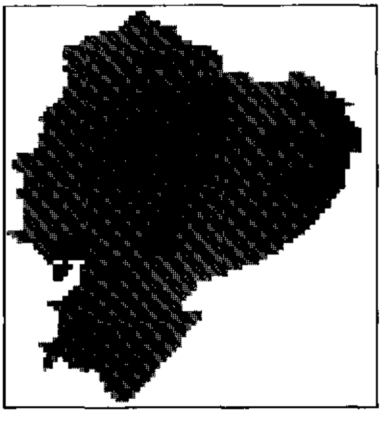

Figure 5.6. Nature parks (source: INEFAN, 1996). 1: Cayapas-Mataje, 2: Cotacachi-Cayapas, 3: El Ángel, 4: Cayambe-Coca, 5: Pululahua, 6: Cuyabeno, 7: Antisana, 8: Sumaco Napo-Galleras, 9: Cotopaxi, 10: Yasuní, 11: Cordillera Galeras, 12: Llanganates, 13: Machalilla, 14: Chimborazo, 15: Sangay, 16: Manglares Churute, 17: Cajas, 18: Podocarpus, 19: Limoncocha, 20: Mangrove forest areas.

5.3.3. Formulation of scenarios, combining national and sub-national developments

Using all combinations of demand developments for each land use type and sub-national conditions regarding land degradation and nature protection, results in a large number of model runs. Only 6 scenarios are presented and discussed here. Table 5.2 gives the assumptions of these scenarios. The national demand development that is used in the demand module is the same for scenarios 1, 2, 3 and 4. For these scenarios the demand increase due to increasing population under constant per capita consumption and export is used. The difference between these scenarios is related to the restrictions imposed in the allocation module. In scenario 1 no restrictions exist. In scenario 2 nature parks are protected, meaning that no agricultural land use takes place at all in these parks. In scenario 3 land use is restricted in areas with the highest erosion risk, meaning that no further increase of existing land use can take place in these areas. In scenario 4, both nature parks are protected and land use in areas with high erosion risk is restricted.

The national demands for scenarios 5 and 6 are higher than are those of scenarios 1 to 4, because under the same population development an increasing per capita consumption and export is taken into account. The sub-national assumptions affecting allocation are for scenario 5 equal to those of scenario 2, and are for scenario 6 equal to those of scenario 4.

Table 5.2. Description of the 6 scenarios.

scenario	national demand		sub-national conditions	
	consumption	export	erosion risk areas	nature parks
1	constant	constant	unrestricted	unprotected
2	constant	constant	unrestricted	protected
3	constant	constant	restricted	unprotected
4	constant	constant	restricted	protected
5	increased	increased	unrestricted	protected
6	increased	increased	restricted	protected

5.4. Modelling results

5.4.1. Land use dynamics

The model output gives for each cell the areas of permanent crops, temporary crops and grassland, expressed as the percentage of the cell area. These three land use types make up the total agricultural land. The remaining land consists almost completely of natural vegetation. Figure 5.7 gives the relative cell areas for permanent crops, temporary crops and grassland as calculated for the year 2010 in scenario 1, the scenario with constant per capita consumption and export, and no restrictions in the allocation module. It can be noticed that permanent crops are mainly grown in the coastal and Amazon regions, while temporary crops are grown in high densities both in the coast and Andes. Grassland shows the widest spatial distribution. The modelled changes over the period 1991-2010 are given as the cell percentage modelled for 2010 minus the cell percentage occupied in 1991. It can be noticed that total area increase is the least for permanent crops. For these crops increases take above all place in the lower altitudes, especially in the coastal region. Modelled decreases over

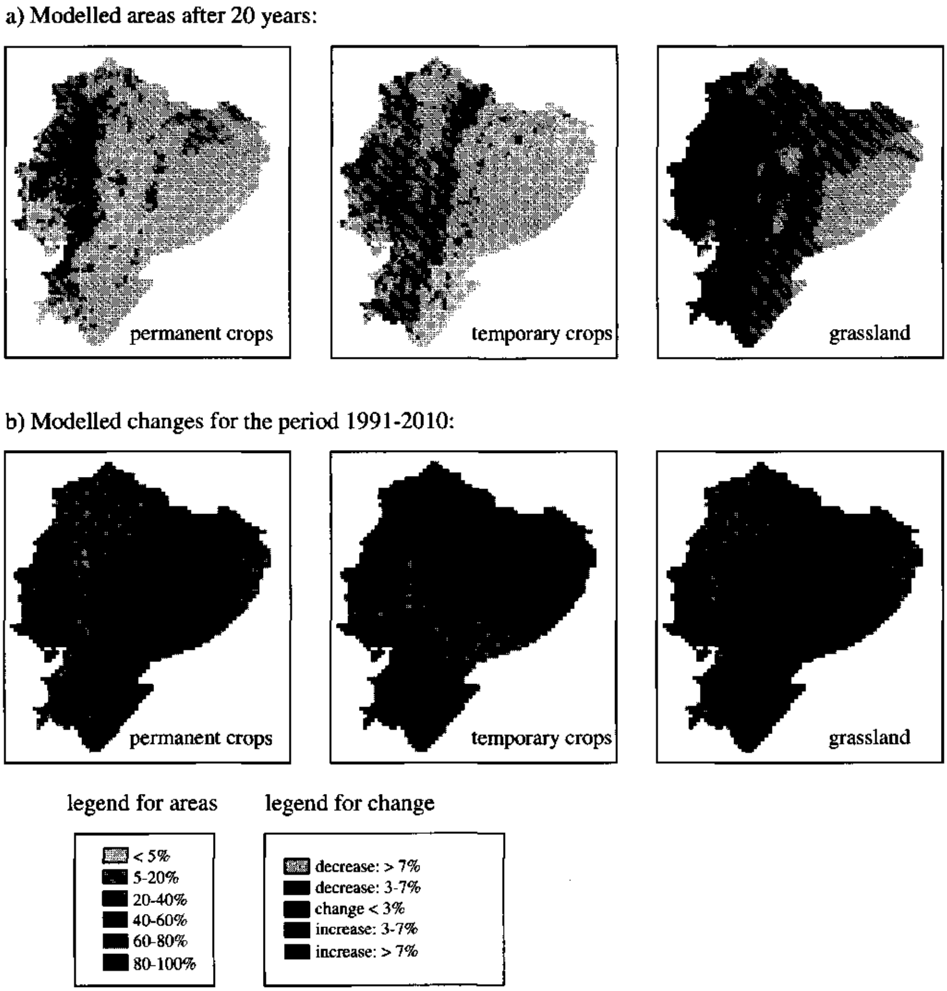

Figure 5.7. Modelling results of scenario 1. a): Modelled results after 20 years. b): Changes in relative cell areas of the period 1991-2010 (negative values indicate decrease, positive values increase).

time are the result of competition for land with the other two, faster growing, land use types. The areas where temporary crops show the strongest increase can be found in the north-western and southern coastal area, but also scattered over the Andean region and the northern Amazon. The central coastal region is the area where the strongest competition exists between the three land use types. Increasing grassland areas are widespread, but especially noticeable is expansion along the Andean footslopes in the northwest and southeast and in the northern Amazon. It should be realised that in areas where agriculture penetrates in formerly non-agricultural land, still significant areas of the cells consists of natural vegetation, as indicated by the low percentages of cell area occupied by the sum of the three agricultural land use types distinguished.

Differences in final outcomes for the year 2010 between scenarios 2, 3 and 4, and scenario 1 are shown in Figure 5.8. The differences are for each land use type given as the percentage of a cell occupied in scenario 2, 3 or 4 modelled for 2010, minus the percentage in scenario 1 modelled for 2010. In all these scenarios the national demand development is equal, the differences indicate the effect of sub-national conditions in the land use allocation. The effect of excluding nature parks under this demand development is shown by the differences between scenario 2 and 1. The clearest differences are seen for grassland, where cells with a negative difference between scenario 2 and 1 indicate where less grassland is allocated in scenario 2. Negative differences obviously occur the nature parks themselves, of which most where affected by grassland expansion in scenario 1. The exclusion of nature parks in scenario 2 results in grassland allocation in other areas, as is indicated with positive differences. For temporary crops, allocation is restricted in for example the nature parks Sangay, Llanganates, Cayambe-Coca, Cayapas-Mataje and Cuyabeno. However, also in other areas less temporary crops are allocated, due to competition with especially grassland that was excluded from nature parks. The smallest changes are observed for permanent crops, of which in scenario 1 relatively little allocation took place in nature parks.

The restriction of allocation of new agricultural land in areas with a high erosion risk introduces more land use allocation changes than that of the protection of nature parks, as is demonstrated by the difference between scenario 3 and scenario 1. Some of the areas where grassland areas increase most in scenario 1, such as the south-eastern Andean footslopes and in the north of the coastal region, are now excluded from allocation. This exclusion leads to rather strong increases in existing agricultural areas and expansion into formerly non-agricultural land. Especially noticeable is the further expansion of the agricultural frontier in the Amazon region along infrastructure and from urban centres. This higher dynamics is also visible for the other two land use types. For permanent and temporary crops modelled increases occur especially in the coastal area, while competition is strongest in the central coastal region.

When both nature parks are protected and no new agricultural land is allocated in erosion risk areas, the impacts on the remaining areas are the highest, as would be expected. This is illustrated by the difference between scenario 4 and 1. Due to the extensive area where no allocation of agricultural land is possible, over large areas clear differences occur for temporary crops and grassland. For permanent crops changes are not as drastic, but this changes in scenarios 5 and 6 where the demand of permanent crops is increasing much stronger due to the combined effect of increasing consumption and export.

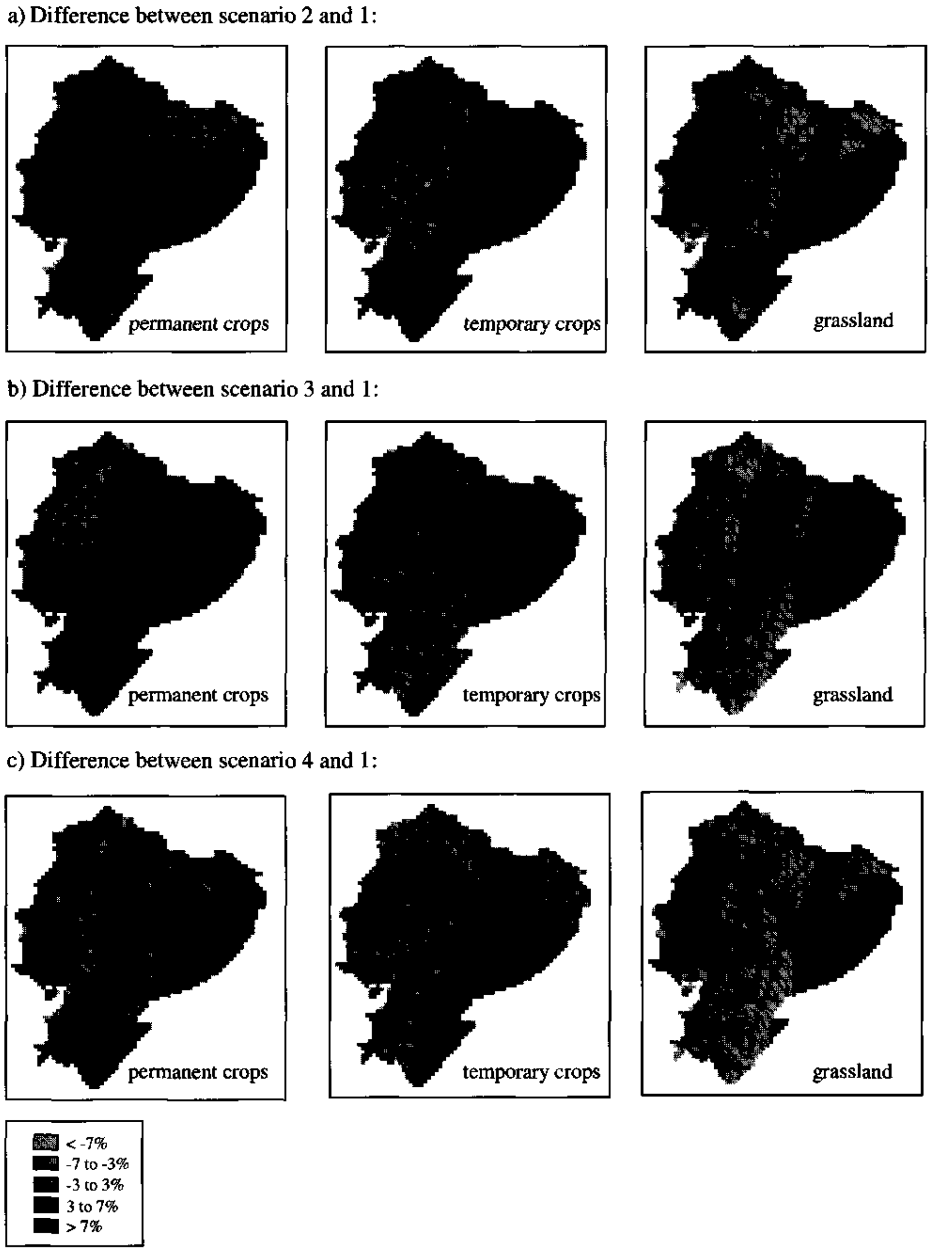

Figure 5.8. Differences in modelled scenario outcomes for the year 2010. All scenarios assume the same national demand development, but are different with respect to sub-national conditions for allocation. Percentages in the legend are the percentage cell area in scenario 2, 3 or 4, minus the percentage cell area in scenario 1. a): effect protection nature parks. b): effect restriction in erosion risk areas. c): combined effect protection nature parks and restriction in erosion risk areas.

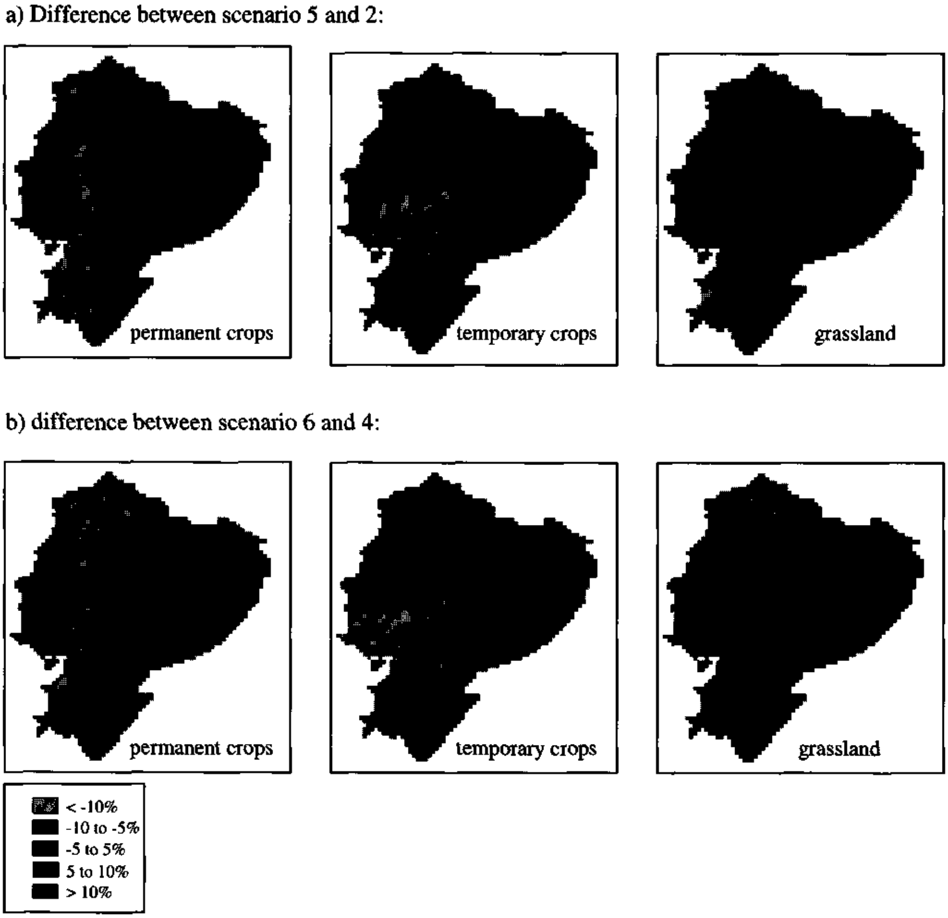

Figure 5.9. Differences in modelled outcomes for 2010 between scenarios. Differences indicate the effect of a higher demand, due to increasing per capita consumption and increasing export of permanent crops. Percentages in the legend are the percentage cell area in the first scenario, minus the percentage cell area in the second scenario. In scenario 5 and 2 nature parks are protected. In scenarios 6 and 4 nature parks are protected and no allocation takes place in erosion risk areas.

Figure 5.9 shows land use changes due to higher demands for the situation of protected nature (comparison between scenario 5 and 2) and for the situation of protected nature and no increase of agricultural land in areas with high erosion risk (comparison between scenario 6 and 4). For permanent crops, land use is now more dynamic, especially in the coastal region. Temporary crops show a rather dispersed pattern of changes due to increasing demand, in scenario 5 as well as in 6. For grassland, changes are again highest. The exclusion of large areas in scenario 6 leads to high differences in the Inter-Andean valley, the north-western and south-western coastal region and in the upper Amazon, especially in the south. Competition in the central coastal region further increases.

5.4.2. Implications for soil fertility balances

In Chapter 4 the inputs and outputs of the main nutrients where estimated for the main land use types, using the NUTMON methodology. Total balances were estimated on basis of the inputs mineral fertiliser, organic fertiliser, atmospheric deposition, biological N-fixation and sedimentation, and the outputs harvested product, removed crops residues, leaching, gaseous losses and water erosion. In general, the results for 1991 showed a depletion of the soil nutrient stock, especially for nitrogen in the land use types permanent crops and temporary crops. The NUTMON-methodology can not be applied directly to all modelled land use changes shown in this chapter, because specific data on cropping systems and animal husbandry are insufficient for cells where agricultural land use was non-existent in 1991, but for which agricultural land use is modelled for 2010. However, in Table 5.3 an evaluation is shown of changes in cells which had agricultural land in 1991. For these cells, the areas of permanent crops and temporary crops in 1991 are classified according to their nitrogen balance. The modelled area increase in these cells in the scenarios 2 and 5 are also classified, using the nitrogen balance data at cell basis from 1991 for these land use types.

Table 5.3. Areas permanent crops and temporary crops classified according to the annual nitrogen balance (N-bal.). Percentages area in each class are given, the total of the 4 classes sums up to 100%. For 1991 the total area is classified. For scenarios 2 and 5 modelled area increases in cells where agriculture was present in 1991 are classified. class 1: losses smaller than 10 kg/ha; class 2: losses between 10 and 35 kg/ha; class 3: losses between 35 and 60 kg/ha; class 4: losses larger than 60 kg/ha

N-bal. class	1991		scenario 2		scenario 5	
	permanent crops	temporary crops	permanent crops	temporary crops	permanent crops	temporary crops
1	25	31	4	14	20	6
2	20	25	0	11	11	6
3	21	15	21	21	13	21
4	34	29	75	54	56	67

Table 5.3 indicates that in scenario 2 relatively more growth occurs in cells where the nitrogen losses are highest, that is in classes 3 and 4. This is especially the case for permanent crops, of which the total area increase is less than that of temporary crops. Data

for scenario 5 illustrate that in this scenario relatively more growth of permanent crops takes place in the classes 1 and 2, compared to scenario 2. This may be caused by the fact that permanent crops in this scenario are more competitive with temporary crops. For temporary crops, relatively more growth takes place in unfavourable areas in comparison with scenario 2.

5.5. Discussion and conclusions

5.5.1. Land use change dynamics in Ecuador

The scenarios used in this chapter are based on the existing situation of stagnant crop yields. Under conditions of a growing national volume demand for agricultural products this leads directly to an expansion of the agricultural area, especially of grassland. The model results indicate areas of potentially rapid change, such as along the outer Andean footslopes, the northern coastal region and along infrastructure and near population centres in the Amazon. Competition between land use types plays an important role in these land use change dynamics.

The model results illustrate the effects of sub-national restrictions in land use due to policy decisions like the protection of nature parks, or due to biophysical constraints like land degradation. Unless natural parks are protected, it is likely that agricultural land use will significantly increase in these parks. The exclusion of erosion risk areas causes more dynamics in total land use than the protection of nature parks. This is above all caused by the fact that erosion risk areas are, more than nature parks, within and close to existing agricultural land. Limitations in areas with erosion problems push frontier-type expansion in areas with rather undisturbed natural vegetation. The model results demonstrate the complexity of land use systems and the influence national and sub-national developments can have over large distances.

Possible consequences of land use expansion have for Ecuador already been stressed in other studies (e.g. Southgate and Whitaker, 1994). The value of the current study is that the spatially explicit modelling of land use changes can support the assessment of the impacts of land use change on the natural resource base in an integrated and quantitative manner. Although deforestation for wood extraction is not explicitly modelled, the results indicate areas with high risks for loss and fragmentation of relatively undisturbed natural vegetation. This can help to assess impacts on biodiversity. The evaluation of land use changes with a nutrient balance model, indicates that increase of agricultural land takes place in areas where on average risks of depletion of the soil nutrient stock are higher. This is aggravated under conditions of higher demand due to increasing per capita consumption. These results confirm that, although Ecuador still has a significant amount of non-agricultural land, the soils that are best suitable for agricultural production are already being used (Southgate, 1990). In marginal areas it is more difficult to maintain high crop yields. This might be one of the causes that yields at aggregated levels are stagnant.

Wether increasing volume demand in Ecuador will really lead to the expansion described in the scenarios will depend on various factors. Increasing national demands can be compensated with imports, but this is strongly politically determined. In many countries, the phase of expansion has been followed by intensification of food production under the pressure of land becoming scarce, for example in Asia (Dyson, 1996; Bilsborrow and Okoth Ogendo, 1992). In South-American countries, agricultural land is often still expanding, at the expense of the natural vegetation (Houghton *et al.*, 1991; Houghton, 1994; Downing *et al.*, 1992). A way to prevent area expansion while meeting demand is to obtain higher crop yields at the land currently used. To achieve this, farmers should be offered the possibilities to maintain economically and socially sustainable livelihoods that allow for food production that does not deplete the soil resources and does not call for the further expansion into marginal lands. This can only be accomplished through complex sets of institutional, socio-economic and technological incentives (Forster, 1992; De Janvry and Helfand, 1990; Whitaker, 1990; Stadel, 1991; Bebbington, 1993). Interaction between stakeholders at different levels could stimulate local, regional and national initiatives aiming at ecologically and socio-economically sustainable food production, taking into account multi-scale developments in land use. This way, bottom-up and top-down processes can be integrated in the management of natural resources.

5.5.2. Characteristics, limitations and possible improvements of the approach

With a time horizon of 20 years, short-term to mid-term developments are evaluated. This time horizon is somewhat arbitrary, but is considered reasonable given that actual land use is the point of departure. Veldkamp and Fresco (1997a) showed for Costa Rica that the relations between the factors determining land use structure are rather robust over such periods of time. Effects of sudden temporal events, for example extreme weather conditions such as occur in Ecuador during the El Niño phenomenon, are not taken into account in the model. Although these can lead to disasters like low yields or even complete crop loss due to flooding of agricultural land (Bravo *et al.*, 1988), changes in areas of land use types are in general much slower and represent the long term perception of, and response to, risk.

For Ecuador on purpose only relatively straightforward factors such as population growth and consumption patterns have been taken into account in the definition of demand developments. Specific scenarios on basis of output data of more complex macro-economic models can be implemented. Population growth in the next 20 years, especially at the aggregated level, can be rather well described because it depends on the existing demographic structure of the population. However, changing consumption patterns are probably less predictable and have higher temporal dynamics. As shown in the scenario formulation, consumption patterns can have a strong influence on total demand.

In areas that are marginal for food production, land may be converted to pasture or crop land, even when this can only be sustained for a limited amount of years. Agricultural land can become successively less productive and secondary vegetation may become predominant again. These phases of land use are not taken into account in this study but would be a worthwhile refinement. Other worthwhile improvements concern the modelling of the main individual crops including their management. This offers options for the inclusion of crop specific yield developments, introducing more temporal and spatial dynamics. Furthermore it allows for more dynamic links with nutrient balance and carbon stock assessment models and could support global change models at higher aggregation levels.

The approach can be used to direct further research, for example by zooming in at more spatial detail in these areas and linking up with household studies. Studies at these detailed scales might also reveal more of the processes that are behind the (proxies of) land use drivers taken into account at the aggregation level of the current study. While village level studies are often hard to extrapolate to other geographical areas, a landscape level study as presented here can help to put the design and outcomes of village level studies within the perspective of the broader setting of land use changes.

5.5.3. Conclusion

The case study presented in this chapter demonstrates a reproducible methodology for the visualisation and quantification of agricultural land use change dynamics and their possible effects on the natural resource base. It is argued that this can assist researchers and policy makers. Studies at the landscape level, such as this one, can provide information necessary to link land use studies at lower as well as higher aggregation levels.

Chapter 6

Landscape level characterisation of potato production systems in the Ecuadorian Andes

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Chapter 6

Landscape level characterisation of potato production systems in the Ecuadorian Andes

Abstract

A method is presented to characterise agro-ecosystems through the analysis of their spatial structure at the landscape level in combination with an evaluation of general land use change dynamics. The method was applied for potato production systems in the Ecuadorian Andes. The spatial variation of areas and yields of potato was quantitatively assessed for spatial units of 9.25 by 9.25 km. The results showed a large spatial variability in conditions of potato production systems. Different combinations of biogeophysical and socio-economic variables explained the spatial structure in potato areas as well as their yields, depending on the geographic area that was analysed. A land use change model for Ecuador was used to evaluate the position of potato production systems within the general dynamics of land use change. Areas were identified where pressure on potato production systems is probable, due to expansion of other agricultural land uses in response to increasing national food demands. Especially competition with grassland is expected in the nearby future. When potato-growing areas are pushed into marginal areas, this can have negative consequences for potato productivity. The results can be used for directing agro-ecological research, especially breeding programs, at specific combinations of environmental conditions and crop management.

6.1. Introduction

Agro-ecosystems can be characterised by their biogeophysical (e.g. climate, soils, vegetation, landform, hydrology) and socio-economic (e.g. management, capital input) conditions (Andriesse *et al.*, 1994). Agro-ecological characterisation can support identification of constraints to sustainable agricultural use, targeting and implementation of research, and extrapolation of research results and technologies to other areas.

The outcome of agro-ecological characterisation is scale dependent (Fresco and Kroonenberg, 1992; Andriesse *et al.*, 1994; Veldkamp and Fresco, 1997). At the landscape level, relatively little agricultural research is being directed, although the importance of eco-regional research is increasingly being recognised (Rabbinge, 1995). Analysis at detailed scales, like fields and farms, addresses processes and dynamics at these levels but hardly relates to landscape processes and dynamics. Analyses at the landscape level are especially appropriate for addressing interactions between land use and the natural resource base in an integrated way. At the landscape level, processes that operate over large distances can be addressed and important changes at national and regional level can be evaluated. For example migration fluxes, changes in food patterns, import and export developments and large-scale deterioration of the natural conditions for food production, such as soil loss through erosion and loss of soil fertility. Also, interaction and competition between land use types and feed back mechanisms can be incorporated. Landscape level analysis can therefore place specific farming systems in the context of the dynamics of the total agro-ecological landscape. Developments at the landscape level may be less relevant for individual land users in the short term, because the spatial and temporal variation for specific local situations is not addressed. However, landscape level research yields information that in the long run can be relevant for local as well as regional sustainable development (Bebbington, 1993).

Agro-ecosystems show spatial and temporal variation. Agrodiversity such as expressed by spatial variation contains valuable information (De Steenhuijsen Piters, 1995; Carter, 1990). Spatial variation offers the possibility to determine the so-called land use drivers, i.e. the factors that determine actual land use (Turner II *et al.*, 1995). These drivers are the combined biogeophysical and socio-economic factors that make up the multi-dimensional space in which agro-ecosystems express themselves. Through an integrated spatial analysis, the relative importance of individual land use drivers can be assessed. This way insight is gained about the factors that determine where and how crops are grown, and crop productivity.

The agro-ecological landscape is continuously changing. Next to an analysis of spatial variation, the temporal dynamics of agro-ecosystems should therefore also be taken into account. This involves a landscape-level study of land use dynamics, including

interaction and competition between different land use types. This way the changing relative position of specific agricultural production systems can be addressed, in comparison to other land uses and in relation to the natural resource base.
The objective of this chapter is to illustrate a method for the characterisation of agro-ecosystems through an analysis of their spatial and temporal variation. Such a methodology can assist to detect the main drivers of (changing) agricultural production systems. The method is illustrated by means of a case study on potato production in the Ecuadorian Andes. Due to the high agro-ecological diversity in this region (Troll, 1968; Knapp, 1991; Espinosa Andrade, 1993) potato can be investigated for different agro-ecological settings. A spatially explicit approach is followed through geo-referencing and linking land use data and data on potential land use drivers. An empirical statistical analysis is applied as a means to describe the dimensions of actual potato production systems for the reference year 1991. The temporal land use dynamics, relevant for potato production, are addressed by using a dynamic land use change model for Ecuador.

6.2. Potato production in Ecuador

Potato is an important staple crop in the Ecuadorian diet. Figure 6.1 illustrates national potato production figures between 1961 and 1995. The total planted areas over the last decades broadly fluctuated between 30000 and 65000 ha. Reported yields in that period varied between 6 and 13 Mt/ha. The yields have been irregular and no clear trend of increasing productivity can be noticed (Figure 6.1). The 1979 low yields were caused by a major drought. These figures have to be interpreted with some caution, because the national system of agricultural statistics has been changed after 1985, which may partially have caused the reported abrupt increase in potato area and decrease in yields between 1985 and 1986. Especially during the 70's, the per capita consumption of potato has decreased (Figure 6.1). This has been caused by the increasing consumption of other products, especially subsidised rice and wheat, and animal products (Crissman and Uquillas, 1989).
In Ecuador, potatoes are grown in the Andes, mostly on the slopes of the inter-Andean valleys where the cool climate is favourable for potato production. The Andes is the centre of origin of the potato plant, it has been cultivated here for at least 6000 years (Brush, 1990). Many potato varieties are grown in Ecuador, although commercial potato production is dominated by a rather limited amount of varieties (Ramos *et al.*, 1993). Over the years a shift has taken place from the production of the native *Solanum tuberosum andigena* varieties to *Solanum tuberosum tuberosum* varieties due to breeding programs looking for more productive varieties with more resistance to pests and diseases

(Crissman and Uquillas, 1989). Many native varieties are grown for home consumption only. Although new varieties are introduced, it is recognised that native varieties should be maintained in formal seed programs in order to prevent genetic erosion (Crissman and Uquillas, 1989; Castillo, 1995).

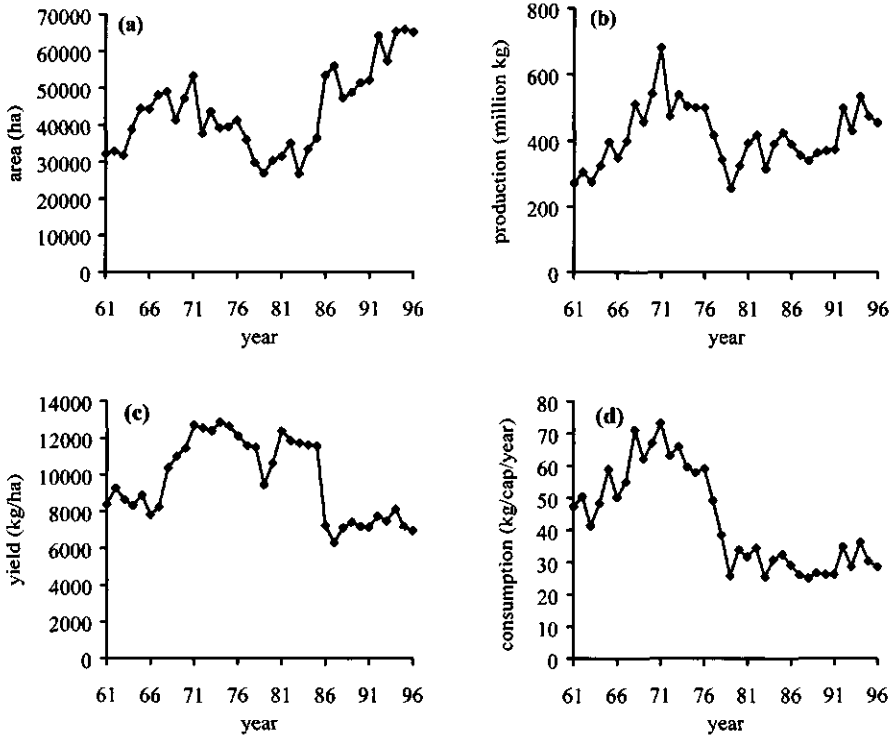

Figure 6.1. Potato production and consumption figures Ecuador (source: FAO, 1998): (a) total potato area, (b) total potato production volume, (c) potato yield, (d) per capita potato consumption.

Potato is a potentially high-benefit, but also high-cost crop. Potatoes are perishable and market prices are not regulated in Ecuador (Crissman *et al.*, 1998). Therefore, farmers are confronted with high economic risks. These risks are also related to pests and diseases, which can cause strong crop damage. The most important disease in Ecuador is late blight (*Phytophthora infestans*), a fungus that damages the foliage and can infect tubers. It favours humid climatic conditions. An important pest is the Andean weevil (*Premnotrypes vorax*), whose larvae penetrate and eat the tubers. Pesticides are therefore widely used in potato production, but sometimes in an unskilled manner (Crissman *et al.*, 1994; Antle *et al.*, 1994; 1998).

The use of good quality disease-free and pest-free seed is an important factor in the production process (Horton, 1987). This seed is however bulky and costly, and often hard to get hold of (Crissman and Uquillas, 1989). Sometimes farmers prefer to use infested tubers of their own harvest for seed, while selling their best tubers at the market. At high altitudes night frost can destroy crops completely in one night. Furthermore, especially in the central and southern Ecuadorian Andes, drought can reduce yields significantly (Bravo *et al.*, 1988). Potatoes are cultivated in rotations with other crops that can be grown at high altitudes, like grass, barley, broad bean and wheat (Knapp, 1991).

Table 6.1. Potato cultivation data for 1991. Source: INEC (1991). (Fertilised and irrigated areas are derived from the unpublished basis data from INEC).

province	planted (ha)	yield (ton/ha)	area with only organic fertiliser (%)	area with only chemical fertiliser (%)	area with both organic and chemical fertiliser (%)	irrigated area (%)
Azuay	1275	2.8	14	43	21	67
Bolivar	1289	2.4	8	77	11	17
Cañar	2684	4.6	17	29	44	50
Carchi	15569	11.8	0	98	0	2
Cotopaxi	5941	5.8	6	74	15	17
Chimborazo	11970	3.7	23	32	34	27
El Oro	217	3.4	2	26	0	6
Imbabura	2506	2.4	6	81	2	11
Loja	116	2.7	47	1	39	12
Pichincha	5366	8.2	12	66	15	37
Tungurahua	7184	7.2	13	36	47	44

Table 6.1 summarises potato production figures in 1991 at province level, obtained from the national agricultural survey (INEC, 1991) (Figure 2.2 shows the provinces of Ecuador). The two most important potato-producing provinces in terms of planted area, are Carchi, in the Northern Ecuadorian Andes, and Chimborazo in the Central Ecuadorian Andes. It can be observed that large differences exist between provinces. Carchi is the province with the highest yields, but compared to attainable yields Ecuadorian yields are generally low. Haverkort (1990) estimated that potential potato yields can be as high as 55 t ha^{-1} per harvest in tropical highlands. Using a crop growth simulation model at a global scale, Van Keulen and Stol (1995), based upon a study by Stol *et al.* (1991), ranked simulated attainable potato yields (without using irrigation) in Ecuador among the word-wide highest.

Carchi has the largest relative area with chemical fertiliser (Table 6.1). Organic fertiliser is more important in the southern and central Andes. Due to the dryer climate the relative area with irrigation is highest in the central and southern Andes, especially the provinces of Azuay and Cañar. Data on pesticide use where not taken in the 1991 agricultural survey.

The production data reflect the characteristics of the production systems throughout the Andes. While in Carchi the production techniques of almost all producers can be classified as semi-technical (Crissman *et al.*, 1998), the central and southern Andes have more traditional production systems. In the period 1974 to 1987 a shift took place in potato growing areas (Crissman and Uquillas, 1989). In the provinces Pichincha (where Ecuador's capital Quito is located) and Cotopaxi, potato areas decreased due to the increase of grassland for dairy production on large farms, a relatively more profitable activity. Potato production in that period has increased in the provinces of Cañar, Chimborazo and Carchi, provinces with more small producers. In Carchi a small-holder class has developed (Lehnmann, 1986) with relatively better economical resources, and using more agricultural inputs. Furthermore, the soil and climate conditions are favourable in this zone and the proximity to the Colombian border means better access to markets, for inputs as well as products. In Chimborazo, more traditional farming systems exist, with small farms on marginal land (Haney and Haney, 1989; Bebbington, 1993; Bravo *et al.*, 1988). Due to land reforms, the pastoral systems and crop cultivation systems have become less integrated (Bebbington, 1993). In this part of the Andes, more native potato varieties are cultivated (Ramos *et al.*, 1993).

6.3. Methods and data

6.3.1 Data collection

The basis for the analysis was a geographical grid with a cell size of 5 by 5 minutes (9.25 by 9.25 km), covering the whole of Ecuador. The Andean region was defined as all cells with an average altitude of at least 1000 meters above sea level (m.a.s.l.). All data were allocated to these cells and stored in a geo-referenced database. The data used are listed in Table 6.2. Below, a description is given of how the data were obtained.

Land use data

Land use data were obtained from the basic data of National System for Agricultural Statistics (SEAN) for the year 1991 (INEC, 1991). Nationally, these were data from 3137 sample sites concerning 65415 farms, of which 1380 sites concerning 37179 farms were located in the Andean provinces. Data of sample sites were related to the geographically corresponding grid cells, thus constructing a land use map. When more than one sample site was found within a grid cell, data of these sites were averaged. The data can be categorised in data for general land use types, individual crops and animal husbandry. Of all land use types and individual crops, their area was expressed as the relative percentage of the total cell area.

Table 6.2. Variables included in the statistical analyses.

biophysical and socio-economic variables:		
variable	**explanation**	**unit**
text1	Percentage soils with texture class 1 (< 35% clay)	-
text2	Percentage soils with texture class 2 (35-55% clay)	-
text3	Percentage soils with texture class 3 (> 55% clay	-
slope1	Percentage soils with slope class 1 (< 8%)	-
slope2	Percentage soils with slope class 2 (8-16%)	-
slope3	Percentage soils with slope class 3 (> 16%)	-
fert1	Percentage low fertility soils	-
fert2	Percentage medium fertility soils	-
fert3	Percentage high fertility soils	-
alt	Altitude	m.a.s.l.
prec	Total annual precipitation	mm
urbdis	Distance to nearest urban centre	km
roaddis	Distance to nearest road	km
riverdis	Distance to nearest river	km
totpop	total population per surface area	km^{-2}
rurpop	rural population per surface area	km^{-2}
urbpop	urban population per surface area	km^{-2}
pov-tot	percentage of total population living in poverty	-
pov-rur	percentage of rural population living in poverty	-
illit-tot	percentage of total population that is illiterate	-
illit-rur	percentage of rural population that is illiterate	-
agric-tot	percentage of total population working in agriculture	-
agric-rur	percentage of rural population working in agriculture	-
potato management variables:		
variable	**explanation**	**unit**
pota_a	percentage area planted with potato	-
pota_i	percentage planted potato area that is irrigated	-
pota_of	percentage planted potato area with only organic fertiliser	-
pota_cf	percentage planted potato area with only chemical fertiliser	-
pota_tfp	percentage planted potato area with organic or chemical fertiliser	-
other land use variables:		
variable	**explanation**	**unit**
barl_a	percentage area sown with barley	-
bean_a	percentage area sown with broad bean	-
whea_a	percentage area sown with wheat	-
cgrass	percentage area with cultivated grassland	-
ngrass	percentage area with natural grassland	-
páramo	percentage area with páramo	-
cattle	number of cattle	-
sheep	number of sheep	-
farm0_1	percentage of farms with an area smaller than 1 ha	-

Soil data

On the 1:1 million soil map of Ecuador (González *et al.*, 1986) 36 great groups are distinguished, which are further subdivided into 62 soil units, using the USDA Soil Taxonomy classification system. The soil units on this soil map were matched with the base grid by assigning to each grid cell the two biggest occurring soil units with their respective surface fractions. These two soil units were maintained as separate units without averaging their physical and chemical properties. Three soil texture classes (less than 35% clay, 35% to 55% clay, more than 55% clay), three soil fertility classes (low, medium, high) and three slope classes (0-8%, 8-16%, more than 16%) were derived from the soil map. This was done on the basis of soil descriptions of González *et al.* (1986) and Beinroth *et al.* (1985). For each cell the relative area of each of these classes was calculated.

Climate data

Climate data were derived from the 1:1 million bio-climatic map of Cañadas (1983). He distinguished 29 climate zones, on basis of altitude/temperature and annual total precipitation. The climate zones on the map were matched with the base grid by assigning to each grid cell the two dominant climate zones with their respective surface fractions. Similar to the assignment of the soil units, the two dominant climate units were maintained as separate units without averaging. The total annual precipitation was calculated for each cell on the basis of the characteristics of the climatic zones. Mean altitude per cell was taken from a 5 by 5 minute altitude database.

Socio-economic data

Socio-economic data were derived from the population census of 1990 (INEC, 1990). Ecuador's provinces are subdivided into cantons, which are further subdivided into parishes. In 1990 the number of cantons (excluding the Galapagos islands) amounted to 162, of which 74 are in the Andean provinces. Ecuador's urban parishes are all located in the capitals of the cantons. The rural population is located in the periphery of these capitals and in rural parishes (738 rural parishes in 1990, of which 413 are in the Andean provinces). Each cell was allocated the (maximally) three main occurring rural parishes (or urban periphery) with their respective surface fractions. In this way the population of all rural parishes was allocated to the grid cells. The urban population of canton capitals was allocated to the cells where these capitals are located. Next to total numbers of rural and urban population, census data were used to determine the percentage of the economically active population working in agriculture, and the level of illiteracy. Furthermore, for 1990, data were available on the percentage of people living in poverty at the parish level in 1990 (Larrea *et al.*, 1996).

Markets and infrastructure

In order to account for the accessibility to urban markets, the distance to the nearest urban centre was calculated through a standard distance operation in a geographical information system (GIS) using the centres of grid cells as reference points. Similarly, the distance to the nearest main roads and rivers was calculated with a distance operation, using vector maps of the main roads and rivers.

6.3.2 Spatial analysis of potato production systems

For the spatial analysis of potato cropping systems statistical methods were used. The data were analysed through correlation and regression analysis, using the cells with their related data for all variables as units. The relation of potato areas and potato yields with variables from Table 6.2 was investigated through correlation analysis. Multiple regression equations explaining potato areas and yields were constructed. In order to account for multicollinearity, variables were first selected with stepwise regression. The analyses were performed for the Andean region as a whole, and separately for Carchi and Chimborazo, the two major potato-growing provinces.

6.3.3 Land use change dynamics

For the analysis of potato production systems within the general land use dynamics, the results of the CLUE (Conversion of Land Use and its Effects) model (see Chapter 3 and Chapter 5) were used.

In Chapter 5, Ecuadorian land use changes between 1991 and 2010 were modelled, using different development scenarios with respect to food demand and sub-national developments concerning land degradation and protection of natural parks. Three major agricultural land use types were considered: permanent crops (perennials), temporary crops (annuals) and grassland. In this chapter the results of the base-line scenario will be demonstrated in relation to potato production areas. In the base-line scenario the projected population was estimated to grow from 10.5 million to 14.6 million between 1991 and 2010. The yields of the main agricultural crops were assumed to be constant and food consumption patterns were assumed to remain unchanged. In the base-line scenario, the calculated area increases of permanent crops, temporary crops and grassland for the whole of Ecuador were broadly 150.10^3 ha, 500.10^3 ha and 1800.10^3 ha, respectively.

The modelled land use changes in the base-line scenario between 1991 and 2010 were analysed for the areas where in 1991 potato was grown, in order to assess the expected near future dynamics in these areas and the possible impacts of these changes on potato cultivation.

6.4. Results

6.4.1 General characteristics of potato growing areas

Figure 6.2 presents the maps of planted potato areas and their yields in 1991, constructed on basis of the gridded agricultural statistical data. It illustrates the north-south orientation of the potato production zone in the inter-Andean valleys. Carchi province shows the highest concentration of potato cultivation. In Chimborazo, the province with the second highest total potato area, cultivation has a less concentrated distribution over a larger area. The highest yields are obtained in Carchi as expected from the aggregated data. However, even within Carchi quite large spatial differences in yields can be observed.

By combining land use data, biogeophysical data and socio-economic data, it is possible to classify potato growing areas according to growing conditions. Of the total potato area, 96% is grown in cells with average altitudes above 2500 m.a.s.l.: 23% between 2500 and 3000 m.a.s.l., 65% between 3000 and 3500 m.a.s.l. and 8% higher than 3500 m.a.s.l.. In terms of climatic conditions, these are the temperate and sub-temperate climatic zones (Table 6.3).

The majority of potatoes is grown in the sub-temperate zone with annual rainfall between 500 and 1500 mm yr^{-1}. The percentage of potato area under irrigation is highest the humid sub-temperate zone, where over 50% of the potato area is irrigated. This percentage is notably lower in the other climatic zones.

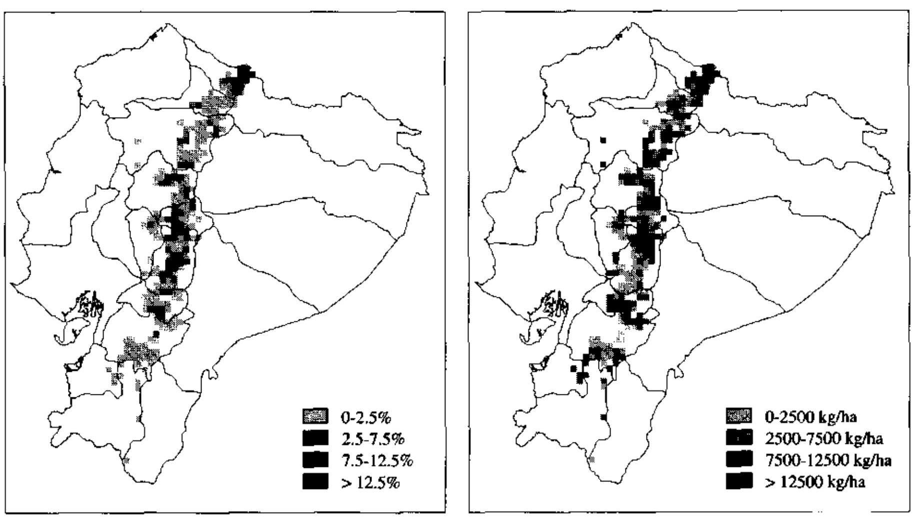

Figure 6.2. Spatial distribution of planted potato area (left) and potato yield (right) in 1991.

Assuming an even distribution of potato areas within a cell, the potato areas can be classified according to USDA soil types. Of the total area, 50% is classified as Andepts, soils of volcanic origin, sub-order of the Inceptisols. Furthermore, 25% is classified as Udolls and 14% as Ustolls, both soil sub-orders of the Mollisols. Of potato area on Andepts, 74% is classified as Dystrandepts, 11% as Hydrandepts and 10% as Vitrandepts. Of the potato areas on Udolls, the majority is grown on Hapludols, while the potato areas on Ustolls are mainly Durustolls (65%) and Haplustolls (35%).

Table 6.3. Potato cultivation in 1991 according to climatic zone.

Climatic zone	Temperature (°C)	Rainfall (mm yr^{-1})	potato area (percentage of total potato area)	irrigated area (percentage of potato area in zone)
sub-humid temperate	12 - 18	500 - 1000	17	22
humid temperate	12 - 18	1000 - 1500	3	3
sub-humid sub-temperate	6 - 12	200 - 500	4	5
humid sub-temperate	6 - 12	500 - 1000	49	52
very humid sub-temperate	6 - 12	1000 - 1500	19	8
rainy sub-temperate	6 - 12	1500 - 2000	3	0
other	-	-	5	-

A classification of potato area on basis of the soil parameters derived with transfer functions from the soil unit descriptions, is shown in Table 6.4. The majority of the soils where potato is grown, is characterised by a relatively low clay fraction, due to the nature of the young Andepts. In terms of soil fertility, there is a more even distribution of potato areas over the three classes. The highest percentage is grown on soils of medium fertility. The distribution over slope classes confirms that the majority of potato areas is located on the steepest slopes of the Andean mountain range.

Table 6.4. Potato cultivation according to soil and slope characteristics.

soil texture class	potato area (percentage of total potato area)	soil fertility class	potato area (percentage of total potato area)	slope class	potato area (percentage of total potato area)
1	82	1	23	1	13
2	15	2	44	2	19
3	3	3	33	3	68

6.4.2 Statistical analysis

In table 6.5 the most important variables that correlate significantly with the planted potato area, expressed as the fraction of the cell area, are given with their correlation coefficients and significance levels. The variables taken into account are grouped as biogeophysical and socio-economic variables, and other land use variables, as presented in Table 6.2. The whole Andean region is analysed, as well as the provinces of Carchi and Chimborazo individually.

Table 6.5. Correlation coefficients for planted potato area in the Andean region and the provinces of Carchi and Chimborazo. *, ** and ***: significant at $p<0.05$, 0.01 and 0.001 respectively.

Andes (n=267)		**Carchi (n=18)**		**Chimborazo (n=49)**	
variable	**corr.coef.**	**variable**	**corr.coef.**	**variable**	**corr.coef.**
biogeophysical and socio-economic variables:					
alt	0.24 ***	text2	-0.55 *	alt	0.45 **
text1	0.23 ***	pov_rur	0.51 *	illit_rur	0.36 *
riverdis	-0.20 ***	slope2	-0.49 *	text3	-0.35 *
agric_rur	0.15 *	slope3	0.49 *		
fert1	-0.14 *	text1	0.49 *		
urbdis	-0.12 *				
other land use variables:					
bean_a	0.46 ***	cattle	0.66 **	barl_a	0.70 ***
barl_a	0.18 **	grass	0.64 **	sheep	0.58 ***
cattle	0.13 *	bean_a	0.59 *	bean_a	0.57 ***
				cattle	0.43 *

For the Andean region a relatively larger number of significantly correlating variables is found, although the correlation coefficients are rather low. With respect to biogeophysical and socio-economic variables, the results for the Andean region demonstrate that of cells with potato cultivation, the relative potato area increases with altitude. A positive correlation is also found with the percentage of soils with low clay content, and with the percentage of the rural population working in agriculture. A negative correlation is found with soils with high clay contents and soils with low soil fertility. Furthermore, the relative potato area decreases with increasing distance to main rivers and urban centres. Of the other land use variables, potato areas are most correlated to broad bean area, whereas a significant positive correlation with barley area and amount of cattle exists as well. Broad bean is widely used in rotations with potato, because it does not need extra nitrogen fertiliser input and can enrich the soils through nitrogen fixation.

The predominance on young volcanic ash soils is confirmed with the correlation with low clay contents. Furthermore, most of these soils have rather high organic matter contents, and are therefore not unfertile, although high contents of allophane can cause problems due to phosphate fixation. Being a bulky and perishable crop, of which the majority is marketed, proximity to markets is an advantage. The population is characterised by a high involvement in agriculture, indicating the generally small-scale production systems in potato growing areas.

When looking at the results for the planted potato areas in Carchi and Chimborazo, the specific conditions of these provinces within the Andean zone as a whole become apparent. For Carchi, the soil variables texture and slope are the most important while potato is also correlated to higher poverty levels within the province. Although in Chimborazo texture is also important, altitude and illiteracy are more correlated. With respect to other types of land use, potato production in Carchi is more clearly related to grassland systems and cattle for dairy products. In Chimborazo, potato is grown in more traditional systems with the subsistence crops barley and bean and extensive grazing of sheep. The only climate variable directly included among those listed in Table 6.2 is total annual precipitation. The fact that precipitation does not enter as a significant correlate is perhaps an indication of the crude level of measurement of this variable for individual cells. The country has a relatively sparse network of weather stations, considering the strong precipitation differences over short differences in the Andean region. The crop associations found in Carchi and Chimborazo can be interpreted as representing differences in rainfall. Potato areas in Carchi receive on average over 1000 mm of rain well distributed during the year, facilitating the establishment and maintenance of pastures. Potato areas in Chimborazo receive much less rain that is received in distinct seasons. Barley can grow on the residual moisture.

In Table 6.6 the most important variables are given that correlate significantly with potato yields. Also potato management variables are included in this analysis. For the Andean region, there is a positive relation between potato yield and potato area. This may be caused by the fact that small potato areas are probably found in marginal areas, less suited for potato cultivation. As rural and inter-regional roads have been improved, reducing market transport costs, potato production has migrated to areas of relative comparative advantage in bio-geophysical terms (Crissman and Uquillas, 1989; Ramos *et al.*, 1993). Carchi and Chimborazo provinces have benefited from this trend. While there is a positive correlation between potato yields and the relative area fertilised with chemical fertiliser, this correlation is negative for the area with organic fertiliser. Organic fertiliser is more applied in traditional production systems with fewer external inputs. Due to the correlation between potato area and yield, the correlation of potato yield with biogeophysical and socio-economic variables shows resemblance with that of potato areas. Additional variables are illiteracy levels, distance to roads and poverty levels, all showing a negative correlation with yields. This reflects the importance of management factors for potato yields. Management, especially the use of chemical inputs, is related to farmers income, education and access to information. Pesticide use, for which no data were available, is probably indirectly represented this way. With respect to other land use types, the negative correlation with the páramo area reflects the fact that potato cultivation at high altitudes operates at the fringe of climatic possibilities for potato production due to low temperatures.

Table 6.6. Correlation coefficients for potato yield in the Andean region and the provinces of Carchi and Chimborazo. *, ** and ***: significant at p<0.05, 0.01 and 0.001 respectively.

Andes (n=267)		Carchi (n=18)		Chimborazo (n=49)	
variable	**corr.coef.**	**variable**	**corr.coef.**	**variable**	**corr.coef.**
potato management variables:					
pota_a	0.47 ***	pota_i	-0.47 *		
pota_cf	0.28 ***				
pota_tfp	0.21 ***				
pota_of	-0.18 **				
biogeophysical and socio-economic variables:					
illit_rur	-0.29 ***	text1	0.64 **	agric_rur	-0.56 ***
alt	0.24 ***	text2	-0.64 **	pov_rur	-0.47 ***
urbdis	-0.20 ***	fert1	-0.60 **	illit_tot	-0.44 ***-
roaddis	-0.18 **	alt	0.57 *	slope1	0.36 *
riverdis	-0.18 **	slope2	-0.55 *	rurpop	0.36 *
text3	-0.14 *	slope3	0.55 *	fert1	0.34 *
pov_rur	-0.13 *	fert3	0.50 *	urbdis	-0.32 *
text1	0.13 *	illit_rur	-0.51 *	totpop	0.30 *
				prec	-0.29 *
other land use variables:					
grass	0.19 **	whea_a	0.66 **	farm0_1	0.55 ***
cattle	0.17 **	grass	0.54 *	cattle	0.38 **
paramo	-0.16 **	cattle	0.50 *	grass	-0.31 *
bean_a	0.16 **				
whea_a	0.13 *				

The results for Carchi and Chimborazo, show a reduced importance of potato management variables because of the fact that management is more homogenous within these provinces. Carchi reflects a semi-technical production system, while management in

Chimborazo is more traditional. For Carchi, soil parameters are predominant among the variables that significantly correlate with yield. Positive correlations are found with soils with low clay percentages, high fertility and on steeper slopes. The only socio-economic variable is illiteracy rate, correlating negatively with yields. Potato yields are positively correlated with grassland and cattle. In this province a rotation of potato with grass for dairy production is common (Crissman *et al.*, 1998). In Chimborazo, more socio-economic variables correlate with yields than in Carchi. Less favourable socio-economic conditions such as indicated with poverty and illiteracy levels, are correlated with low yields.

Table 6.7 illustrates the multiple regression models for potato areas and potato yield in the Andean region and the provinces of Carchi and Chimborazo. All models are significant at the $p<0.001$ level and the individual variables at the $p< 0.05$ level. The variables are ordered according to decreasing standardised betas, as an indication of the relative importance of the variables in the regression equation. The coefficients of determination (R^2) are low in the Andean region, especially for potato areas. For the provinces Carchi and Chimborazo coefficients of determination are higher, while in all cases potato yields are better explained than potato areas. The multiple regression analysis emphasises the complex nature of potato production systems. For the Andean region, education and occupation of the population and altitude are important variables in the model for areas as well as yield. The models show some resemblance due to the correlation between areas and yields. In the model for yield, fertiliser application is represented with two variables.

For Carchi, the best explanation is obtained. Soil parameters are dominant, while in the model for yield the variables distance to river (which could reflect soil parameters) and farm size are included. The models for Chimborazo under-line the importance of population characteristics in this province.

Table 6.7. Selected variables in multiple regression models for planted potato area and potato yield in the Andean region and the provinces of Carchi and Chimborazo. The variables are ordered according to standardised betas, highest on top.

Andes (n=267)		Carchi (n=18)		Chimborazo (n=49)	
area adj. R^2= 0.17	**yield** adj. R^2=0.27	**area** adj. R^2= 0.44	**yield** adj. R^2=0.69	**area** adj. R^2=0.35	**yield** adj. R^2=0.54
agric_rur	illit_tot	text2	text1	alt	agric_rur
alt	alt	fert1	riverdis	illit_rur	text1
illit_rur	pota_tfp		farm0_1	pov_rur	farm0_1
text1	agric_tot			fert3	urbdis
riverdis	fert1				
	roaddis				
	pota_of				
	riverdis				

6.4.3 Land use dynamics

The modelled land use changes between 1991 and 2010 in the base-line scenario, such as described in section 3.3, were analysed in relation to the 1991 potato cultivation areas. In this scenario the increase of temporary crops, to which potato belongs, and grassland is especially relevant for potato production, because these are the land use types with the highest dynamics. Almost all changes in permanent crops take in this scenario place in the tropical lowlands.

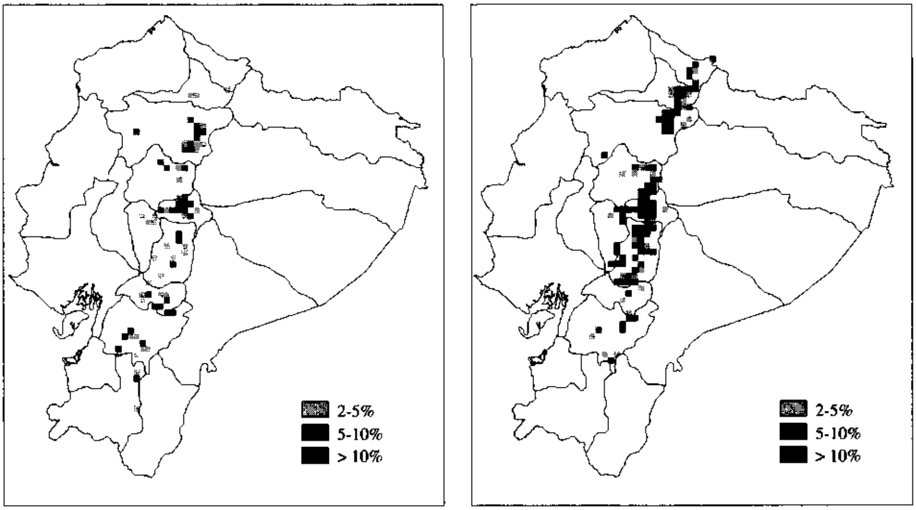

Figure 6.3. Modelled increases of temporary crops (left) and grassland (right) in the period 1991-2010 in the cells where potato was cultivated in 1991. Percentages in legend refer to the percentage of the total cell area.

Figure 6.3 shows the modelled increase of the relative area of the temporary crops and grassland land use types over the period 1991 to 2010 in the cells where potato was grown in 1991. The growth of temporary crops in this scenario mainly takes place in the central Andes and to a lesser extent in the southern Andes. In the province of Pichincha there will probably be especially heavy competition with other temporary crops, such as horticultural crops, because of the proximity to Quito, a major market for agricultural products. The modelled growth of grassland in potato growing areas is much stronger than that of temporary crops, and is predominant in the central and northern Andes. In these areas the competition with potato might increase, even though the two land uses can to a certain extent be combined in crop rotations, such as in Carchi. The results of these high dynamics may be that potato cultivation is pushed to less favourable areas, such as to higher altitudes and to areas with higher erosion risk. This phenomenon has already been described for example for Carchi by Crissman *et al.* (1998) who report a decrease of páramo (natural alpine vegetation) area due to potato cultivation.

6.5. Discussion

The study presented in this chapter underlines that a landscape-level study of agro-ecosystems should ideally have a spatial and temporal component. The spatial analysis for 1991 quantified the multi-dimensional relations in Andean potato production systems. The analysis of the whole Andean region demonstrated the general conditions of potato production and the results for Carchi and Chimborazo gave insight in the specific conditions in these provinces. The factors explaining potato areas and yield were different for the different geographical areas considered, indicating spatial scale effects. Correlation analysis indicated that in Chimborazo socio-economic factors are more important in the explanation of the spatial structure of potato production than in Carchi. While the study demonstrates that potato areas are correlated with less favourable socio-economic conditions, this is even more so the case for potato yields, emphasising the crucial role of management in potato production. This was confirmed with the multiple regression analysis.

When publishing a land use map for the Andean region of Ecuador, Gondard (1988) recognised the disadvantage of solidifying a map on paper, while in reality land use in the Andes is highly dynamic. In the past, potato production zones in the Ecuadorian Andes have undergone major shifts and changes will probably continue in the near future, as was demonstrated with modelled dynamics for the major land us types in a base-line scenario. Due to the pressure on the land and the relative growth of other, more profitable, land uses such as grassland, potato production may be increasingly pushed towards sub-optimal production conditions. In the scenario used, this is especially the case in the areas where potato is already grown in less favourable areas. The estimates of the soil nutrient balance for different land use types (Chapter 4) indicated a net depletion of the main soil nutrients for temporary crops in the Andean region. If more production is going to take place in marginal areas, this situation will worsen, potentially affecting potato productivity. Other developments are the increasing use of the páramo for potato production. On the one hand this reduces the area of this natural ecosystem that has an important role in soil and water conservation, on the other hand this increases risks in potato production systems, due to night frost. It is therefore clear that while socio-economic factors limit optimal potato management directly, indirect effects on potato production are the result of land use changes in response to national developments in food demand.

The data used in this study are taken from existing databases. Key data in the study are those on land use, like the areas and yields of specific crops, and the use of inputs such as fertilisers and irrigation. Data from national agricultural surveys and censuses contain such data and offer a complete coverage of the study area. Although remotely sensed data can give additional information, these alone do not contain sufficient information on land use variables. The reliability of national agricultural surveys and censuses can be a major problem. In the specific case of Ecuador, data quality has probably improved since the introduction of a new yearly statistical survey in 1985. Unfortunately, due to budget shortfalls in the national census bureau, the agricultural survey was discontinued after the 1995 year. A full agricultural census has not been executed since 1974, a new census has been funded for 1999 and will greatly contribute to a better validation of land use data.

Data on pesticide use are not included in the census. Pesticide use could only be accounted for indirectly through the socio-economic conditions, which are related to access to means of production. As indicated before, pests and diseases play an important role in potato management. Quantitative data on pesticide use could therefore improve the explanation of crop yields. Also data on which potato varieties are used would improve the analysis.

Instead of characterising the dominant land use type or crop, the relative areas of individual crops within cells were considered. For soil and climate characteristics the relative areas of the major soil and climate units were also taken into account. This increases the amount of information available for cells. Still, with the use of grid cells as spatial units for analysis some information is lost. Within cells no specific information is available about the exact location of soils and crops. Especially for those cells with small potato areas, this means that specific local (within cell) conditions for potato growth are missed. This is inherent to the aggregation level of analysis and the data available.

Potato areas and yields for 1991 were analysed. Yearly climatic variations can cause strong variation in yields, such as the yield depression in 1979. At the national level, potato yields in 1991 were at the same level as the average yields since 1985. However, locally extreme events such as droughts, frosts and hail, may cause important deviations from the yields under average climatic conditions (Bravo *et al.*, 1988). The land use change model showed a broad picture of the areas with the highest dynamics. It would benefit from further refinement. Inclusion of all major individual crops with their (changing) management would capture real agro-ecosystem dynamics better because it can take into account interaction among these crops.

Quiroz *et al.* (1995) emphasised the important role modelling can play in sustainable development of the Andean region. The methodology presented here could be a contribution to these efforts. The results of this study indicate the wide variety of biophysical and human environments in which potatoes are grown in the Ecuadorian Andes and the possible changes that may occur in the near future. The advantage of the approach is that it can be applied relatively quickly and on the basis of existing data. Although it does not provide the detail of farm or village studies, it offers an integrated assessment of a wide range of production situations. This way a typology can be given of the existing production systems in relation to their environment. This can support research directed at finding the best solutions for the improvement of potato production for specific situations. Genetic diversity in potato can play an important role in such research (Zimmerer, 1991). The results underline that within research programs special attention should be given to the investigation of varieties adapted to sub-optimal conditions.

Chapter 7

General discussion

Chapter 7

General discussion

In this chapter the methodologies used in the previous chapters of this thesis are discussed. The potential applications of the methodologies are given as well as the limitations and options for improvement and further research. Finally, the main conclusions of this thesis are drawn.

7.1 The spatial structure of land use

7.1.1. Spatial analysis of complex systems

The results presented in Chapter 2 showed that the spatial structure in Ecuadorian land use systems is scale-dependent. The variables were identified that best describe the relative areas of permanent crops, temporary crops, grassland and natural vegetation. These variables varied with land use type, aggregation level and eco-region.

The results confirmed ecosystem theory that states that the interpretation of ecosystems depends on the scale of observation because different processes are dominant at different scales (Allen and Starr, 1992; Holling, 1992; O'Neill *et al.*, 1986; Odum, 1994). Examples of multi-scale statistical landscape analyses for natural ecosystems are studies by Reed *et al.* (1993) and Walsh *et al.* (1997). They conclude that the inclusion of multiple scales of observation can be critical for understanding patterns and processes. Walsh *et al.* (1997) state that discontinuous scale domains may exist for certain relations between processes and patterns because of existing hierarchical levels. However, because of the complex nature of ecosystems continuous shifts are often observed rather than discontinuous ones.

The methodology used in Chapter 2 drawed upon work of Veldkamp and Fresco (1997a) who analysed scale dependence of the drivers of Costa Rican land use systems. The technique used in the Costa Rica case was slightly different form the one presented here. Veldkamp and Fresco (1997a) used a fixed set of drivers, and compared their relative importance at different aggregation levels, while in the present study different drivers were selected at different scales. However, some general agreements could be found in the results, such as the higher fraction of the variation explained at higher aggregation levels, and the agreements in the types of variables selected. Furthermore, continuous rather than discontinuous shifts seem to take place between aggregation levels. Currently, similar analyses are being carried out for other study areas, such as China (Verburg *et al.*, 1997) and the North Atlantic Zone of Costa Rica (Kok and Veldkamp, in press). By applying the method for different cases, a growing body of evidence can arise on the processes underlying the observed spatial patterns. With respect to deforestation processes, Lambin (1994) states that it is impossible to identify the unique combination of causes for deforestation in different regions, where general forces are mediated by contextual variables. The challenge is to design conceptual models with sufficient degree of abstraction and flexibility to be applicable in several geographical contexts, but specific enough to be meaningful for specific cases.

The starting point of the spatial analysis was not a full-fletched theoretical model that defines processes and relationships between land use drivers for the different hierarchical levels within the complex system. Instead, a set of potential land use drivers was first defined on the basis of knowledge originating from different scales of observation. The actual land use drivers at different scales were then narrowed down through a statistical selection procedure based on finding the best explanation for the observed land use structure. The results can then lead to redefinition of the main processes in land use. One could call this is an inductive spatial approach, with which relations are derived from the combined geo-referenced information (Aspinall, 1993).

The strength of the empirical approach is the powerful way to quantitatively assess the relationships in complex multi-dimensional systems at different scales in an objective way. Such an approach is especially useful for higher aggregation levels because of the problems that arise when applying biophysical knowledge of processes at detailed scales to coarser scales (Wagenet, 1998; Easterling, 1997; Turner II *et al.*, 1995). These problems become even more apparent in the integration of biogeophysical and socio-economic processes because no *a priori* assumptions can be made about the exact levels at which these processes interact and what the relative contribution is of each of the processes

Causality is not always easy to verify although case studies can support interpretation of the results. At the most detailed level, the coefficient of determination was not in all cases high. This is related to the complexity of the investigated systems. Hobs (1997) recognises that uncertainty is an inherent characteristic of landscape processes and stresses that this should not prevent the use of flexible and integrative approaches which foster rather than inhibit the development of a greater understanding of the observed landscape. Part of the uncertainty in the analysis was reduced by the way the information of different land uses is integrated in the dynamic model. In the model the better explanation at higher hierarchical levels was used, and information of different land use types was combined (see Section 7.2.1).

Statistical methods other than multiple regression are possible for the analysis of spatial structure such as factor analysis and canonical correlation analysis (Johnston, 1978). The advantage of the multiple regression techniques used in Chapter 2, is the possibility for a relatively straightforward interpretation of the results, with land use areas as independent variables. Multicollinearity between explanatory variables complicates the analysis. The assumption was made that multicollinearity was reduced to acceptable low levels after stepwise selection. The outcomes of the analysis could be easy implemented in the dynamic CLUE model.

The methodology proved to be suited for the analysis of land use structure (Chapter 2), but also for the analysis of crop distribution and yield patterns of potato (Chapter 6).

7.1.2. The multi-dimensional niche

The results of the spatial analysis of Ecuadorian land use (Chapter 2) demonstrate the applicability of the agro-ecological niche concept. The results quantitatively describe the combined biogeophysical and socio-economic conditions under which certain crops are actually grown. These conditions make up the multi-dimensional hypervolume of the agro-ecological niche. The niche concept is scale dependent, as illustrated by the changing relative importance of each of the variables at different aggregation levels. The interaction between crops is to some extent being accounted for, because the relative area of a crop in a spatial unit depends on the relative suitability of the crop in comparison to other crops, non-agricultural land use and natural vegetation. The resources that are obtained by the crops from their environment were only partly taken into account, by means of the nutrient balance (Chapter 4). The analysis of potato production systems extended the concept from just looking at the mere occurrence of a crop, to an analysis of its productivity. With respect to productivity of crops the resources for crop growth are important and therefore human management. Management on the one hand determines the administration of inputs necessary for growth such as fertiliser and water, but also controls other organisms that compete with the crops (weeds, pests and diseases). The spatial analysis is static, while in reality the conditions for specific land use change over time. These changes were accounted for in the dynamic CLUE model (see Section 7.2).

Zhiyun *et al.* (1994) illustrated an application of the niche concept within a model for land use planning for a region in China. They defined sets of physical and socio-economic conditions that determine the suitability for certain land uses. With respect to such approaches, the agro-ecological niche as used here, does not aim at describing relative suitability for crop production, but at describing the conditions where crops are actually grown.

7.2 Dynamics of land use

7.2.1. The CLUE model for land use change

The concept of scale dependencies in land use systems was extended in the dynamic CLUE land use change model. An extra hierarchical level was introduced, namely the national level. The national level is used for the determination of total demands for agricultural commodities. The spatially explicit multi-scale allocation of land use change in the model takes into account the non-linear complexities of land use systems through competition between land use options and interconnectivity of landscape elements. Phenomena that operate over large distances like the influence of urban centres, the proximity to infrastructure, and migration fluxes are addressed. In the allocation module top-down and bottom-up effects are integrated and autonomous developments and spatial feedbacks incorporated. This way aspects of structure, function and change in the landscape addressed (Verburg *et al.*, 1999), following principles of landscape ecology (Turner and Gardner, 1991; Forman and Godron, 1986).

The model extends the agro-ecological niche concept from only spatial scale dependent to spatio-temporal scale dependent. Over time, the relative contribution of the variables that make up the multi-dimensional hypervolume changes. These changes cause shifts in the occurrence of certain land uses, a process that is also determined by competition between these land uses.

Chapter 3 described how the model was applied for the Ecuadorian situation and illustrated the dynamics of the land use types permanent crops, temporary crops and grassland. The backward calibration confirmed a rather realistic spatial allocation of land use changes. The agreement with modelled and actual land use was better than expected from the explained variation in the regression models only. The results confirmed that part of the variation that could not be explained in the statistical analysis was captured through the modelling of the combined land use systems with their interactions. Because of data limitations the validation was executed at the aggregated level of cantons. The considerable amount of cantons allowed for a rather good assessment of landscape patterns. However, at the levels of the smallest grid cells substantial errors might be found, preventing a direct interpretation of the model outcomes at this level. This is confirmed by a study of Verburg *et al.* (submitted) who applied the model for the island of Java. In their model validation they found that deviations between modelled and actual land use at the cell level can be considerable, but that very good agreement was found at the level of agro-ecological zones. Kok and Veldkamp (in press) obtained good results in a validation of modelled land use changes in the North Atlantic Zone of Costa Rica at the level of the 20 districts in this zone.

7.2.2. Exploration through scenarios

Research has been challenged to provide information about possible future developments in order to support scientific analysis and policy making. In future-oriented studies, frequent use is being made of scenarios (Turner II *et al.*, 1995; Schoute *et al.*, 1995; Van Ittersum *et al.*, 1998; Van Latesteijn, 1998). Veeneklaas and Van Den Berg (1995) define a scenario as 'a description of the current situation, of a possible or desirable future state as well as of the series of events that could lead from the current state of affairs to this future state'.

In the current study scenarios were not presented for a desirable future state, but for possible future states of land use depending on different plausible developments (events) in the factors driving land use. With the method no static end-results are calculated, but with time steps of 1 year different scenario pathways can be shown (Veldkamp and Fresco, 1997b). In Chapter 5, a number of scenarios was defined for Ecuador on the basis of national developments in demand for agricultural commodities, and sub-national developments that affect sub-national options for land use. With the model effects of changing consumption patterns and export developments were evaluated. The spatially explicit changes depended on the protection of natural parks and the possible feedback of land use induced land degradation. Such results not only indicate potential impacts on natural vegetation, but also on natural resources essential for food production, such as soil fertility. Although the population growth rate is decreasing, the next few decades will be crucial because total demand will continue to grow and large areas of land will be affected by expansion under the current situation of low crop productivity as was shown in Chapter 5. This expansion can have strong irreversible effects on natural resources such as soil quality and natural vegetation before total demands may stabilise in the next century.

The scenarios indicated the interconnectivity in Ecuadorian land use systems and are therefore essential tools for the exploration of pathways of land use change under changing external and internal driving forces. Such scenarios are therefore useful in the evaluation of possible consequences of policy changes.

The case study in Chapter 6 on potato production systems showed that general land use dynamics can also be used to place specific cropping systems within the dynamics of the agro-ecological landscape.

7.2.3. Limitations of the land use change model

The possibilities and limitations of the land use change model are in the first place related to the spatio-temporal scales addressed. The time horizon was set, somewhat arbitrarily, at

20 years. This means that short-term to mid-term developments are evaluated. The chosen time horizon is related to the fact that the model is based on the spatial structure of actual land use. Although the relative contribution of different land use drivers may change over time in the model, the basic relations between drivers are supposed to remain fairly stable in that time period. Veldkamp and Fresco (1997a) demonstrated for Costa Rica that the relations between the factors determining land use structure are indeed rather robust over such periods of time.

For all cells the relative areas of the different land use types are calculated. The exact location of these areas within cells is unknown. Small crop areas within cells may grow under special conditions that are not captured with the description of the whole cells area. This became evident in the analysis of potato production systems.

For Ecuador, the dynamics of the main land use types were modelled. No changes of individual crops were modelled explicitly, although Chapter 6 demonstrated how general land use change patterns can be interpreted with respect to the situation of a specific cropping system. No methodological objections exist against the modelling of separate crops and currently such an exercise is done for the North Atlantic Zone of Costa Rica (Kok and Veldkamp, in press). The modelling of individual crops will allow a more specific assessment of crop management and productivity. It is particularly relevant to include information on the factors that drive technology adoption by farmers. With such information changes in these factors can be explicitly included in scenarios, offering more insight in causes and effects of changing crop management. This is especially relevant for parts of the world were land use change is dominated by intensification instead of expansion (Vitousek *et al.*, 1997).

7.2.4 Data needs and quality

Data are needed that cover the complete extent of the study area. Although for developments in food demand data at the national level can be used, spatially explicit data are required for the quantification of land use drivers and for the allocation of land use changes in the dynamic model. The resolution of these data should correspond with the resolution of the units of analysis.

A potentially important source of data with a high resolution and extent are remote sensing data. However, although the areas of land use types and some individual crops types may be identified, remote sensing data do not provide enough information (yet) on demography, socio-economic conditions and actual land use management. Management data should include specific information on the areas and yields of individual crops, the use of inputs such as fertiliser, pesticides, and irrigation water, and the size and structure of farms. For such data agricultural censuses and surveys are needed. A disadvantage is that reliable information on the uncertainty of these data is generally lacking. Census data are obtained from farm visits of which the quality is unknown, although some checks on consistency can be performed. Especially crop yields are often rather crude estimates and can be highly variable over years. In some cases the basic data are not systematically geo-referenced. Furthermore, in several countries the execution of expensive agricultural censuses is under pressure due to budget shortfalls. Both problems apply to Ecuador.

For soil and climate data a tradition exists to present geo-referenced data in maps at various scales. However, also for these data quality and reliability is often a problem. Socio-economic data are often not geo-referenced, and just available for specific case studies or for the national level. Valuable information is provided by the population censuses. In Ecuador, poverty maps where constructed by Larrea *et al.* (1996) by means of a statistical linkage between the national population census data and the data of a living standard measurement survey under selected households. This approach seems promising for deriving more geo-referenced socio-economic information.

Various initiatives are being taken to develop conceptual databases for land use research (Dumanski *et al.*, 1993; Gallopin, 1996; Baulies and Szejwach, 1998). Also, there are ever more global databases available through central collection, storage and distribution (e.g. websites of FAO, World Bank, CIAT, WRI and others). These initiatives will greatly support land use change modelling studies.

7.3 Opportunities for assessing the impacts of land use change

Human-driven land use change is an important factor in environmental change because of its impacts on sustainability, biodiversity and global climate change. Quantitative modelling can support the assessment of these impacts (Turner II *et al.*, 1995).

7.3.1. Nutrient balances and sustainability

Without discussing here the many existing definitions and interpretations of sustainable development, it is clear that soil fertility is only one of the many factors that determine the sustainability of production systems. With respect to the Ecuadorian Andes, Bebbington (1993) states that sustainable farming systems allow farmers to obtain a livelihood that does not force them to migrate, temporarily or permanently. The concept of sustainability depends very much on the scale of analysis (Fresco and Kroonenberg, 1992; Wolf and Allen, 1995; Dovers, 1995; Cocklin *et al.*, 1997). While Ecuadorian farmers may not consider soil erosion or loss of soil fertility as their main direct concern (Stadel, 1989), it could affect their livelihood considerably over the longer term.

Barrett (1992) argues that long-term sustainable approaches can best be implemented by management at the landscape scale because the flux of material and organisms at the these scales is the result of activities in the landscape mosaic. At various levels, complex interactions exist between development and the environment (Myers, 1993b). A fundamental challenge facing agriculture is the integration of multiple considerations across levels in the system (Wolf and Allen, 1995). Coherent strategies are needed that aim at upper-level objectives (soil, water and biodiversity conservation) while at the same time supporting the integrity of lower level sub-systems.

The results of Chapters 4 and 5 do not relate to risks for individual farmers, but indicate possible landscape level effects of land use on soil fertility at the mid-term. Such information could be used to direct natural resource management in a way that is beneficial for farmers in the long run. In Chapter 4 nutrient balances were estimated for Ecuadorian land systems in the year 1991. The results for 1991 at the level of eco-regions indicated that on average the balances of nitrogen and potassium where negative. Especially in the Andes and Amazon loss of soil nutrients endangers the sustainability of different agro-ecosystems. A crucial component of the nutrient balance is the loss of nutrients through erosion, confirming earlier findings of Smaling (1993) for Africa. Within Ecuador erosion is considered a major agro-ecological problem (Southgate and Whitaker, 1994). However, data on soil erosion processes in Ecuador are scarce and the estimations for erosion used in this study would benefit from further refinements. Especially useful would be a link with landscape process modelling, including erosion as well as sedimentation at different spatial and temporal scales. An example is the erosion and sedimentation model that is currently being developed for southern Spain by Schoorl *et al.* (1998).

Nutrient balance estimates are informative in order to support integrated nutrient management (Smaling *et al.*, 1996; Deugd *et al.*, 1998). However, they can also be used in order to estimate potential effects of land use change on soil fertility. In Chapter 5 a link between the modelled land use changes and the nutrient balances for 1991 was made. For the two scenarios considered, the results indicated an increasing use of agricultural land in areas with relatively high risks for soil nutrient depletion, especially in the scenario with the strongest demand increase. Such expansion into marginal areas is a threat for agricultural productivity and soil resources. These results should be considered a first attempt to demonstrate the feasibility of such a link. For a more dynamic account of the interactions between land use and soil fertility, developments in the management of specific crops, such as the use of different types of fertiliser or crop rotations, should be considered. When the cropping systems are modelled in more detail over the years, progressive changes in the soil nutrient stocks can be accounted for.

7.3.2. Natural vegetation and biodiversity

Deforestation for wood extraction is a major threat to natural vegetation in Ecuador (Sierra and Stallings, 1998). This type of deforestation was not explicitly modelled because the demand for forestry products was not taken into account. Another important cause of deforestation is expansion of agricultural land. The results of Chapter 5 indicate areas where expansion of agricultural land into areas with natural vegetation is likely in different scenarios. Such results could be used to assess potential impacts on biodiversity due to disappearance and fragmentation of natural habitats. Myers (1988) indicates areas in tropical forests with exceptionally high concentrations of species with high levels of endemism. Among these ten so-called hot-spots are the lowland wet forest of western Ecuador and the uplands of western Amazonia in Colombia, Ecuador and Peru. By combining geo-referenced biodiversity maps with maps of possible land use changes, areas with high risk for biodiversity loss can be identified. Next to a complete loss of habitats, biodiversity is affected by habitat fragmentation (Skole and Tucker, 1993). The effect of fragmentation on individual species could be assessed by estimating the total area requirement of a specie and its gap crossing abilities (Dale *et al.*, 1998). By combining this information with fragmentation maps, risks for individual species may be estimated. For these fragmentation maps the pattern of agricultural land use within undisturbed forest is important. The resolution of the current study is probably too course for such detailed assessments but the results can indicate areas where further zooming in is needed. Another aspect that could be taken into account, is the ability for regeneration of natural vegetation after abandonment of agricultural land (Sarmiento, 1997).

7.3.3. Land use and global climate change

An important issue is the impact of human induced land use change on global change (Turner II *et al.*, 1993; 1995; Meyer and Turner II, 1994; Ojima *et al.*, 1994; Dale, 1997). Next to global impacts on soil degradation and biodiverstity these are impacts on global water and energy balances, and on sinks and sources of greenhouse gasses. The use of fertilisers in crop production contributes significantly to the emission of N_2O and CH_4 (Kreileman and Bouman, 1994; Rosenzweig and Hillel, 1998). The conversion of natural vegetation into agriculture, or the regeneration from agricultural land to secondary forest have important effect on global CO_2 balances (Klein Goldewijk *et al.*, 1994; Dale, 1997). These effects are related to the storage and release of organic carbon in above ground biomass and in soil organic matter. As underlined in the Kyoto protocol, land use can play a crucial role in the mitigation of global warming.

The results of the CLUE model can contribute to the integrated assessment of the impacts of land use change. The spatially explicit results might be linked with models that estimate the greenhouse gas emissions from agricultural land and estimates of carbon balances related to land conversions. A nutrient balance such as demonstrated in Chapter 4 may be able to support emission estimates but would then need a more detailed assessment of the fate of fertilisers and a more dynamic interaction with crop management. Carbon was not treated in the balance. If information is available on the specific C-dynamics under different soil and climate conditions and in different stages of land use conversion, this might offer a dynamic link with the modelled land use changes. In such linkages, the issue of dealing with different spatial and temporal scales will be crucial (Roswall *et al.*, 1988). Greenhouse gas emissions are often measured and modelled at the point or field scale, and scale-specific transfer functions are necessary to link these with landscape level changes (Keller and Matson, 1994; Plant, 1999).

For global modelling, land use change information will be needed for larger areas than a country of the size of Ecuador. There are no theoretical objections against applying the method for larger areas. For such areas a coarser resolution can be used, such as demonstrated in a study of Verburg *et al.* (1997), who used a cell size of 32 by 32 kilometres for the whole of China. This way the CLUE model might contribute to more realistic land use change modules within integrated assessment models (Easterling, 1998).

7.4 Comparison with other approaches

A large amount of approaches has been developed for the analysis and modelling of land use, its changes and the possible consequences of these changes. Land use studies have been developed from different disciplines, and can be distinguished on basis of their aim, the spatio-temporal scale addressed and, related to that, the methodology used. Reviews have been given by Kaimowitz and Angelsen (1998), Lambin (1994), Sklar and Costanza (1991) and Riebsame *et al.* (1994). In this section only the main characteristics CLUE will be given and compared with examples of other approaches.

The CLUE model can be typified as a dynamic system model based on empirical regression analysis. Different nested (artificial) spatial scales are addressed, in the statistical analysis as well as in the dynamic modelling part. The model operates mainly at the landscape level (meso-scale) and partly, the demand module, at the national level. Field and farm levels are not addressed. The allocation module takes into account system properties such as competition, interconnectivity, feed-backs, and top-down and bottom-up processes.

An example of another explorative model, is the land cover model within the larger IMAGE model for integrated modelling of global climate change (Zuidema, 1994; Alcamo, 1995). The main differences with CLUE are that IMAGE operates at a lower resolution and explores for a much further time horizon, due to its specific goal of global assessments. In IMAGE, land use change is to a large extent driven by the potential productivity of crops on basis of biophysical conditions. In CLUE such an approach is not used because actual land use and its productivity is often not closely related to biophysical potentials due to system complexities and the importance of socio-economic drivers (Veldkamp and Fresco, 1997b).

Van Ittersum *et al.* (1998) describe a number of explorative land use studies using multiple goal linear programming, using various objective functions. An example is a study of WRR (1992) in which windows of opportunities are described over longer time frames, assuming that ways can be found to direct land use towards certain desired configurations. Technical information is sometimes based on potentially possible production techniques and productivity (Rabbinge and Van Latesteijn, 1992; De Koning *et al.*, 1995) but can also be based on actually existing production techniques (Schipper, 1996; Bouman *et al.*, 1998). The degree to which economic information is incorporated varies with the scale and aim of these models (Bouman *et al.*, 1998). Compared to such studies, CLUE is above all based on the multi-scale spatial structure of actual land use. It does not aim at designing land use systems, but at describing probable land use developments when drivers change. In the case of Ecuador, crucial changes are expected to take place in a period of just 2 decades. The model quantifies these possible developments and yields important information on where, when and to what extent the biggest changes and their effects can be expected. In other words, its shows likely pathways of short-term development in different scenarios, due to intrinsic complex structures that are not easily changed or planned (Veldkamp and Fresco, 1996).

7.5 Potential stakeholders

A major challenge in land use studies is to establish a close interaction with stakeholders, such as farmers, planners or politicians. Bouma (1997) stresses the importance of a pro-active interaction between researchers and stakeholders. In discussing integrated nutrient management, Deugd *et al.* (1998) advocate the development of a praxeology, meaning theory informing practice, which in turn feeds theory. By doing so, an interplay can be established between research and practice. Dynamic modelling tools can be used for problem scoping and consensus building among a broad range of stakeholders (Costanza and Ruth, 1998). Spatially explicit modelling approaches showing maps with likely land-use changes allow land-use implications to be discussed and provide a direct feedback to research and policy (Aspinall, 1993).

The approach presented in this thesis is, in its current state, above all a research tool without major involvement of stakeholders. Due to the scale levels chosen, it does not address the specific conditions of individual farmers, although landscape level developments and their implications for sustainability can be very relevant for these farmers in the longer run. This relevance was described in Chapter 6, when dealing with Andean potato production systems. The spatial and temporal analysis of specific production systems can support national and international research centres in developing new technologies in need by farmers. For example, the analysis of potato production systems in Chapter 6 focused on areas that are of major importance for the regional office of the International Potato Centre in Ecuador and showed how a rapid landscape level analysis can indicate constraints in crop production.

A closer link to local dynamics may be established by follow-up studies at a higher spatial detail. The areas chosen for such studies can be based on the current model results, choosing places where the highest changes and effects are modelled. An example of an application of CLUE with a higher resolution is given by Kok and Veldkamp (in press) for the North Atlantic Zone of Costa Rica, using spatial units of 2 by 2 kilometres.

The main application of the model is the interpretation of regional developments in the relation between food production and natural resources. Next to directing and focussing further research this can support regional-level management of resources. This is mainly of interest for governmental and non-governmental organisations dealing with these issues, provided that they are involved in the design of the study. For example, the results for Ecuador indicate the potential consequences of the combination of low agricultural productivity and growing demands. The increasing use of marginal land may put productivity under further pressure and can worsen the mining of soil fertility. Extensive areas of natural vegetation may be affected, along the Andean footslopes, in the tropical forest in the north-west of the Pacific Coast, and especially in the Amazon region. The results showed that measures in one area can affect other regions at considerable distances. The protection of natural parks will be necessary to prevent agricultural expansion into these areas, but will partly displace problems to other natural areas if no other measures are taken. Land degradation will not only endanger the sustainability in the areas that are directly affected, but can have also major consequences in other areas. This process has already been described for land degradation in the Southern Andes that has forced significant numbers of farmers to colonise new land. For solving such wide-scale problems, complex sets of institutional, socio-economic and technical solutions have to be found. Quite crucial is the need for higher crop production per surface area. Therefore, the problems of individual farmers will have to be addressed in order to achieve higher-level objectives related to the management of natural resources. These objectives can only be achieved if farmers are offered the possibility to produce food in a sustainable and productive way, that also warrant their livelihood and does not force them to abandon their land.

7.6 Conclusions

- A multi-scale empirical system analysis demonstrated scale dependence of Ecuadorian land use.
- The results of the multi-scale analysis of land use systems could be integrated in a spatially explicit, dynamic, land use change model.
- Scenarios studies with the model allowed for the exploration of possible future land use changes.
- The quantitative, spatially explicit, information on land use changes generated by the model offers possibilities for the assessment of the effects of land use change on sustainability of food production, biodiversity and global climate change.
- Priorities in further methodology development are linkage with geophysical landscape processes and a better incorporation of crop specific management.

Summary

Introduction and objectives

Within agricultural research increasing attention is paid to the integrated study of agro-ecosystems in order to address issues related to sustainable food production at the eco-regional level. This has been stimulated by the awareness that the world-wide demand for food will continue to increase while at the same there is high pressure on natural resources needed for food production, such as suitable soils and available water. Human-driven land use change is also relevant for global change because of its influence on greenhouse gas emissions, water and energy balances, and biodiversity.
These issues have confronted research with substantive methodological challenges, such as the integration of biophysical and socio-economic disciplines over various spatio-temporal scales, and the development of modelling approaches for the exploration of future changes in land use and their effects.
The general objective of this thesis is the analysis of spatial variation and temporal dynamics of agricultural land use systems in order to quantitatively assess the interaction between land use and the natural resource base. This is addressed through three derived objectives. Firstly, the spatial analysis of land use systems with the aim to detect the main biophysical and socio-economic drivers of actual land use at different spatial scales. Secondly, the spatially explicit modelling of near-future land use change dynamics, taking into account the multi-scale structure of actual land use and its drivers. Thirdly, the quantification of possible effects of future land use change on the natural resource base and agricultural production.

The study area

The study area is the South-American country of Ecuador. Agriculture is important in Ecuador, both for the production of subsistence crops as well as export crops. The country is characterised by a high agro-ecological diversity. A wide variety of climate and soil conditions exist and land use is diverse, with respect to the crops that are grown as well as the technology levels that are used. Agricultural land use is dynamic due to resource degradation, changes in demand for agricultural products, migration, export and import developments, economic developments and sector policies. A number of land use developments are causing serious threats to the natural resource base.

Statistical multi-scale analysis of actual land use systems

Land use in Ecuador was investigated for the year 1991 by means of statistical analysis with the purpose of deriving quantitative estimates of the relative areas of land use types on the basis of biogeophysical, socio-economic and infrastructural conditions (Chapter 2). The smallest spatial units of investigation were 5 by 5 minute (9.25 x 9.25 km) cells of a geographical grid covering the whole country. Through aggregation of these cells, a total of six artificial aggregation levels was obtained with the aim of analysing spatial scale dependence of land use structure. For all aggregation levels independent multiple regression models were constructed for the estimation of areas within cells of permanent crops, temporary crops, grassland and natural vegetation. The variables used in the regression models were selected from a set of potential land use drivers or their proxies. A spatial stratification was applied by dividing the country into three main eco-regions. The results showed that at higher aggregation levels, the independent variables explained more of the variance in areas of land use types. In most cases, biogeophysical, socio-economic as well as infrastructural variables were important for the explanation of land use. The variables included in the models and their relative importance varied between land use types and eco-regions. Also within one eco-region the model variables varied with aggregation level. The results demonstrated spatial scale dependence of land use drivers.

Spatially explicit modelling of land use change dynamics

A spatially explicit multi-scale land use change model was explained and demonstrated in Chapter 3. Important inputs for the model were the results of the multi-scale system analysis of Chapter 2. The model consists of two main modules: the demand module and the allocation module. Changes in the national demand for agricultural commodities are estimated with the demand module. The sub-national changes in land use following changes in demand are calculated in a multi-scale allocation module. The finest resolution for which changes were calculated for Ecuador, were the 5 by 5 minute cells. The allocation module takes into account the non-linear complexities of land use systems by dealing with competition between land use types and interconnectivity of landscape elements. Phenomena that operate over large distances like the influence of urban centres, the proximity to infrastructure and migration fluxes are addressed.

The allocation of land use changes was validated by modelling backwards from the year 1991 to the year 1974, a year for which an independent data set was available. The validation results showed a rather good agreement with actual land use data at the level of administrative units called cantons. A hypothetical future base-line scenario of increasing demands for agricultural commodities was used to demonstrate how dynamics of land use are modelled. The results indicated “hot-spots”, areas with potentially highly dynamic land use change where impacts of land use change on the natural resource base can be expected.

Nutrient balances as indicators of sustainability

Using a nutrient balance model, inputs and outputs of nitrogen, phosphorus and potassium were estimated for each cell for the main land use types for the year 1991 (Chapter 4). Inputs considered were mineral fertiliser, organic fertiliser, atmospheric deposition, biological N-fixation and sedimentation; outputs considered were harvested product, removed crop residues, leaching, gaseous losses and erosion. The outcomes for cells were aggregated to sub-national and national level.

In general, the estimates showed a depletion of the soil nutrient stock in Ecuadorian agro-ecosystems. Nationally, for temporary crops there was mainly a deficit of nitrogen (42 kg ha^{-1} yr^{-1}), while for permanent crops both nitrogen and potassium balances were clearly negative (40 and 25 kg ha^{-1} yr^{-1}, respectively). For grassland overall, losses are smaller. Erosion is a major cause of nitrogen loss but leaching and denitrification also contribute significantly. In permanent crops relatively large amounts of potassium leave the agro-ecosystem through harvested products, due to high potassium concentrations in these products and high yields.

At sub-national scale, nutrient depletion under current land use is more severe in the Andean region than the coastal region, mainly as a result of higher erosion losses. The Amazon region is still largely unexploited but this study suggests that the current conversion of forest to agricultural land may cause serious nutrient balance problems at a local level.

Exploration through scenarios

The land use change model for Ecuador was used for the dynamic and spatially explicit exploration of near future agriculural land use changes (Chapter 5). A number of plausible scenarios were formulated for the period until the year 2010. At the national level, different developments in national food demand were defined on the basis of assumptions for population growth, consumption patterns and export developments. At the sub-national level the protection of nature parks and land use restrictions due to land degradation were evaluated with respect to their possible spatial impacts on the land use change dynamics within the country. Under the assumptions of the demand scenarios, the area agricultural land expanded significantly, resulting in more use of land in existing agricultural areas and frontier-type expansion into rather undisturbed natural areas. The patterns of change

depended on the increase in demand, competition between land use types, changes in the drivers of land use, and the area of land that was excluded from agricultural use.
Soil fertility impacts were considered by linking the results of the nutrient balances calculated in Chapter 4 with the results of the land use change model. The results indicated potential negative effects of land use changes on the soil nutrient balance. It was argued that quantification of land use dynamics at the landscape level can support research and policy aimed at understanding the drivers of land use change and the behaviour of complex agro-ecosystems under changing conditions at different spatial scales. This way, issues dealing with sustainable food production and the management of the natural resource base can be addressed in a more integrated and quantitative manner.

Spatial and temporal characterisation of Andean potato production systems

Chapter 6 described how a statistical analysis of the spatial structure of cropping systems can be combined with the land use change model in order to characterise a specific cropping system. The method was applied for potato production systems in the Ecuadorian Andes. The variation of areas and yields of potato was analysed on the basis of the data for the grid-cells. The results showed a large spatial variability in conditions of potato production systems. The combinations of biophysical and socio-economic variables that best explained the spatial structure of potato areas as well as their yields depended on the geographic area analysed. The whole Andean region was analysed, as well as the provinces Carchi and Chimborazo. Output of the land use change model was used to evaluate the position of potato production systems within the general dynamics of the main land use types. In this way, areas were located where pressure on potato production systems is probable, due to expansion of other agricultural land uses in response to increasing national food demands. Especially competition with grasslands is expected in the near future. When potato-growing areas are pushed into marginal areas, this is likely to have negative consequences for potato productivity. With the results a typology can be given of production systems in relation to their environment. Such information can be used to direct agro-ecological research at specific interactions between environment and crop management.

Conclusions

- A multi-scale system analysis demonstrated scale dependence of Ecuadorian land use.
- The results of the multi-scale system analysis could be integrated in a spatially explicit, dynamic, land use change model.

- Scenarios studies with the model allowed for the exploration of possible future land use changes.
- The quantitative, spatially explicit, information on land use changes generated by the model offers possibilities for the assessment of the effects of land use change on sustainability of food production, biodiversity and global climate change.
- Priorities in further methodology development are linkage with geophysical landscape processes and a better incorporation of crop specific management.

Resumen

Introducción y objetivos

Dentro de la investigación agrícola existe un creciente interés por los estudios integrales de agro-ecosistemas, para tratar la problemática relacionada a la producción sostenible de alimentos al nivel eco-regional. Este interés ha estado estimulado por la conciencia que la demanda alimentaria mundial continuará creciendo, mientras a la vez, se ha ejercido alta presión sobre los recursos naturales necesitados para la producción de los alimentos, tales como suelos aptos y agua disponible. El cambio que la actividad humana ha implicado para el uso de la tierra también ha sido relevante en el cambio global; por su influencia en la emisión de gases invernadero, balance de agua y energía, y biodiversidad.
Estos problemas han confrontado a la investigación con desafíos metodológicos substantivos, tales como la integración de disciplinas biofísicas y socio-económicas a varias escalas espacio-temporales, y el desarrollo de enfoques de modelación para la exploración de los cambios futuros del uso de la tierra y sus efectos.
El objetivo general de esta tesis es analizar la variación espacial y la dinámica temporal de los sistemas de uso agrícola de la tierra, para evaluar cuantitativamente la interacción entre el uso de la tierra con los recursos naturales. Hay tres objetivos derivados: Primero, el análisis espacial de los sistemas de uso de la tierra, para detectar las principales fuerzas directrices biofísicas y socio-económicas del uso actual de tierra, a diversas escalas espaciales. Segundo, la modelación espacialmente explícita de la dinámica del cambio del uso de la tierra a futuro mediato, considerando la estructura de escala múltiple del uso actual de la tierra y sus directrices. Tercero, la cuantificación de los efectos posibles del cambio del uso de la tierra futuro, para los recursos naturales y la producción agrícola.

El área del estudio

El área de estudio es el país Sudamericano, Ecuador. La agricultura es importante en Ecuador, tanto para la producción de cultivos de subsistencia, como para cultivos de exportación. El país está caracterizado por una alta diversidad agro-ecológica. Existe una amplia variedad climática y de las condiciones del suelo, y el uso agrícola de tierra es diverso (con respecto a los cultivos sembrados, así como a los niveles de tecnología utilizados). El uso de la tierra es dinámico debido a la degradación de los recursos, a los cambios en la demanda de productos agrícolas, a la migración, al desarrollo de las exportaciones y de las importaciones, a la influencia de la economía y de las políticas sectoriales. Una serie de eventos en el uso de la tierra causa amenazas serias a los recursos naturales.

Análisis estadístico de escala múltiple de los sistemas actuales de uso de la tierra

Se investigó el uso de la tierra en Ecuador del año 1991, con análisis estadísticos para derivar estimaciones cuantitativas de áreas relativas de los diferentes tipos de uso de la tierra, en base a condiciones bio-geofísicas, socio-económicas y de infraestructura (capítulo 2). Las unidades espaciales mínimas de investigación fueron celdas de 5 por 5 minutos (9,25 x 9,25 km) de una rejilla geográfica que cubrió el país entero. A partir de la agregación de estas celdas, se obtuvo un total de seis niveles artificiales de agregación para analizar la dependencia de la escala espacial de la estructura del uso de la tierra. Para todos los niveles de agregación, se construyó modelos independientes de regresión múltiple para estimar las áreas dentro de las celdas de cultivos permanentes, cultivos temporales, pastos y vegetación natural. Las variables utilizadas en los modelos de regresión fueron seleccionadas de un grupo de direcctrices potenciales (o sus aproximaciones) del uso de la tierra. Se estratificó espacialmente al país en tres eco-regiones principales. Los resultados mostraron que a niveles más altos de agregación, las variables independientes explicaron mejor la variación entre las áreas de cada tipo de uso de la tierra. En la mayoría de casos, variables bio-geofísicas, socioeconómicos, así como de infraestructura fueron importantes para explicar el uso de la tierra. Las variables incluidas en los modelos y su importancia relativa variaron según los tipos de uso de la tierra y según las eco-regiones. Dentro de cada eco-región las variables del modelo también variaron según los niveles de agregación. Los resultados demostraron dependencia de las escalas espaciales de las fuerzas direcctrices del uso de la tierra.

Modelación espacialmente explícita de la dinámica en el uso de la tierra

En el capítulo 3 se dilucidó un modelo espacialmente explícito, de escala múltiple del cambio de uso de la tierra. Las entradas de información importantes para éste modelo, fueron los resultados del análisis de escala mútiple del sistema explicado en el capítulo 2. El modelo consiste de dos módulos principales: el de demanda y el de asignación. Con el módulo de demanda, se estiman los cambios de la demanda nacional de los productos agrícolas; con el módulo de asignación de escala múltiple, se calculan los cambios sub-nacionales de uso de la tierra, resultantes de los cambios nacionales de demanda. La resolución mínima con la que los cambios para Ecuador se calcularon, fue la rejilla de celdas 5 por 5 minutos. El módulo de asignación toma en cuenta las complejidades no lineares de sistemas de uso de la tierra, al considerar la competencia entre los tipos de uso

de la tierra y la interconnexión de los elementos del paisaje. El modelo toma en cuenta fenómenos que operan sobre distancias grandes, tales como la influencia de centros urbanos, la proximidad a la infraestructura y los flujos de migración.
La asignación de los cambios del uso de la tierra fue validada por modelación retroactiva desde el año 1991 hasta el año 1974 (año para el cual se obtuvo datos independientes). Los resultados de la validación mostraron alta concordancia con datos reales de uso de la tierra, al nivel de las unidades administrativas cantonales. Un escenario base, futuro e hipotético del aumento de la demanda de insumos agrícolas fue utilizado para demostrar cómo las dinámicas del uso de la tierra son modeladas. Los resultados determinaron la existencia de "áreas claves", donde potencialmente el uso de la tierra es altamente dinámico, y los impactos del cambio del uso de la tierra en los recursos naturales pueden ser previsibles.

Balance de nutrientes como indicadores de sostenibilidad

Con un modelo del balance de nutrientes se calculó por cada celda las entradas y las salidas de nitrógeno, fósforo y potasio para los tipos principales de uso de la tierra en el año 1991 (capítulo 4). Las entradas consideradas fueron: fertilizante mineral y orgánico, deposición atmosférica, fijación biológica de N y sedimentación. Las salidas consideradas fueron: productos cosechados, remoción de residuos de cosechas, lixiviación, pérdidas gaseosas y erosión. Los resultados de las celdas fueron agregados al nivel sub-nacional y nacional.
En general, las estimaciones mostraron un agotamiento de la provisión de nutrientes del suelo en los agro-ecosistemas ecuatorianos. Al nivel nacional, se obtuvo que en los cultivos temporales hay principalmente un déficit de nitrógeno (42 kg ha^{-1} $año^{-1}$), mientras que para los cultivos permanentes los balances, tanto de nitrógeno como de potasio, son claramente negativos (40 y 25 kg ha^{-1} $año^{-1}$, respectivamente). Para el total de pastos las pérdidas son más pequeñas. La erosión es una causa importante de la pérdida de nitrógeno, pero la lixiviación y la desnitrificación también contribuyen significativamente. En cultivos permanentes, relativamente grandes cantidades de potasio salen del agro-ecosistema en forma de productos cosechados, debido a las altas concentraciones de potasio en tales productos, y rendimientos relativamente altos.
En la escala sub-nacional, el agotamiento de nutrientes bajo el uso actual de tierra es más severo en la región andina que en la región costera, principalmente como resultado de pérdidas por erosión. La región amazónica sigue siendo en gran parte aún inexplotada, pero este estudio sugiere que la conversión actual del bosque en áreas de uso agrícola, podría causar problemas serios en el balance de nutrientes al nivel local.

Exploración a través de escenarios

El modelo de cambio de uso de la tierra fue utilizado para la exploración dinámica y espacialmente explícita de los cambios en el futuro cercano del uso de la tierra en Ecuador (capítulo 5). Un número de escenarios plausibles fue formulado para un período que cubre hasta el año 2010. Al nivel nacional, diversos incrementos de la demanda alimenticia fueron definidos en base de las presunciones del crecimiento de la población, patrones de consumo y desarrollo de las exportaciones. Se evaluó al nivel sub-nacional la protección de los parques naturales y las restricciones en el uso de la tierra por degradación, con respecto a sus posibles impactos espaciales en la dinámica del cambio del uso de la tierra dentro del país. Bajo las suposiciones de los escenarios demandados, el área de tierra para agricultura se expandió significativamente, resultando en más usos de tierra en áreas agrícolas existentes y en la expansión del tipo frontera en áreas naturales imperturbadas. Los patrones de cambio dependieron del aumento de la demanda, competencia entre los tipos de uso de la tierra, cambios de las fuerzas direcctrices del uso de la tierra, y del área excluida del uso agrícola.
Al establecer la relación entre el balance de nutrientes calculado en el capítulo 4, con los resultados del modelo de cambio en el uso de la tierra, se pudo considerar el impacto en la fertilidad del suelo. Los resultados indicaron los potenciales efectos negativos de los cambios del uso de la tierra en el balance de los nutrientes del suelo. Se discutió que la cuantificación de la dinámica del uso de la tierra al nivel del paisaje, puede respaldar la investigación y las políticas dirigidas a entender las direcctrices del cambio del uso de la tierra, y el comportamiento de agro-ecosistemas complejos bajo condiciones cambiantes a diversas escalas espaciales. De ésta manera asuntos relacionados a la producción sostenible de alimentos y al manejo de los recursos naturales, pueden ser abarcados de una manera más integrada y cuantitativa.

Caracterización espacial y temporal de los sistemas de producción andinos de papa

En el capítulo 6, se explicó cómo un análisis estadístico de la estructura espacial de los sistemas de cultivos, se puede combinar con el modelo de cambio del uso de la tierra para caracterizar a un sistema de producción específico. El método fue aplicado para caracterizar la producción de papa en los Andes ecuatorianos. La variación de área y rendimiento de papa fue analizada cuantitativamente, con base en los datos de las celdas. Los resultados mostraron una variabilidad espacial grande en las condiciones de los sistemas de producción de papa. Diferentes combinaciones de variables bio-geofísicas y socio-económicas explicaron mejor, la estructura espacial del área cultivada con papa, así como su productividad, dependiendo del área geográfica analizada. La región andina en conjunto fue analizada, así como las provincias de Carchi y Chimborazo. La salida del modelo de cambio de uso de la tierra fue utilizada para evaluar la posición de los sistemas de producción de papa, dentro de la dinámica general de los tipos principales de uso de la tierra. De esta manera se localizaron áreas donde probablemente hay presión sobre los sistemas de producción de papa, debido a la expansión de otros usos agrícolas de tierra en respuesta a la creciente demanda nacional de alimentos. De esta manera se localizaron áreas donde hay una probable presión sobre sistemas de producción de papa, debido a la expansión de otros tipos de uso de tierra, resultando de la creciente demanda nacional de alimentos. Especialmente se espera competencia con áreas dedicadas a pastos. Cuando las áreas sembradas con papa sean empujadas hacia áreas marginales, seguramente existirán consecuencias negativas para la productividad de papa. Con éstos resultados se pude hacer una tipología de sistemas de producción relacionados a su ambiente. Esta información se puede usar para dirigir la investigación agrícola hacia interacciones específicas entre medio-ambiente y manejo de cultivos.

Conclusiones

- El análisis de escala múltiple del sistema demostró dependencia de escala especial del uso de la tierra en Ecuador.
- Los resultados del análisis de escala múltiple se pudieron integrar en un modelo de uso de la tierra explícito y dinámico.
- Estudios de escenarios con el modelo permitieron la exploración de los cambios posibles que a futuro podrían haber en el uso de la tierra.
- La información cuantitativa y espacialmente explícita, del uso de la tierra generada por el modelo ofrece posibilidades para la valorización del efecto de los cambios en el uso de la tierra en cuanto a sostenebilidad en la producción de alimentos, biodiversidad y cambio global del clima.
- Las prioridades en posteriores desarrollos de la metodología están ligadas a procesos geofísicos del paisaje y a una mejor incorporación de manejo de cultivos específicos.

Samenvatting

Introductie en doelstellingen

In het landbouwkundig onderzoek wordt in toenemende mate aandacht besteed aan de integrale studie van agro-ecosystemen, in relatie tot duurzaamheidaspecten van voedselproductie op eco-regionaal niveau. Deze aandacht wordt gestuurd door de vaststelling dat de wereldwijde vraag naar voedsel zal blijven toenemen, terwijl er tegelijkertijd sprake is van een een sterke druk op natuurlijke hulpbronnen, zoals geschikte bodems en beschikbaar water. Veranderingen in landgebruik door menselijk handelen zijn van belang voor mondiale milieuveranderingen vanwege hun invloed op de emissies van broeikasgassen, op water- en energiebalansen, en op biodiversiteit.
Deze thema's hebben het onderzoek geconfronteerd met methodologische uitdagingen, zoals de integratie van biofysische en sociaal-economische disciplines over verschillende tijdschalen en ruimtelijke schalen, en de ontwikkeling van modelbenaderingen voor de verkenning van de toekomstige veranderingen in landgebruik en de effecten daarvan.
De algemene doelstelling van dit proefschrift is de analyse van de ruimtelijke variatie en temporele dynamiek van agrarische landgebruiksystemen, met als doel de interactie tussen landgebruik en de natuurlijke hulpbronnen te kwantificeren. Dit wordt gedaan aan de hand van drie afgeleide doelstellingen. Ten eerste, de ruimtelijke analyse van landgebruiksystemen, om zo de drijvende biogeofysische en sociaal-economische krachten van huidig landgebruik op verschillende ruimtelijke schalen te achterhalen. Ten tweede, het ruimtelijk expliciet modelleren van landgebruikdynamiek in de nabije toekomst, daarbij gebruik makende van kwantitatieve informatie over de drijvende krachten van huidig landgebruik op verschillende ruimtelijke schalen. Ten derde, de kwantificering van de mogelijke effecten van toekomstige landgebruikveranderingen op natuurlijke hulpbronnen en op landbouwproductie.

Het studiegebied

Het studiegebied is het Zuid-Amerikaanse land Ecuador. Landbouw is in Ecuador belangrijk voor zowel de productie van voedselgewassen als voor de productie van exportgewassen. Het land wordt gekarakteriseerd door een grote agro-ecologische diversiteit. Er bestaat een grote variatie in bodem- en klimaatomstandigheden, en ook het agrarisch landgebruik is divers, zowel wat betreft de gewassen die worden verbouwd als de productietechnieken die worden gebruik. Landgebruik is er dynamisch door de degradatie van natuurlijke hulpbronnen, veranderingen in de vraag naar landbouwproducten, migratie, export- en importontwikkelingen, economische ontwikkelingen en sectorbeleid. Sommige ontwikkelingen in het landgebruik vormen een bedreiging voor de natuurlijke hulpbronnen van het land.

Statistische analyse van landgebruiksystemen op verschillende schaalniveaus

Landgebruik in Ecuador werd onderzocht voor het jaar 1991 door middel van een statistische analyse. Het doel van de analyse was om kwantitatieve schattingen te geven van de arealen van verschillende landgebruiktypes, op basis van de biogeofysische, socio-economische en infrastructurele condities (Hoofdstuk 2). De kleinste ruimtelijk eenheden van onderzoek waren cellen ter grootte van 5 bij 5 minuten (9.25 bij 9.25 kilometer) van een geografisch raster dat het hele land besloeg. Door aggregatie van deze cellen werd een totaal van zes kunstmatige aggregatieniveaus verkregen, met als doel de schaalafhankelijkheid van de landgebruikstructuur te analyseren. Voor alle aggregatie-niveaus werden onafhankelijke regressiemodellen geconstrueerd voor de schatting van de arealen binnen cellen van meerjarige gewassen, eenjarige gewassen, grasland en natuurlijke vegetatie. De variabelen in de regressiemodellen werden geselecteerd uit een set potentiële (benaderingen van) sturende variabelen. Er werd een ruimtelijke stratificatie uitgevoerd door het land in drie eco-regio's in te delen. Uit de resultaten bleek dat op hogere aggregatieniveaus een groter deel van de variatie in de arealen van de verschillende landgebruiktypes verklaard kon worden. In de meeste gevallen waren zowel biogeofysische, sociaal-economische als infrastructurele variabelen van belang voor de beste verklaring van landgebruik. De variabelen in de regressiemodellen, en hun relatieve bijdrage, hingen af van landgebruiktype en eco-regio. Binnen eco-regio's varieerden de modelvariabelen ook met het aggregatieniveau. De resultaten lieten zien dat er een schaalafhankelijkheid bestaat met betrekking tot de sturende krachten van landgebruik.

Ruimtelijk-expliciete modellering van de dynamiek van landgebruik-veranderingen

Een ruimtelijk-expliciet landgebruikverandering-model voor meerdere schaalniveaus werd beschreven en gedemonstreerd in Hoofdstuk 3. Belangrijke invoergegevens voor het model waren de resultaten van de systeemanalyse op verschillende schaalniveaus van Hoofdstuk 2. Het model bestaat uit twee hoofdmodules, de vraag-module en de allocatie-module. Veranderingen in de nationale vraag naar voedsel wordt geschat met de vraag-module. De sub-nationale veranderingen in landgebruik als gevolg van veranderingen in de vraag worden berekend in de allocatie-module voor verschillende schaalniveaus. De hoogste resolutie waarvoor veranderingen werden uitgerekend voor Ecuador waren de cellen van 5 bij 5 minuten. De allocatie-module incorporeert non-lineaire complexiteit van landgebruiksystemen, door rekening te houden met competitie tussen verschillende

landgebruiktypes en met de verbondenheid van ruimtelijk distante landschapselementen. Processen die over grote afstanden effect hebben, zoals de invloed van urbane centra, de nabijheid van infrastructuur, en migratie, kunnen worden meegenomen.
De allocatie van landgebruikveranderingen werd gevalideerd door vanaf het jaar 1991 terug te modelleren naar het jaar 1974, een jaar waarvoor een onafhankelijke gegevensset beschikbaar was. De resultaten van de validatie lieten een goede overeenkomst van de modelberekeningen met de werkelijke landgebruikgegevens zien op het niveau van kantons (administratieve eenheden). Een hypothetisch basisscenario voor de nabije toekomst werd gebruikt om te demonstreren hoe de dynamiek van landgebruik wordt gemodelleerd. De resultaten geven een indicatie van de zogenaamde 'hot-spots', plaatsen waar een grote landgebruikdynamiek waarschijnlijk is, en waar effecten op de natuurlijke hulpbronnen te verwachten zijn.

Nutriëntenbalansen als indicators voor duurzaamheid

Met een nutriëntenbalans-model werden voor elke rastercel de aanvoer en afvoer van stikstof, fosfor en kalium geschat voor de belangrijkste landgebruiktypes voor het jaar 1991 (Hoofdstuk 4). De aanvoerposten van de nutriëntenbalans die in beschouwing werden genomen waren: kunstmest, organische mest, atmosferische depositie, biologische stikstoffixatie en sedimentatie. De afvoerposten betroffen: geoogst product, afgevoerde gewasresten, uitspoeling, vervluchtiging en erosie. De resultaten werden geaggregeerd tot sub-nationaal en nationaal niveau.
In het algemeen lieten de schattingen een afname van de nutriëntenvoorraad zien voor Ecuadoraanse agro-ecosystemen. Op nationaal niveau was er voor eenjarige gewassen vooral een tekort van stikstof (42 kg ha^{-1} jr^{-1}), terwijl voor meerjarige gewassen zowel de stikstofbalans als kaliumbalans duidelijk negatief waren (respectievelijk 40 en 25 kg ha^{-1} jr^{-1}). Voor grasland waren de verliezen kleiner. Erosie is een belangrijke verliespost voor stikstof, maar ook uitspoeling en vervluchtiging kunnen van belang zijn. In meerjarige gewassen worden naar verhouding grote hoeveelheden kalium afgevoerd met het geoogste product, door de hoge kaliumconcentraties in die producten en de relatief hoge opbrengsten.
Op sub-nationaal niveau zijn de nutriëntverliezen bij het huidige landgebruik sterker in de Andes dan in het kustregio, voornamelijk door grotere verliezen via erosie. Het grootste deel van het Amazone-gebied wordt vooralsnog niet geëxploiteerd, maar deze studie suggereert dat de in gang zijnde conversie van bos naar landbouwgrond ernstige consequenties kan hebben voor bodemvruchtbaarheid op lokaal niveau.

Verkenningen met scenarios

Het landgebruikverandering-model voor Ecuador werd gebruikt voor een dynamische en ruimtelijk-expliciete verkenning van agrarische landgebruikveranderingen in de nabije toekomst (Hoofdstuk 5). Een aantal plausibele scenario's werd geformuleerd voor de periode tot het jaar 2010. Op nationaal niveau werden verschillende ontwikkelingen met betrekking tot nationale voedselvraag geformuleerd op basis van aannames voor bevolkingsgroei, consumptiepatronen en export-ontwikkelingen. Op sub-nationaal niveau werden de bescherming van natuurparken en landgebruikbeperkingen als gevolg van bodemdegradatie geëvalueerd met betrekking tot hun mogelijke ruimtelijke consequenties voor de landgebruikdynamiek in het land. Onder de aannames van de vraag-scenario's nam het totale landbouwareaal duidelijk toe, hetgeen resulteerde in uitbreiding in bestaande landbouwgebieden en expansie in gebieden met een relatief ongestoorde natuurlijke vegetatie. De gemodelleerde patronen van veranderend landgebruik hingen af van de toename in vraag, de competitie tussen verschillende landgebruiktypes, veranderingen in de sturende krachten van landgebruik, en de oppervlakte land dat werd uitgesloten voor agrarisch gebruik.
De effecten op bodemvruchtbaarheid werden bepaald door de uitkomsten van de nutriëntenbalans beschreven in Hoofdstuk 4, te relateren aan de resultaten van het landgebruikverandering-model. De resultaten gaven de negatieve effecten aan die landgebruikveranderingen kunnen hebben op de bodemvruchtbaarheid. Er werd bediscussieerd dat de kwantificering van landgebruikdynamiek onderzoek en beleid kan ondersteunen dat is gericht op het begrip van de sturende krachten van landgebruikveranderingen en het gedrag van complexe agro-ecosystemen onder veranderende omstandigheden op verschillende ruimtelijke schalen. Op die manier kunnen kwesties, gerelateerd aan duurzame voedselproductie en management van natuurlijke hulpbronnen, op een meer kwantitatieve en geïntegreerde manier onderzocht worden.

Ruimtelijke en temporele karakterisering van aardappel-produktiesystemen in de Andes

Een statistische analyse van de ruimtelijke structuur van teeltsystemen kan worden gecombineerd met het landgebruikverandering-model om een bepaald teeltsysteem te karakteriseren. De methode werd toegepast voor aardappel-produktiesystemen in het Andesgebergte van Ecuador (Hoofdstuk 6). De variatie in aardappelarealen en aardappelopbrengsten werd geanalyseerd op basis van de data voor de rastercellen. De resultaten lieten een grote ruimtelijke variatie zien in de condities van aardappel-produktiesystemen. De combinaties van biofysische en sociaal-economische variabelen die de ruimtelijke structuur van aardappelarealen en aardappelopbrengsten het best verklaarden waren afhankelijk van het geografische gebied dat werd geanalyseerd. De gehele Andes-regio werd geanalyseerd, en tevens de provincies Carchi en Chimborazo. De uitkomsten van het landgebruikverandering-model werden gebruikt om de positie van aardappel-produktiesystemen te evalueren binnen de algemene dynamiek van de belangrijkste land-gebruiktypes. Op deze manier werden de gebieden gelokaliseerd waar aardappel-produktiesystemen onder druk kunnen komen staan als gevolg van expansie van andere agrarische landgebruikvormen in reactie op toenemende voedselvraag. Vooral competitie met grasland wordt verwacht in de nabije toekomst. Als aardappelproduktie meer in marginale gebieden plaats gaat vinden zal dit negatieve gevolgen hebben voor de productiviteit van de aardappelteelt. Met zulke resultaten kan een typologie gegeven worden van produktiesystemen in relatie tot hun omgeving. Deze informatie kan gebruikt worden om agro-ecologisch onderzoek te richten op specifieke interacties tussen omgeving en gewasmanagement.

Conclusies

- Een systeemanalyse op verschillende schalen liet zien dat landgebruik in Ecuador schaalafhankelijk is.
- De resultaten van de systeemanalyse op verschillende ruimtelijke schalen konden worden geïntegreerd in een ruimtelijk expliciet dynamisch landgebruikverandering-model.
- Met het model konden toekomstige landgebruikveranderingen worden verkend door middel van scenario's
- De door het model gegenereerde kwantitatieve en ruimtelijk expliciete informatie over landgebruikveranderingen biedt mogelijkheden voor het vaststellen van effecten van landgebruikveranderingen op de duurzaamheid van voedselproductie, op biodiversiteit en op mondiale milieuveranderingen.
- Prioriteiten voor verdere methodologie-ontwikkeling zijn het maken van een functionele verbinding met geofysische landschapmodellen en het incorporeren van gewasspecifiek management.

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Curriculum vitae

Godefridus Henricus Johannes de Koning was born on May 25, 1962, in Sint-Oedenrode, The Netherlands. In 1980 he completed secondary education (V.W.O.) at the Zwijsen College in Veghel, and started his study at Wageningen Agricultural University.
In 1988 he graduated in crop science at Wageningen Agricultural University. His MSc research included investigations related to crop physiology, crop ecology, environmental studies, and theoretical production ecology.
From 1988 to 1991 he was employed at the DLO Winand Staring Centre (SC-DLO), and worked within the "Ground for Choices"-project for the Dutch Scientific Council for Government Policy (WRR). The research concerned the quantitative exploration of the crop growth potential of the European Union.
From 1991 to 1994 he worked at the DLO Research Institute for Agrobiology and Soil Fertility (AB-DLO) and was involved in various projects. In a continuation on the project of WRR, he determined technical coefficients of cropping and livestock systems in the European Union. He also participated in a study on the global agro-ecological characterisation for potato production. Furthermore, he was involved in a project for the European Joint Research Centre, directed at the development of a yield forecasting system for Europe.
In 1994 he started at the Agronomy Department of Wageningen Agricultural University with the PhD-research that is described in this thesis. The research was executed in collaboration with the International Potato Centre (CIP) and he was partly stationed at the regional office of CIP in Quito, Ecuador.
Currently he is working at Wageningen Agricultural University as project co-ordinator within the project "Multi-scale land use modelling", financed by the Dutch National Research Programme on Global Air Pollution and Climate Change.