Stellingen

1. Holling's theorieën over de complexiteit van het ecosysteem kunnen de vereiste ontwikkeling van een aparte theorie voor het evenzo complexe landgebruiksysteem in de weg staan.
   Dit proefschrift
   Holling, C.S., 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systems 4: 1-24.

2. Een empirische beschrijving van het gehele landgebruiksysteem is te prefereren boven een procesbeschrijving van een bekend deelsysteem.
   Dit proefschrift

3. Het pleidooi van landgebruiksmodelleurs voor het analyseren op meerdere resoluties is niet relevant voor Midden-Amerika door het nagenoeg ontbreken van het effect van ruimtelijke resolutie op de relaties tussen landgebruik en de sturende factoren.
   Dit proefschrift
   Turner II, B.L., Skole, D.L., Sanderson, S., Fischer, G., Fresco, L.O., Leemans, R., 1995. Land-use and land-cover change. Science/Research Plan. IGBP report no. 35 and HDP report no. 7, Stockholm and Geneva.

4. Ruimtelijk expliciet modelleren van landgebruik op mondiale schaal met behulp van wereldregio's, zoals binnen het IMAGE model, is onrealistisch, omdat een staat de grootste organisatorische eenheid is die als één geheel beschouwd kan worden.
   Dit proefschrift
   Zuidema, G., van den Born, G.J., Alcamo, J., Kreileman, G.J.J., 1994. Simulating changes in global land cover as affected by economic and climatic factors. Water, Air, and Soil Pollution 76: 163-198.

5. Het is onaanvaardbaar dat de suggestie van beleidsrelevantie, zoals die is opgenomen in veel projectvoorstellen op het gebied van de landgebruikmodellering en op grond waarvan deze mede worden goedgekeurd, onvoldoende wordt getoest door modellen toe te passen onder praktijkomstandigheden.

6. John Daly's bewering dat de door het IPCC gepresenteerde 'hockeystick' – de mondiale opwarming van de laatste 30 jaar – fout gebruik van gegevens is, is een schoolvoorbeeld van liegen met statistiek, waarmee hij feitelijk zijn gelijk aantoont.
   http://www.vision.net.au/~daly/

7. Het citaat "Where you come from is gone, and where you thought you were going to was never there" gebruiken om modellen gebaseerd op het verleden en projecterend naar de toekomst af te kraken, is leven verwarren met wetenschap bedrijven.
   Citaat uit: Jesus built my hotrod (Redline/Whiteline version), Ministry.

8. De conclusie dat "tropical rainforest does not exist and never has existed … in geological time" is om schaaltechnische redenen onjuist.
   Stott, P., 2000. Tropical rain forest: A political ecology of hegemonic mythmaking. Studies in the Environment 15. Institute of Economic Affairs, London.

9. Politici begrijpen heel goed hoe wetenschappers statistiek kunnen misbruiken, getuige de uitspraak "Sommige mensen gebruiken statistiek zoals een dronkeman een lantaarnpaal: niet ter verlichting maar ter ondersteuning".
Henk Vonhoff als Commissaris der Koningin van Groningen in een interview met Harold Schuil, 1995.

10. Sceptici van het gebruik van regressiemethodes ontkrachten hun eigen argument door het eindeloos aandragen van het voorbeeld van de bestaande correlatie tussen ooievaars en geboortecijfers van mensen.

11. Mensen met een visie zijn te zeker van hun zaak en daarom blind voor verrassingen.

12. De verloedering van de Nederlandse taal blijkt uit de schijnbare onvertaalbaarheid van de Engelse titel van dit proefschrift.

13. Door de opkomst van de 'global village' kan het spreekwoord "beter een goede buur dan een verre vriend" beter omgedraaid worden.

Stellingen behorende bij het proefschrift
Scaling the land use system. A modelling approach with case studies in Central America
Kasper Kok, Wageningen, 29 januari 2001

Scaling the land use system
A modelling approach with case studies for Central America

Promotoren: Prof. Dr. Ir. J. Bouma
Hoogleraar in de bodeminventarisatie en landevaluatie

Prof. Dr. Ir. L.O. Fresco
Voormalig hoogleraar plantaardige productiesystemen met bijzondere aandacht voor de tropen, tevens persoonlijk hoogleraar externe betrekkingen

Co-promotor: Dr. Ir. A. Veldkamp
Universitair hoofddocent bij het Laboratorium voor Bodemkunde en Geologie

Samenstelling promotiecommissie:
Dr. W. Steffen, Royal Swedish Academy of Sciences, Stockholm, Zweden.
Prof. Dr. A.K. Skidmore, ITC, Enschede.
Prof. Dr. E.C. van Ierland, Wageningen Universiteit, Wageningen.
Prof. Dr. Ir. A.K. Bregt, Wageningen Universiteit, Wageningen.

Scaling the land use system

A modelling approach with case studies for Central America

Kasper Kok

PROEFSCHRIFT
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit,
Prof. Dr. Ir. L. Speelman,
in het openbaar te verdedigen
op 29 januari 2001
des namiddags te vier uur in de Aula

Land use systems in Central America are highly complex and it would be haughty to consider them like anything but a series of nested black boxes.

CIP-gegevens Koninklijke Bibliotheek, Den Haag

The research reported in this thesis was funded by the Dutch National Research Programme on Global Air Pollution and Climate Change (NRP-II)

Kok, K., 2001

Scaling the land use system. A modelling approach with case studies for Central America.
Thesis Wageningen University – with summaries in English, Spanish, and Dutch.

ISBN 90-5808-355-1

Keywords: land use, scale, spatial analysis, modelling, GIS, natural resources, Costa Rica, Honduras, Central America

Acknowledgements

I feel privileged considering the work I have been conducting for the past almost five years. Not only because of the fantastic learning experience it was, the freedom that my (co-)promotors gave me, and the inspiring working environment, but also because of the places I was able to visit, the people that I got to know and friends that I made. I believe all those factors have contributed to the quality of this thesis. Unfortunately I can't thank everybody personally here and I apologise for those that I haven't mentioned that do feel they added to the work.

First in this hierarchically nested list are my (co-)promotors, Louise Fresco, Johan Bouma, and Tom Veldkamp. Louise, the fact that I still lament your departure to FAO indicates how I value your input, although mainly restricted to the first year. Your drive for new challenges and to incorporate 'fresh blood' has been an inspiration for me as well as for the CLUE-work as a whole. Tom, you were a better supervisor than I had ever imagined I would have. Tedious paperwork, correcting papers, numerous brainstorm sessions, meetings, I can't think of any main activity that you weren't involved in from time to time. Johan, thanks for the interest and enthusiasm you have shown from the very moment you became my promotor, despite the sudden and unanticipated way it started.

Second are my fellow members in what has become known as the CLUE group, Free de Koning, Peter Verburg, Aldo Bergsma, Jörg Priess, and Jeroen Schoorl. Guys, I am very happy to have worked with such a diverse group of scientists that took the time and effort to oppose my sometimes hardheaded attitude. Free, I have always very much enjoyed our endless conversations about anything during the years that we shared an office at the Agronomy department, although we probably distracted each other from work more than we should have. Peter, you know how I have appreciated your almost passionate input in the CLUE work. And of course I have to thank you for always being a few months ahead of me, which saved me a lot time! Aldo, thanks for staying friendly, helpful, and willing towards a stubborn deadline worker that needs everything finished yesterday. Jörg, thanks for giving the CLUE model its well deserved (inter)face. Too bad Göttingen is a bit too for away from here. Jeroen, it seems ages ago you were part of the team, but to date your are still the only person that has bothered to write a decent documentation.

The following level in the hierarchy is based on location, since I've carried out the work at several places. During the first couple of years, my office was at the former department of Agronomy, where I was part of the sudden invasion of CLUE-minded people. I thank my former colleagues for their interest and respect for our line of work, as most of them were involved in very different types of research. I want to especially thank Nico de Ridder for his involvement in CLUE, Tjeerd Jan Stomph for being a willing victim of my frustrations on the squash court, Rik Schuiling for accompanying me in the evening hours (with or without opera music) and furthermore, Jan Wienk, Marieke Bosman, and Wampie van Schouwenberg for the professional support.

The last year I spent at the Laboratory for Soil Science and Geology, mostly hiding behind a computer screen. I'd like to especially thank Joke Cobben, Thea van Hummel, Henny van den Berg, and Marcel Lubbers for the logistic support and Virginie, Marthijn, and Ellis for the lively lunch break discussions.

Besides, I chose to spend a considerable amount of time in Latin America. Those of you who know my love for Colombia and its people understand how happy I was when I could return to that beautiful country. I stayed close to a year and a half at CIAT in Cali, Colombia. I would like to thank Bill Bell and Ron Knapp for the initial invitation (that I gladly accepted) and for providing me with data, an office, and support every time I came to CIAT. Manuel Winograd and Andy Farrow deserve my gratitude for believing in the model and giving me the opportunity to test its value outside the scientific realm. I thank Glenn Hyman, Gregorie LeClerc, Natalie Beaulieu and Peter Jones for their logistic support and help with compiling the datasets. Furthermore, Andy & Bregje, Andy & Brechje, Nanda, thanks for your friendship. Silvia Elena, gracias. No necesito palabras, tu me conoces como nadie. Vicky, mi chismosa amiga, siempre me has dado tanto respeto y amor. Gracias.

During the 6 months that I have spent in the Research Centre of Wageningen University, I enjoyed the hospitality of numerous Costa Ricans and Dutch people. I like to especially mention Hans Jansen, Bas Bouman, André Nieuwenhuyse, Huib Hengsdijk and Peter Roebeling for discussions and sharing their knowledge on the land use system in the Atlantic Zone and Guanacaste. Cor, thanks for relieving me of the tedious data processing. Astrid, I sincerely hope that during the next world championship your head will feel better.

And that leaves all the people that endured my presence in off-work situations. Even though I would love to use two pages, I really can't name more than a few. Robert, thanks for the long nights with green and gold, buddy. The distraction from work that you and Ana have given me was invaluable. Jella, well... you know. The more you love somebody, the less words fit to describe it. Marcela, our friendship surely goes back a long way and has brought us together in quite a few unexpected but wonderful places. I don't expect this to cease! Laurens, I won't repeat again how I enjoy beating you by a fortnight, and I'll see you in Mainz. Edwin, thanks for allowing me discussions 'at the same level' and I hope to see your thesis one day! Mark and Inge, you made my stay in Arnhem very pleasant and I'm sure that we'll be playing shithead somewhere ten year from now. Judith, you and I have redefined 'bad timing', but you have nevertheless been my muse in the final year. And of course my housemates. Astrid, and Rick, Rio (and Rik), Norbert, Manon, Erwan, Esther. Thanks a million for coping with my strange working hours, stranger social habits, and strangest music preferences.

En tenslotte mijn ouders. Hoewel jullie me de afgelopen jaren waarschijnlijk minder vaak gezien hebben dan mijn promotoren, hebben jullie natuurlijk ontzettend veel bijgedragen aan het feit dat dit boekje er nu ligt. En dan heb ik het niet alleen over het corrigeren van een samenvatting of telkens maar weer komen uitzwaaien op Schiphol. Enorm bedankt voor alles.

Preface

This thesis describes and discusses the application of a land use change model that quantitatively accounts for various aspects of 'scale'. The unique aspect of the model is its aim to apply a multi-scale methodology as opposed to a theoretical elaboration on the existence of the 'scale-effect'. The overall objective of this project is to analyse the scale sensitivity of land use modelling. Furthermore, it is the intention to show how different parts of the model function, how model results can be interpreted and to discuss validation results. The thesis can be read independently, but has by no means been the work of one person. Including this one, three PhD theses are available that are largely based on the same land use model, and it is only when read together, that all aspects and subtleties of the model will become apparent. So, for any further clarification, reference is made to the PhD theses of Peter Verburg (Verburg, 2000) and Free de Koning (De Koning, 1999). This thesis applies the land use change model to Central America, in which main land use change processes are in many ways complementary to particularly the study areas of Peter Verburg (China and Java). The main reaction of land use in Central America to the fast growing demand for agricultural products is an area expansion, which results in a continuing deforestation. Among others, high population growth rates, a relatively high accessibility of forested areas, and the vicinity of the US market ensure continuation of present trends. Past, present, and future developments of land use and its drivers will be discussed in the various chapters. Because of my background in ecology, I often refer to the theories that concern the ecosystem, which have a longer history and are more developed than land use system theories. In particular, many of the principles of multi-scale analysis resemble those derived in the field of landscape ecology, and ecosystem theories as formulated by Holling fit to describe the modelled behaviour of the land use system. This thesis is intended to add to the general understanding of modelling the land use system, and will keep alive the discussion about how to model land use best. Chapter 2 till 7 form the core of the thesis and will be published as articles or book chapters. The advantage of presenting results in the form of number of concise and clear messages outweighs possible discontinuities between the chapters. Chapter 1 and Chapter 8 clarify and summarise key issues and merge findings of separate chapters.

Kasper Kok
Wageningen, December 2000

Table of contents

CHAPTER 1
General introduction

This chapter aims at introducing the key issues in land use modelling that are addressed in this thesis. In order of appearance the following issues will be discussed: Definitions of land cover and land use; agricultural census as data source; history and land use in the case study area; Central America, behaviour of complex systems and the role of ecosystem theory; and land use change models. Finally, an outline of the thesis is given.

1.1 Land use and land cover

Land use and land cover relate to two basically different concepts. *Land cover* is the *vegetation (natural or planted) or man-made constructions (buildings etc.) which occur on the earth surface. Water, ice, bare rock, sand and similar surfaces also count as land cover* (FAO, 1994). Even though not completely unambiguous, the definition constrains land cover to immediately visible features. Forest, grassland, and built-up land are good examples of land cover classes. *Land use* can be defined as *involving both the manner in which the biophysical attributes of the land are manipulated and the intent underlying that manipulation* (Turner *et al.*, 1995). Forestry, conservation practices, livestock herding, and fertiliser application are examples of land use classes. Although theoretically distinct, in literature both terms are often used interchangeably. Confusion arises because of the close dependency of land cover and land use. Once land cover is known (*e.g.* natural vegetation), many aspects of land use (*e.g.* conservation) can often be inferred, depending on availability of auxiliary information. The translation of land cover in terms of associated land use is common when using remotely sensed data, such as satellite images or aerial photographs. Similarly, a certain land use (*e.g.* maize sowing) will often lead to a related land cover (*e.g.* maize) that consequently can be easily identified based on land use information. This thesis deals with a basically different data source, which further diminishes the differences between land use and land cover, namely, agricultural census data.

Census data is collected by interviewing a large number of farmers. Information is gathered on various categories of land use that are subsequently presented as land cover classes like maize, pasture, or fallow land. The output classes of an agricultural census can be best described as '*land cover with aspects of land use*'. In the remainder of this thesis this definition will be used and referred to as land use rather than land cover. The class 'natural vegetation' will, for instance, include multiple land covers (forest, natural pasture, secondary vegetation, etc.) *and* multiple land uses (conservation, selective logging, no use); the class 'maize' basically includes a single cover (maize), but many land use related management practices, like ploughing, weeding, fertiliser application, harvesting. Following Turner *et al.* (1995) we discriminate between *land use modification* and *land use conversion*, where the former relates to land use change and the latter to land cover change. In this thesis, land use change mostly refers to land use conversion.

1.2 Agricultural census data

In many countries in the world, especially in Latin America, agricultural censuses are conducted once every decade. They are based on a very large number of interviews with farmers and contain a wealth of information on a large variety of agricultural land uses and practices. Data are usually aggregated to administrative units and are made available in the form of books with tables. The most recent census that was conducted in Honduras (SECPLAN, 1994) lists *e.g.* area sown and harvested, production, and fertiliser use for more than 200 crops, including 8 varieties of maize and beans for over 300 municipalities. Despite the huge amount of information, little use has been made of this potential data source. Often heard criticisms include the poor spatial resolution, unknown data quality, and outdated nature of the information. Indeed, administrative units are not the best way to aggregate agricultural data, because boundaries of the political system upon which they are based do not necessarily coincide with boundaries of the natural system. The lack of a data quality indication is worrying, but should not be a reason to refrain from using the data. This thesis aims to substantiate the advantages of agricultural census data, especially when applied to larger areas, by using this type of information as main source of information. The data set used in Chapter 4 and 5, for example, is most likely the best map of actual land use for Central America available to date. Its spatial resolution is more than sufficient and its thematic detail is far better than any remote sensing technique might offer.

1.3 Central America

All model applications in this thesis deal with (parts of) Central America. The region offers excellent modelling possibilities, because of the small size of its countries, combined with a diverse and dynamic land use and strong environmental gradients. Central America included Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, and Panama following the political definition (Brockett, 1988; Diaz-Bonilla, 1990; Bulmer-Thomas, 1998). Much of what will be concluded on land use (change) in these six countries relies on historical developments and historical importance of land use drivers. Present land use patterns can perhaps be *explained* by the present distribution of land use drivers, but to fully *understand* patterns, an understanding of past developments is essential. Only then can a model about possible future relationships be defined and implemented with any degree of confidence.

1.3.1 History

Historical developments in Central America have been discontinuous and erratic but with clear thresholds between various periods (Pelupessy and Weeks, 1993; Weaver, 1994). Most important changes in recent history that influenced Central America were related to either the occurrences of civil wars or to (macro-)economic developments (Brockett, 1988; Diaz-Bonilla, 1990; Ardon and Eade, 1999). Especially the latter marks the transition between periods. Civil wars influenced the history of most countries, particularly that of El Salvador, Nicaragua, and Guatemala (Weinberg, 1991). But although the wars passed by on Costa Rica and Honduras, the whole of Central America suffered large periods of political instability during the last decades (Diaz-Bonilla, 1990). The influence of wars on the political system directly and ultimately on land use indirectly is evident, though hard to evaluate. The present relative stability seems to minimise the risk for a renewed outbreak of guerrilla activity. Since about the 1920s, the countries of Central America have followed an export-led strategy of economic development based on agricultural products. After years of generally favourable economic circumstances, the 1970s were characterised by political instability and external shocks (*e.g.* the first oil crisis, the Green Revolution), which lead to the marginalisation of the peasantry and rising inflation (Pelupessy and Weeks, 1993). Land redistribution programs, especially in Honduras and Costa Rica, were formulated to deal with increasing poverty (Thorpe, 1997b; Becker, 1998). The result was a large-scale migration of rural population to undisturbed rainforest. At the same time at regional level, the second oil crisis hit hard. Between 1979 and 1982 per capita GDP (Gross Domestic Product) growth rates were highly negative, poverty increased, and export was reduced. Over the past two decades Central America entered the slow process of recovery, embodied by a dramatic process of market liberalisation (Rueda-Junquera, 1998; Geske Dijkstra, 2000; David *et al.*, 2000).

Table 1.1. Key socio-economic indicators for countries in Central America. Values are averages for the period 1990-1995 as reported by World Bank (World Bank, 1998).

Country	GDP (US$)	Population density (ind./km^2)	Population growth (% yr^{-1})	Illiteracy (%)	Access to safe water (%)
Costa Rica	2610	67	2.3	5	100
El Salvador	1610	270	2.2	29	62
Guatemala	1340	98	2.9	44	64
Honduras	600	53	3.0	27	70
Nicaragua	380	36	3.1	34	57
Panama	2750	35	1.7	9	82

These processes, although largely comparable between the countries, resulted in substantially different present economic situations as listed in Table 1.1 (see also World Bank, 1998; World Bank, 2000). Honduras and Nicaragua rank among the poorest in the Western Hemisphere with a very low GDP per capita and more than 50% of the population still living in poverty. Both countries, however, have a relatively low population density and Nicaragua has abundant natural resources, allowing room for improvement. The GDP per capita in El Salvador is much higher, but the extremely high population density, lack of natural resources, and long-time civil wars provide little positive future prospects. The same holds for the largest economy in the region, Guatemala, where a relatively high GDP per capita is counteracted by a highly unequal income distribution. Although on its way to become a more equitable society, Panama's poverty incidence continues to be relatively high in comparison to its per capita income. For several years, Costa Rica has been one of the more stable and robust democracies of Latin America, based on a strong export-led development. Healthy GDP growth is coupled with social well being, and besides, the country has been a pioneer in environmental protection. This combination has triggered a blooming tourist industry.

1.3.2 Factors of land use and land use change

At different scales, different factors have played a key role in the development of Central American land use and land use patterns. Perhaps most intensively studied is the deforestation process, which can serve as an example of the complexity of land use changes. There is an ongoing debate on which factors ultimately triggered deforestation (see Bawa and Dayanandan, 1997). Angelsen (1999) proposes a distinction into two types: planned and unplanned. Planned deforestation is driven by national and international markets and demand for both timber and beef that augment the need for pasture or wood. International demand for beef has indeed influenced the deforestation process in Central America (Lutz and Daly, 1991; Howard-Borjas, 1995; Thorpe, 1997a; Humphries, 1998). The proximity of the large US market triggered large-scale deforestation. Howard-Borjas (1995) argues that an increased beef demand from the US initiated deforestation and formation of large farms that in turn forced small farmers into other virgin forest stands. This touches upon the unplanned deforestation as proposed by Angelsen (see also Harrison, 1981; Rudel and Roper, 1997). Sheer population pressure and poverty will drive people out of populated areas and into the forest. This type of deforestation might be more important than many authors believe, as it was strongly promoted by several countries during the 1960s and 1970s, through land redistribution programs (Jones, 1989), and road construction to increase in accessibility of forest areas. Finally, tradition and status to own land and cattle will also have contributed to the forest destruction. The above factors basically have a bearing on the amount of land use change and have little to do with the exact location. When the pattern of deforestation is the topic of study, a whole range of other groups of factors become influential. Climatic conditions (altitude, rainfall), biophysical circumstances (soil characteristics, slope steepness), and accessibility (distance to road), to name a few, determine exact locations of deforestation. Although there are many other land use changes, at the range of scales considered here, the forest to pasture conversion was the most important one in the recent history of Central America. With the ongoing process of environmental awareness and the shift from traditional agriculture to a greater variety of new crops, it is questionable whether deforestation will continue at the same magnitude as in the past. When the example of deforestation is generalised, it can be concluded that modelling of spatially explicit land use change needs to incorporate the following:

- a projection of macroeconomic developments inside and outside the region
- population migration patterns in the region
- a broad range of climatic, biophysical, demographic, social, and political factors that might constrain or enhance local changes.

A selection of some of the factors that are mentioned in literature as influencing and controlling land use change in Latin America is given in Table 1.2.

Table 1.2. Driving forces of spatially explicit land use change

Land use change driver	Type	Source
Population density	Demographic	Rudel and Roper (1997), Angelsen (1999), Pfaff (1999), Veldkamp and Fresco (1997)
Distance to city		Southgate *et al.* (1991)
Distance to road		Sader and Joyce (1988), Parayil and Tong (1998)
Topography	Biophysical	Hall *et al.* (1995), Rudel and Roper (1997)
Elevation		Veldkamp and Fresco (1997), Pontius *et al.* (2001)
Slope		Sader and Joyce (1988), Kammerbauer and Ardon (1999)
Soil type		Ludeke *et al.* (1990), De Koning *et al.* (1998)
Climate variability	Climatic	Chomitz and Gray (1995), De Koning *et al.* (1998)
Life zone		Sader and Joyce (1988), Ludeke *et al.* (1990)
Land redistribution programs	Political	Brockett, (1988), Jones (1989)
Park protection		Chomitz and Gray (1995), De Koning *et al.* (1998)
Subsidy system		Quiros *et al.* (1987), Hansen-Kuhn (1993)
Land tenure	Economic	Becker *et al.* (1998), Humphries (1998)
Farm size		Thorpe (1997)
Income		Stonich (1993), Rudel and Roper (1997)
Distance to market		Chomitz and Gray (1995), Godoy *et al.* (1997)
Tradition	Social	Joly (1989), Edelman (1992)
Status		Schelhas (1996)
Education level		Godoy *et al.* (1997), De Koning *et al.* (1998)
Diseases	Miscellaneous	Jones (1989)
Civil war		Diaz-Bonilla (1990)

This far from exhaustive list of actual factors driving land use change underlines the complexity of the land use system. A consequence is the need for an integrated analysis where as many of the above factors as possible are included.

1.4 Behaviour of complex systems

The land use system is highly complex (Hart, 1985; Fresco and Kroonenberg, 1992; Skole *et al.*, 1994). Through a web of bottom-up and top-down feedback mechanisms, relationships between land use and their driving forces can disappear, can be strengthened, or can become non-linear. The notion of complexity has consequences for the way the system should be described (Kolasa, 1989; Pickett *et al.*, 1989). In recent years, awareness is growing within the community of land use/cover change (LUCC) researchers (Turner *et al*, 1995; Nunes and Augé, 1999), that a correct interpretation of observed processes is only possible when acknowledging the complexity of the land use system. The land use change community lags behind in the recognition of the need for research that deals specifically with complex systems. Much of the remainder of this section draws from theories that were developed in ecology, a field of science that has ample experience in describing the complexity of a given ecosystem. Although equally complex, it is different in some aspects. Firstly, the ecosystem can be considered 'goal-free' (Conway, 1987), whereas especially human-influenced land use systems can ultimately be regarded as profit maximising. Secondly, an ecosystem is considered to be closed, while a land use system receives multiple inputs, both products and information, from outside the system boundaries. Other differences are related to the low species diversity and dominance by often a single species in a land use system. Despite these differences, complex system theories as developed for the ecosystem might apply to the land use system (see Loucks, 1977; Conway, 1987, Fresco, 1995). Figure 1.1 illustrates the ideas developed by Holling (Holling, 1992; Holling *et al*, 1995) about resilience and stability of ecosystems. It is a representation of the 'cups' and 'balls' example. Holling argues that resilient systems can resist external shocks and return to the former equilibrium (A). When the disturbance is too strong, the system will restructure into a different equilibrium (C), after a transition period (B). More research is needed to determine to what extent this theory applies to land use systems, but throughout this thesis the notion and consequences of complexity serve as a key concept.

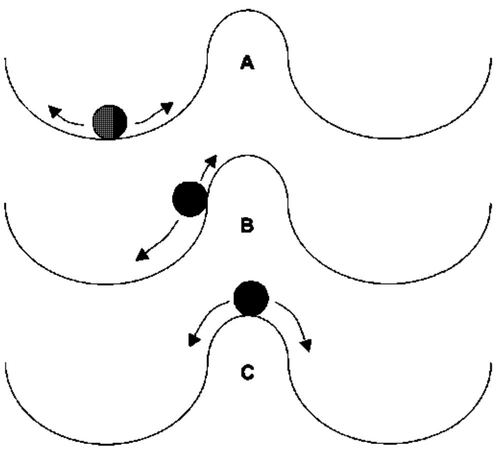

Figure 1.1. Schematic representation of various states (cups) of a complex system (ball). The system can be highly resilient (A), in transition (B), or not resilient (C). Cups represent various equilibria; arrows represent the degree of disturbance. Based on Holling et al. (1995).

Ecologists have particularly stressed two aspects of a complex system (Allen and Starr, 1982; Kolasa and Pickett, 1992; Jørgensen, 1994): functional complexity and structural complexity. The system is functionally complex in the sense that it is influenced by a great number of different factors, from a great variety of disciplines. Structural complexity relates to the fact that the observed patterns and processes differ with the scale of observation.

1.4.1 Level and scale (structural complexity)

The key concept of structural complexity is the existence of hierarchically nested levels within the system. Allen and Starr (1982) first conceptualised the Hierarchy Theory for ecology, which was later elaborated by O'Neill (O'Neill *et al.*, 1986; O'Neill, 1988). An example of a nested hierarchy is the sequence cell - tissue - leaf - branch - tree - stand. To avoid confusion, it is essential to differentiate between *scale* and *level,* following O'Neill and King (1998) in landscape ecologists' most recent plea for recognition of scale dependency (Peterson and Parker, 1998). *Level* is defined as *level of organisation* and *scale* as *level of observation*. Whether the existence of organisational levels emerges from the analysis depends on the adopted scales, which are mostly selected arbitrarily. For some disciplines, level and scale coincide. Particularly in the social sciences (economy, sociology, politics), levels are often defined by those who determine the scale. Provinces and planning regions are examples of units at which planning measurements are implemented (level) as well as data collection takes place (scale). This might also explain the lack of scale recognition by these disciplines. For other disciplines, particularly the natural sciences, a link between level and scale does not necessarily exist. Data are mostly available for either administrative units in the case of agricultural censuses, or for arbitrary areas with an arbitrary pixel size in the case of satellite imagery. Levels will most likely be connected to *e.g.* watershed boundaries, (micro-)climatic regions, topography, or any combination of those. Be that as it may, while the levels of organisation within land use systems are still poorly understood, data collection takes place at scales that are defined by other disciplines or techniques. Throughout this thesis, the concepts of scale and level are used in a somewhat arbitrary way. When not explicitly stated, the assumption is that a scale represents a level.

A different issue, which is related to the level of observation is the so-called 'aggregation error'. This systematic 'error' always occurs when non-linear relationships are translated to more aggregated scales and can be explained with simple mathematics (see Rastetter *et al.*, 1992; Easterling, 1997). In Figure 1.2, the aggregation effect is illustrated. Consider a hypothetical negative relation between population density and forest cover. At the most detailed scale, forest cover is assumed to decrease logarithmically with increasing rural population density (Figure 1.2a). The best logarithmic relationship is indicated. Subsequently, data points are aggregated, averaging the data of two points as indicated by the numbers in Figure 1.2a. This aggregation procedure is repeated, resulting in Figure 1.2c. The best relationship between population and forest cover is now linear. The three lines are plotted together in Figure 1.2d. Rastetter and his co-workers have mathematically proven how non-linear relationships will always become more linear when data are aggregated. An example that is known to occur is the non-linear relation between yield and fertiliser input at the field scale, which tends to become linear at coarser scales. In literature, this property is often referred to as aggregation error (*e.g.* Bartel

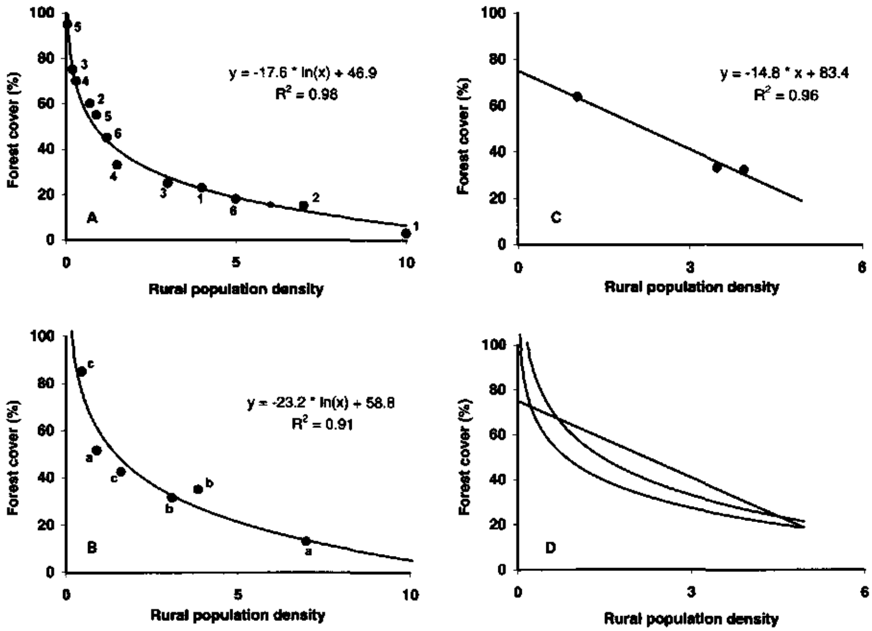

Figure 1.2. A hypothetical example of the effect of aggregating the non-linear relationship between rural population density and forest cover.

et al., 1988; Turner and O'Neill, 1994; Jansen and Stoorvogel, 1998), but in fact it is an aggregation effect that needs to be accounted for and consequently not an error.

Summarising, there are two fundamental problems related to structural complexity when describing the land use system. First, processes that are established at a certain *scale* cannot be linearly translated and used at higher scales because of the aggregation effect. Second, processes that are established at a certain *level* cannot be translated to other levels because of differences in the hierarchical structure. So far, the only readily available solution to these problems is the adoption of an empirical methodology to determine the relationships in the land use system at the scale that data are available.

1.4.2 Integrated approach (functional complexity)

Functional complexity indicates that a complete analysis of any complex system needs to be multidisciplinary (Loucks, 1977; Clayton and Radcliffe, 1995). An integrated approach is indispensable when the system's behaviour is to be fully understood. Until now, spatially explicit land use studies have focussed primarily on biophysical land use drivers enthused by data availability in various earth sciences. Recently, incorporation of data from other disciplines has been promoted (Turner *et al*, 1995; Musters *et al.*, 1998; Wilbanks and Kates, 1999), but up until now mostly demographic and some socioeconomic variables have been considered. Incorporation of social, political, and more economic factors is being discussed, but is usually hampered due to lack of spatially explicit data. Unfortunately, the statement that there is a "theoretical and methodological failure to combine social and natural science..." (Blaikie and Brookfield, 1987) still appears to be valid. During the data preparation of this study, a special effort was made to collect spatially explicit data on economic and social factors, which mostly proved a difficult task.

1.4.3 Land use system versus ecosystem.

Hypothesised properties of the land use system were largely based on ecosystem theory. It has already been stated that the ecosystem and the land use system are of a comparable complexity, thus justifying the assumptions on the functioning of the land use system. It has also been noted, however, that there are differences between both systems that might call for new theories, or additions to the notion of complexity discussed above. The most influential difference is probably the relative openness of the land use system (Musters *et al*, 1998). Especially the free influx of information might influence the land use system in ways that cannot be described by existing ecosystem theory. For example, a new high-yielding variety of rice, that might be developed in IRRI, Philippines will be adopted rapidly in Central America, thus making rice cultivation potentially more profitable. Large-scale population migration is an example of 'matter flow' between land use systems. These kinds of fluxes do not have a parallel in ecosystems and will probably become more important due to the continuing globalisation. Stability and resilience of a land use system might be influenced at levels of organisation that go beyond those of the traditional ecosystem. This thesis aims to offer insights into the importance of structural and functional complexity in land use modelling.

1.5 Models as tools to understand the system

A model can serve as a good tool to mimic part of the complexity of the land use system. It offers the possibility to test the sensitivity of land use (patterns) to changes in selected variables and the stability of the entire system by executing a range of scenarios. While a model will always fall short in incorporating all aspects of the 'real world', it provides valuable information on the system's behaviour under a range of different future pathways of land use change.

1.5.1 Scope of land use models

There are many ways to classify land use models. A particularly effective differentiation is based on the main scope. A useful scheme, proposed by Becker and Dewulf (1989), has recently been used to classify various methodologies to model land use (Van Ittersum *et al.*, 1998; Van Latesteijn, 1999). Four types are distinguished, based on degree of uncertainty and causality (Table 1.3).

Table 1.3. Types of land use models, based on degree of uncertainty and causality.

	Low uncertainty	High uncertainty
High causality	Predictive	Explorative
Low causality	Projective	Speculative

The land use model that was selected in this thesis, the CLUE modelling framework, (see Section 1.5.3) is a projective model. Causality is low, because relationships are determined empirically, but because an attempt is made to model the entire system, uncertainty is relatively low. In the context of the development of a modelling tool-box (see Chapter 8), projective modelling can be preceded by a speculative model, and can be followed by a predictive model that uses the results of the projective model to focus its efforts.

1.5.2 A spatially explicit land use model

It is not the purpose of this chapter to provide an extensive list of all the models that deal with land use (change). Exhaustive overviews exist to which there is little to add (Sklar and Costanza, 1991; Lambin, 1994; Lambin *et al.*, in press). Although an overview would clarify the position of the applied model, a short description of a large number of models does not do justice to the complexity and specific applications of most models. The model that has been chosen in this thesis as the core tool to analyse the land use system has a unique combination of features that makes it more suitable than other existing land use models. Models and modelling techniques that are comparable to the model discussed here include GEOMOD (Hall *et al.*, 1995, Pontius *et al.*, 2001), Land Use Scanner (Hilferink and Rietveld, 1999), and cellular automata (for a review, see Baltzer *et al.*, 1998).

The following features were considered indispensable to any meaningful spatially explicit modelling effort of land use change, many of which have already been touched upon in previous sections:

- Address functional complexity, *i.e.* dynamically incorporate the following types of driving forces:
    - biophysical
    - climatic
    - (macro-)economic
    - social
    - demographic

- Address structural complexity, *i.e.* dynamically incorporate space and time by:
    - applying a multi-resolution, multi-extent methodology
    - producing spatially explicit results
    - adopting temporally explicit future projections

In short, the interest was in a dynamic, multi-scale, real-time, and spatially detailed land use model.

1.5.3 The CLUE modelling framework

The CLUE (Conversion of Land Use and its Effects; Veldkamp and Fresco, 1996b; Schoorl *et al.*, 1997) is a projective model that was designed to deal with the issues mentioned above, and can be described as a spatially explicit, multi-scale land-use change model. Within the framework, an attempt is made to describe land use patterns at different spatial scales with a set of potential land-use change drivers. Using this description, the dynamics of the system are examined by analysing the spatial effects of different possible future pathways of land use change. In order to quantify scale dependencies, the statistical description of land use patterns by a set of drivers is determined at a basic grid and at a series of coarser resolutions. At national level, scenarios are developed to explore plausible future land-use changes, mostly based on macro-economic and demographic developments. Those yearly changes are subsequently allocated in a spatially explicit manner in the grid-based allocation module (Verburg *et al.*, 1999a), that consists of a two-step top-down iteration procedure with bottom-up feedbacks. The allocation module uses the statistical descriptions of two scales, the basic grid and a higher resolution that is considered optimal in terms of statistical properties. The general structure of CLUE is given in Figure 1.3. The methodology is explained in more detail in the various chapters. In Chapter 6, model sensitivity for some key parameters of the allocation module is analysed.

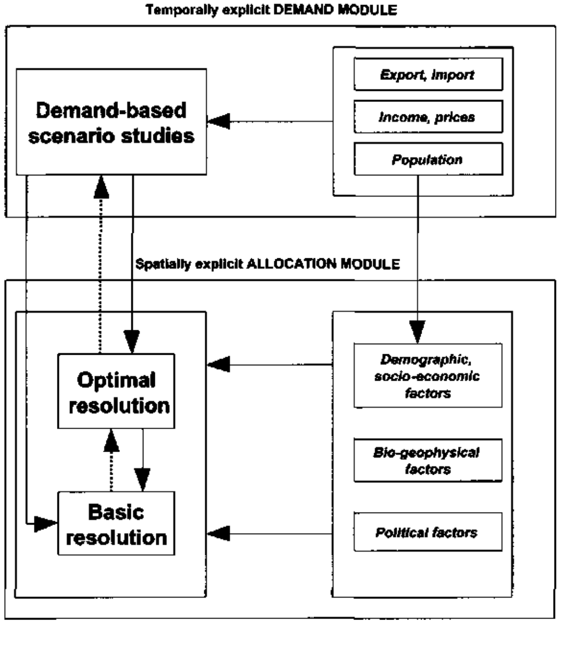

Figure 1.3. General structure of CLUE.

The model was initially developed (Veldkamp and Fresco, 1996b) and tested (Veldkamp and Fresco, 1997) for the country of Costa Rica. The first version was designed to run on a VAX machine (Schoorl *et al.*, 1997), it was later adapted to run in a PC environment. Since then, the model has been applied to a range of countries and regions. De Koning applied the model to Ecuador (De Koning, 1999; De Koning *et al.*, 1999). Verburg focused on Asia with applications to Java (Verburg *et al.*, 1999b), China (Verburg *et al.*, 1999c), and Sibuyan, a small island of the Philippines (Verburg *et al.*, 2000). In this thesis, applications of the CLUE methodology to four Central American cases at various scales are presented: The Atlantic zone of Costa Rica (Kok and Veldkamp, 2000); Costa Rica (Veldkamp and Fresco, 1996b; Kok, unpublished results); Honduras (Kok, unpublished results; Kok and Bouma, submitted); and Central America (Kok *et al.*, 2001).

1.6 Structure of the thesis

The core of this thesis consists of six chapters that together describe all major parts of the working methodology of the CLUE modelling framework, including the statistical analysis, scenario development, model runs, and model validation. Chapter 2 deals with the most detailed CLUE-application, the Atlantic Zone of Costa Rica, and provides an overview of the whole methodology, including model validation. In Chapter 3, the hierarchical level is the country (Honduras) and a detailed description of the multi-scale statistical analysis is given, focusing on the effects of spatial resolution. In Chapter 4 and 5, we move up one level and analyse the land use system at the subcontinental level of Central America. Chapter 4 discusses the statistical analyses and focuses on the effects of spatial extent. In Chapter 5, a number of scenarios are described and the spatially explicit land use changes are analysed, with special attention to the effects of hurricane Mitch. Chapter 6 provides a detailed description of sensitivity of the key parameters in the allocation module, and discusses the results of model calibration and multi-scale validation of the CLUE application to Central America. Finally, in Chapter 7 a synopsis is given of scale effects on different levels of the hierarchy and at different phases of the working methodology. Chapter 8 returns to some of the issues raised Chapter 1 and discusses two key questions. Firstly, what did this thesis add to the scientific discussion on multi-scale land use modelling? And secondly, who are potential users of the model?

CHAPTER 2[#]

Overview modelling sequence using data from the northern Atlantic Zone of Costa Rica

Abstract

Analyses of changes in land use and land cover have recently received ample attention in literature. So far, dynamic and integrated modelling approaches that are essential for modelling of complex systems are relatively few. An empirical multi-scale land use change modelling framework called CLUE (Conversion of Land Use and its Effects) was developed to fill part of this gap. CLUE combines a statistical land use description with scenarios of changes in regional commodity demand to model the possible pathways of future land use changes in a spatially explicit manner. In the Atlantic Zone of Costa Rica CLUE was applied for the first time at sub-national scale. Multiple regression analyses resulted in equations with coefficients of determination between 0.58 and 0.91 for the dominant land uses (forest, pasture and bananas). The statistical analysis demonstrated the importance of including both biophysical and socioeconomic variables as driving forces of changes in land use. Predicted changes in spatial patterns between 1984 and 2005 under different scenarios could be related to processes, as they are known to take place in the Atlantic Zone. Forest was predicted to be largely replaced by pasture and to become limited to areas unfavourable for agricultural land use. Model validation yielded highly significant results with correlation coefficients ranging from 0.87 to 0.95 for the dominant land uses. The study demonstrates that dynamic, multi-scale empirical modelling is a suitable tool to model land use changes at sub-national level.

2.1 Introduction

2.1.1 Issues in land use change research

Land use and land cover change have been regarded as important issues over the past 20 years (Turner *et al.*, 1995). Besides local and direct effects like loss of biodiversity through deforestation or soil degradation through unsustainable land use, increasing importance is given to the global impact of more indirect effects like greenhouse gas emissions and carbon fixation. Boosted by modern computer technology, a rapidly increasing number of land use models have been developed, addressing a huge spectrum of different topics at different scales and with different aims (comprehensive overviews are given by Sklar and Costanza (1991) and Lambin (1994)). However, the

---

[#] Based on: Kok, K., Veldkamp, A., 2000. Using the CLUE framework to model changes in land use on multiple scales. In: Bouman, B.A.M., Jansen, H.G.P., Schipper, R.A., Hengsdijk, H., Nieuwenhuyse, A. (Eds.), Tools for land use analysis on different scales. With case studies for Costa Rica. Kluwer Academic Publishers, Dordrecht, pp. 35-63.

majority of these models address a small range of topics or scales (Veldkamp and Fresco, 1997; Dumanski *et al.*, 1998). When examining a complex system like land use and its change, the typical response is to conduct research about limited but tractable topics (Rosswall *et al.*, 1988). The problem then becomes how to transfer results of detailed studies to higher levels, as relationships established at one hierarchical level cannot necessarily be used at higher or lower levels (Easterling, 1997). Moreover, bottom-up models are often incomplete because of the lack of knowledge on interactions and feedbacks (Jarvis, 1993). Especially socioeconomic systems are operating at multiple spatial-temporal scales and consequently can be exhaustively described neither at a single scale nor by a single discipline. Finding ways to translate information among scales is one of the fundamental challenges faced by researchers in land use analysis (Levin, 1993). In several disciplines awareness on the effects of scale is growing. For example, in ecology (O'Neill, 1988; Holling, 1992), soil science (Bouma, 1997), and the field of greenhouse gas emissions (Sellers *et al.*, 1997) the understanding on how to deal with problems concerning scale effects is increasing. Although many underlying processes act at the lowest possible, visible or workable scales (Reynolds *et al.*, 1993), at higher aggregation levels proxies for those processes become apparent (Fresco and Kroonenberg, 1992; Veldkamp and Fresco, 1996b). Given the changes in emergent properties of the system when scaling up, there arises a need for empirical modelling besides process based modelling to correctly address the relationships between land use change and (proxies for) its drivers.

2.1.2 CLUE Modelling framework

The CLUE modelling framework was designed to deal with several of the issues mentioned above. A general description of the CLUE modelling framework as well as previous research concerning the spatial determinants of land use at different spatial scales are given in Chapter 1. Within this chapter, special interest is given to the demand module and development of scenarios. Data at sub-national level cannot be extracted from existing large databases like FAOSTAT (FAO, 1999) that only offer data at country level. For similar reasons, existing scenarios cannot directly be used. Furthermore, the present study is the first attempt to use CLUE at a more detailed scale.

2.1.3 Objectives

The overall objective of this study was to analyse the present land use patterns and to project possible future pathways of the spatially explicit patterns of land use change dynamics in the northern Atlantic Zone of Costa Rica, using an empirical multi-scale approach. Using the CLUE modelling framework, three secondary objectives were defined:

1. Analyse the land use pattern and its driving forces in the northern Atlantic Zone at two points in time, using multiple regression techniques.

2. Analyse demand at the regional level for the major agricultural commodities produced in the northern Atlantic Zone and define a limited number of possible future pathways of land use change until the year 2005.
3. Analyse in a spatially explicit way the effects of those pathways on land use dynamics.

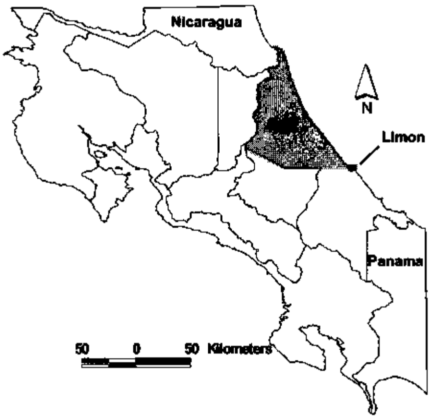

Figure 2.1. Location of study area

2.1.4 Study area

The northern Atlantic Zone (NAZ) is situated in the eastern part of Costa Rica (Figure 2.1). The region is administratively subdivided into twenty districts (Figure 2.2). Although the landscape is predominantly flat, it encompasses a small part of the sloping areas of the central mountain range. Its climate is perhumid with an average rainfall ranging from 3000 to 7000 mm/y without a pronounced dry period (Gomez, 1986). The soils in the region are predominantly classified as andosols and inceptisols (Wielemaker and Vogel, 1993). Major influence of humans on land cover started 100 years ago with the construction of a railroad from the Central Valley to the harbour of Limón, but accelerated during the last two decades (Pelupessy and Weeks, 1993). By the mid 1980s more than fifty percent of the original tropical rainforest had disappeared (TSC/WRI, 1991) and though the absolute deforestation rate of Costa Rica is decreasing, this does not apply to the NAZ. In recent years especially the expansion of the export crops banana and palm heart is noteworthy, though the main agricultural land use is pasture for cattle both for meat and milk production. As in other Central American countries, development of agricultural land use in the recent past depended directly on the market expansion in developed countries (Goluboay and Vega, 1988).

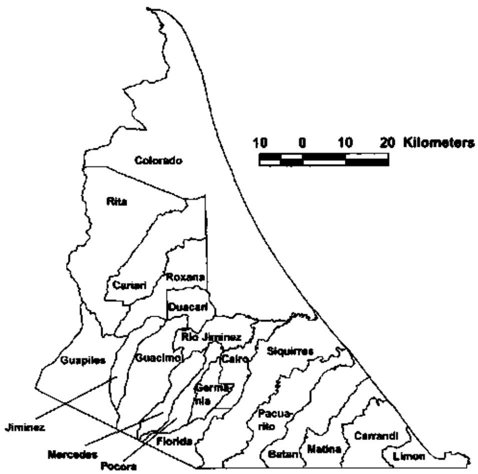

Figure 2.2. Administrative boundaries of the northern Atlantic Zone in 1984.

2.2 Methods and material

In accordance with the objectives, this section is divided into four parts: The statistical analysis, demand/supply analysis, scenario development, and model validation.

2.2.1 Statistical analysis

The data used for the statistical analysis originated from two sources: the atlas of the NAZ as compiled by Stoorvogel and Eppink (1995), and the Costa Rican population and agricultural censuses conducted in 1984 (DGEC 1987a, b). The latter were only used as additional sources when maps from the atlas did not contain sufficient information. The statistical analysis was done in two steps. First, a set of variables was selected using a stepwise regression procedure. Subsequently, the selected variables were used to construct multiple regression equations. The adjusted coefficient of determination (R^2) was used as a measure for the amount of variation explained. The standardised betas (regression coefficients) were used to indicate the relative importance of individual variables in a given equation.

Data format

A grid-based approach was used with a pixel size of 2 × 2 kilometres as the basic unit for analysis. Instead of using uniform grid cells with one dominant land use and one type of soil, sub-grid information was present for most of the driving forces and each land use. In every cell, *e.g.*, the percentage of fertile soils present and the cover of each land use were known. This meant that although spatial uncertainty increased, we did not lose any information when either gridding the data or scaling up.

Dependent variable: land use

Two land use maps were available in the atlas of the NAZ: a 1984 map of the entire area (scale 1: 80,000), and a 1992 map covering 60% of the total area (scale 1:

60,000), both based on aerial photograph interpretation. As 1984 is the year of the most recent agricultural and population censuses, it was decided to use that year as the base year for statistical analysis. The spatial distribution of the following nine land uses was analysed: beans, maize, rice, cassava, annuals (total of the previous four), bananas, forest, pasture, and palm heart. The spatial distribution of maize, rice, beans, and cassava was derived from a combination of census data and the 'annuals' class from the 1984 land use map; the spatial distribution of the other land uses was taken directly from the 1984 land use map. The spatial distribution of palm heart could not be statistically analysed due to its absence in 1984. Palm heart was nevertheless included in the model runs, because of its rapid increasing importance, both in terms of area and economic value.

Independent variables

A total of 40 potential driving forces were identified and grouped into four categories to facilitate interpretation. Numbers between brackets indicate for every sub-group (*e.g.* every soil characteristic) the number of variables that were included in the analysis. A complete list of variables is given in Appendix 1:

1. Eighteen soil variables: base saturation (1), pH (2), cation-exchange capacity (2), acidity class (2), soil development stage (2), soil depth (2), soil fertility (2), soil drainage (2), and soil texture (3). Every variable was subdivided into 2 to 4 classes and the percentage of each class was used as input. In this way, every grid cell is assigned a value for the percentage of *e.g.* both low and high fertile soils present. Soil data are described in detail by Wielemaker and Vogel (1993) and Stoorvogel and Eppink (1995).
2. Ten other biogeophysical variables: mean altitude (1), average yearly rainfall (1), slope steepness (2), stoniness (2), flooding risk (2), and distance to nearest river (2).
3. Six demographic variables: rural population density (1), urban population density (1), agricultural labour force (1), distance to nearest road (2), and distance to nearest urban centre (1). Densities were based on a combination of census data at district level, a town distribution map and national yearly population growth rates derived from the FAOSTAT database (FAO, 1999), Inter-American Development Bank (US Census Bureau, 1998) and USDA (USDA, 1998). Yearly growth rates were used to calculate annual population increase, which was spatially distributed using census data and location of towns.
4. Six policy-related variables: presence and age of IDA (Institute for Agricultural Development) settlements (4) and the presence of national parks or nature reserves (2). IDA is a government institute that bought considerable tracts of land mainly between 1960 and 1990 with the objective to stimulate smallholder development. About 50% of all IDA settlements in Costa Rica are located in the NAZ (CCE, 1990).

Spatial and temporal dynamics

Three artificial resolutions were created in order to examine the effect of scale. The basic resolution was set at a pixel size of 2.0 × 2.0 km, aggregations were made to 3.7 × 3.7 km and 7.5 × 7.5 km, the latter being the basic grid cell size used for the analysis of the entire country by Veldkamp and Fresco (1996b).

The statistical relationships are important factors in the allocation module. Although mostly in an adapted form, relations derived from the 1984 situation are used until 2005. It is thus important to analyse whether spatial relationships between components of land use change over time. If they do, those changes have to be accounted for during the allocation procedure. To check for changes in land use description between 1984 and 1992, an additional subset, covering the same area as the 1992 map, was created from the 1984 data. Only part of the area was characterised, but a direct comparison between 1984 and 1992 was enabled.

Interpretation pitfalls

One of the pitfalls of the interpretation of a multiple regression analysis is related to multicollinearity between variables. Although a stepwise regression procedure was followed to minimise multicollinearity effects, great care should be taken with interpretation. The ordinary least square estimation procedure requires independent explanatory variables for unbiased coefficient estimation, but this cannot be expected in our regressions due to the complexity of land use and its drivers. Various obvious and less obvious interdependencies exist between explanatory variables. At higher resolutions correlations between almost all potential drivers increase, thus increasing multicollinearity effects. Every analysis that was made and every statistical model that was eventually used in the allocation procedure, was carefully scrutinised for multicollinearity. The effects of multicollinearity were minimised by excluding highly correlated variables from the initial set of possible drivers. The decision to exclude certain variables was based on analysis of (two by two) correlation matrices. Despite these efforts, individual statistical models remain hard to interpret directly. Multicollinearity effects as well as the lack of explanatory power of multiple regression analysis weaken the validity of statements about any single regression equation. It was therefore decided to group the results of several statistical models in order to strengthen interpretation. Specific cases will be used to illustrate changes between years and at different resolutions. An important question to be answered is whether the different categories of variables contributed equally to the regression models at different resolutions and in different years. To test the hypothesis that an integrated approach was necessary (*i.e.*, different types of variables were important drivers), the share of different categories of variables in the total set of input variables was compared with the share in the different models. As an additional test comparisons were made between input percentages and most important variables in the correlation matrices.

2.2.2. Demand development

The basic assumption in estimating the yearly supply from the NAZ was that supply equals demand, after accounting for exports and imports. Total demand for a specific commodity is assumed to consists of eight elements: food, feed, seed, stock changes, waste, processed, exports, and imports (FAO, 1999). We concentrated on modelling food demand, including its influence on exports and imports. Changes in the remaining categories were analysed using data at national level, and certain assumptions regarding future changes were made. In this way processes like increasing feed demand for maize and decreasing waste losses for bananas were recognised and accounted for. Feed, seed, waste, processed and stock changes accounted for at most 30% of total demand (supply). To estimate future demand for a food commodity one needs to know present population size, demand per capita, income and price elasticities, and the expected relative population, income and price changes. Using the foregoing data, the following relationships were applied to estimate future demand:

$$\text{Food\_demand}_{cy} = \text{Population}_{y} \times \text{Demand\_per\_capita}_{cy} \quad (1)$$

$$\text{Population}_{y} = \text{Population}_{y-1} \times \text{popgrow}_{y} \quad (2)$$

$$\text{Demand\_per\_capita}_{cy} = (1 + (\text{Relative\_income\_change}_{y} \times \text{Income\_elasticity}_{c} + \text{Relative\_price\_change}_{cy} \times \text{Price\_elasticity})) \times \text{Demand\_per\_capita}_{cy-1} \quad (3)$$

Where the suffix c stands for the type of commodity, and y for year.

Food demand	= total demand of NAZ-population (tonnes)
Population	= total population of NAZ (capita)
Demand per capita	= average demand for an individual (tonnes capita^{-1})
Popgrow	= population growth rate + 1
Relative income change	= percentage income change (%)
Income elasticity	= effect of income change on demand (%)
Relative price change	= percentage price change (%)
Price elasticity	= effect of price change on demand (%)

A division was made between export commodities (bananas and palm heart) and commodities that are consumed primarily within Costa Rica (annuals, beef[1], milk[1]). Changes in income, price, and population in the EU and the US influence the demand for export crops, while changes within Costa Rica are more important for the demand for commodities of the second group.

Population

Population data for the year 1984 were obtained from the population census of that year (DGEC, 1987b). Low, medium, and high population growth scenarios exist (Heilig, 1996; UN, 1997; US Census Bureau, 1998; USDA, 1998) in which population growth for Central America between 2000 and 2025 ranges between 1.5%

[1] Pasture was subdivided in the commodities 'beef' and 'cow milk' for demand purposes.

per year and 2.1% per year. Annual population growth rates of 1.8% for Costa Rica and 0.4% for the EU and US were assumed, based on yearly data (US Census Bureau, 1998) and in accordance with the medium variant of the UN (UN, 1997).

Income

Geurts *et al.* (1997) provided estimates for income elasticities of demand by income quartile for major agricultural commodities in Costa Rica. For bananas, being consumed in the US and EU, the income elasticity estimate was based on Hallam (1995). Estimates regarding future income changes were based on future domestic or foreign (bananas) GDP projections (USDA, 1998). The effect of changes in income on demand was derived by assuming that GDP growth can be directly translated into income growth and by adopting an average income elasticity. Two growth scenarios were discerned, a medium GDP growth of 3% per year and a high GDP growth of 5% per year. Income growth per capita per year is derived by correcting for population growth. Per capita income growth was subsequently multiplied by the income elasticity to obtain the effect of income on demand per capita.

Price

Since no unambiguous price change relationships could be established, it was decided to exclude prices from the analysis. It is thus assumed that future price changes will be conform the changes in the recent past. This assumption was confirmed by a report from USDA (USDA, 1998), in which it was stated that projected prices for the major commodities will continue to decline in real terms through 2005. Recent research (Roebeling *et al.*, 1999) will contribute to a better understanding of price fluctuations.

Imports and exports

In this study population growth as well as income changes are assumed to influence demand. Import and export quantities determine whether supply will come from the NAZ or from elsewhere, or in the case of export-oriented crops whether demand from the NAZ will be altered by external factors. Recent changes in the banana import policy of the EU, for instance, significantly influenced supply from the NAZ (Hallam, 1995). A second well understood phenomenon is the virtual disappearance of annuals from the NAZ as a result of the various structural adjustment programs implemented in Costa Rica since 1987 (see Hansen-Kuhn, 1993). Estimates of the importance of imports and exports are based on the response of commodity supply to similar events in the recent past, or on statements provided by USDA (USDA, 1998). Estimates regarding percentage changes in imports and exports, population growth, and income are given in Table 2.1.

2.2.3 Scenario formulation

Two types of scenarios were formulated: scenarios that influence total area to be allocated based on demand development (demand controlled scenarios), and a scenario that restricts allocation possibilities (allocation controlled scenarios). Scenarios were calculated for the period 1997 until 2005. Palm heart was not included in the analysis, as quantitative information was lacking. Instead, possible future changes were either based on the response of the banana area or on expert guesses on likely future developments in demand.

Table 2.1. Effects (% y-1) of population, GDP, import and export on annual demand growth from the northern Atlantic Zone.

	Population growth	GDP growth		Import		Export	
		Medium	High	Decrease	Increase	Decrease	Increase
Annuals	1.8[1]	0.3	0.7	-35	-35	n.a.	n.a.
Bananas	0.4[1]	0.7	1.6	n.a.	n.a.	-2.5	4
Milk	1.8	0.5	1.1	0	0	n.a.	n.a.
Beef	1.8	0[2]	0[2]	0	-2	n.a.	n.a.
Palm heart[3]	0.4	1.0	2.0	n.a.	n.a.	0	4

[1] Demand for commodities produced for the national market is influenced by Costa Rican population growth (1.8% y^{-1}); demand of export oriented commodities is governed by the average population growth of the EU and US (0.4% y^{-1}).
[2] Even though meat demand has been estimated as income-elastic (Geurts *et al.*, 1997), the replacement of beef by chicken meat is not incorporated in that study. Total meat demand increase in recent years was accounted for entirely by increased chicken meat consumption. It is not likely that similar income effects (1% and 2% for medium and high GDP growth, respectively) on beef demand will be realised.
[3] Quantitative information on demand for palm heart is lacking. It was assumed that its responses largely resemble demand for bananas.

Demand scenario formulation

Based on studies dealing with past changes in Costa Rican land use (*e.g.*: Easterly *et al.*, 1997; May and Bonilla, 1997; Fields, 1988) three macroeconomic policy scenarios were defined affecting GDP and imports and exports differently, that were used as input scenarios in the CLUE allocation module.

1. **Base scenario.** Medium GDP growth and similar import/export growth as in the recent past. Main driving force is the increasing demand of a growing population.
2. **Market protection scenario.** The EU will continue to favour African, Caribbean and Pacific countries which slows banana exports from Costa Rica, while imports of basic grains from the US are impeded as well. It is postulated that the decrease of supply of annuals from the NAZ continues. GDP growth remains at medium level.
3. **Market liberalisation scenario.** The EU will completely open its market, boosting banana (as well as palm heart) exports, while staple crops and beef will more and more be imported from the US. Income growth will be higher than in the previous two scenarios.

Development of demand for commodities in the Atlantic Zone according to the three scenarios is summarised in Table 2.2. Numbers are derived by adding up the separate growth rates given in Table 2.1. The effect of export/import changes are visible in bananas and palm heart. Demand for milk is constant, while beef demand will decrease when markets open further. Annuals will disappear both when markets are more protected and when markets are more open.

Table 2.2. Development of demand for commodities in the northern Atlantic Zone according to three scenarios. Percentage change per year between 1997 and 2005.

Scenario	Annuals	Bananas	Milk	Beef	Palm heart
Base	2.1	1.1	2.3	1.8	1.1
Protection	-32.9	-1.4	2.3	1.8	1.1
Liberalisation	-32.9	6.0	2.9	-0.2	6.0

Effects of the three scenarios on land use areas are presented in Table 2.3. Up until 1996 supply from the zone is known and is translated directly into an area estimate, by dividing the total supply with regional average yields. Absolute changes are largest for pasture and forest. Banana area grows very fast in the liberalisation scenario. Despite these changes, pasture will continue to be the dominant land cover and forest the second largest land cover.

Table 2.3. Quantitative effects of three scenarios on land use area in the northern Atlantic Zone (ha). Differences indicate total growth between 1996 and 2005.

	Annuals	Bananas	Pasture	Palm heart	Forest	Rest[1]
1996 situation	484	53,330	243,298	2,000[2]	123,369	65,496
2005 base	891	54,962	262,701	4,700	92,727	69,996
2005 protection	31	44,985	262,701	2,700	110,064	65,496
2005 liberalisation	401	80,261	223,766	6,500	109,953	65,496
Difference Base	407	3632	19,403	2,700	-30,642	4,500
Difference Protection	-453	-6345	19,403	700	-13,305	0
Difference Liberalisation	-83	28 931	-19,532	4,500	-13,416	0

[1] The rest group is made up of other plantations, urban areas, lakes, and a large area of secondary vegetation.
[2] Based on an extrapolation of the 1992 situation.

Allocation controlled scenario

There is one important way in which allocation of land for agricultural use in the near future could be restricted. A large part of the NAZ has a protected status and although only 5% of the NAZ is considered to be within a national park, a further 25% has some kind of protected status (Stoorvogel and Eppink, 1995). Maintaining 30% of the area under complete protection in the future will have large consequences for land use. Full protection would be difficult to realise, considering the extent of the area and means available. This is suggested by the fact that despite their status and despite all efforts undertaken, every year a part of the area within the national parks is deforested (Ramirez and Madonado, 1988). Nevertheless, international aid or pressure might change this situation. Thus, the effect of total protection of national parks and partial protection of other protected areas were examined in an adapted version of the base scenario.

CLUE model runs

The existing allocation module was adapted and parameterised for the NAZ, and run for the four scenarios described above. For the first period (1984 – 1996) existing data on regional supply from the NAZ were used, while for the second period (1997 – 2005) data as calculated above were incorporated.

2.2.4 Validation

A statistical analysis was conducted for a subset of the 1984 land use map that only included the part for which data for 1992 were available. Area changes between 1984 and 1992 for every land use were calculated by subtracting the two land cover maps. The small time gap of eight years was not considered a problem, as in this period changes were extremely rapid. Next, the parameterised CLUE was run, starting in 1984, which resulted in a prediction for the land cover situation in 1992. Correlation between the actual and predicted map was analysed by aggregating land use areas to administrative unit averages. The performance of these aggregated results was examined as we were interested in capturing patterns of change and not in detailed grid to grid changes.

2.3 Results

2.3.1 Statistical analysis

Model performance

Fits of multiple regression models were acceptable to very good (Figure 2.3). Adjusted coefficients of determination (R^2) for one land use invariably increased with resolution. For the most important land uses R^2 statistics ranged between 0.25 for annuals at level 1 (2×2 km) to 0.92 for forest at level 3 (7.5×7.5 km). Especially the spatial distribution of forest and pasture, together accounting for more than 80% of the total cover, was well described. The models for individual annuals were less satisfying, but the cover of all annuals amounts to no more than 8% of the total area.

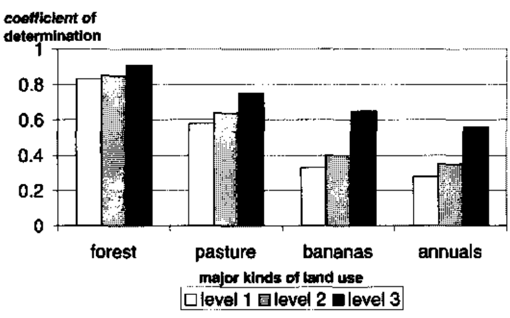

Figure 2.3. Coefficients of determination for three resolutions and dominant land uses.

Variable importance

The complete regression results can be found in Appendix 2 and Appendix 3 in Kok and Veldkamp (2000). The relative contribution of the various groups of driving forces in the multiple regression analyses and correlation analyses is summarised in Table 2.4. The correlation analyses between land use and driving forces were summarised by adding up the five highest correlating variables (always > 30%) for every analysis for a given year, level, or land use. The proportion of every variable group in the sum was subsequently divided by the proportion of the variable group in the input data. Multiple regression models were summarised in a similar manner, except that all variables contributing significantly ($P < 0.05$) were included in the sum of variables. In Table 2.4a differences between year and level are analysed; in Table 2.4b, differences between land uses are examined. The sign indicates whether a group of variables contributed more or less than expected based on the input proportion. For instance, when counting contributing variables of all multiple regression equations in 1984, 25% were policy variables, although only 15% (6 out of 40) of the input variables was policy oriented. The sign in Table 2.4a is thus positive.

Table 2.4. Relative contribution of main groups of driving forces to highest correlating variables and multiple regression models.
Table 2.4a. Correlation analysis and multiple regression models, grouped by resolution or year and independent of land use.

	Correlation Analysis				Multiple Regression Analysis			
Variables	1984	1992	L1	L3	1984	1992	L1	L3
Soil	-	0	-	0	0	0	0	0
Other biogeophysical	0	+	+	0	0	0	0	0
Demographic	+	+	+	+	-	-	-	-
Policy	+	-	0	0	+	0	+	+

Table 2.4b. Multiple regression models, grouped by land use and independent of resolution and year, unless noted otherwise.

Variables	Pasture	Forest (1984)	Forest (1992)	Bananas	Annuals (1984)	Annuals (1992)
Soil	-	-	0	+	0	0
Other biogeophysical	+	-	-	-	0	+
Demographic	-	+	0	-	-	0
Policy	+	+	-	0	+	-

Note: Positive signs indicate that a particular group of variables contributed more than expected based on the input percentage; negative signs indicate a less than proportional contribution; zeros indicate less than 10% deviation. For correlations, the five most explaining variables were included; for multiple regression, all significant variables were included ($P < 0.05$). L1 = level1, grid size 2 km; L3 = level3, grid size 7.5 km.

The results from the correlation analysis indicate that at least a number of variables from all groups correlate strongly with land use. This signifies that all groups have a potential importance. The potential is confirmed by the summarised results from the multiple regression analysis. A general conclusion is thus that the distribution of land use cannot be analysed successfully without including different types of potential driving forces. Analysing land uses separately (Table 2.4b), the population variables hardly contributed to explaining the distribution of pasture, bananas and annuals. Biophysical variables (stoniness, flooding), soil variables (fertility) or policy variables (parks, IDA settlements) had a greater influence.

Temporal dynamics

Considering the multiple regression models, soil and biophysical variables tended to gain importance between 1984 and 1992, while at the same time especially the importance of policy related variables lessened. This tendency could mostly be attributed to multicollinearity effects between *e.g.*, the presence of national parks and poor soil conditions. There was, however, one driving force and one land use that consistently changed between 1984 and 1992: The presence of IDA settlements (driving force) and annuals (land use). The percentage of a grid cell within recently (in 1980 – 1984) established IDA settlements lost significance between 1984 and 1992. The loss of importance is consistent with land use changes that are expected to happen after the foundation of a settlement (Stoorvogel, 1995; Schipper, 1996): An initial dominance by annuals will gradually disappear and be replaced by a more diverse pattern in which differences with the area outside a settlement become less obvious. Of the most important land uses (bananas, forest, pasture, annuals), regression models had the lowest coefficients of determination for annuals. In 1984 IDA settlements and soil conditions were the main factors, but because of the former losing importance the models for 1992 were less satisfying. The main explaining factors are probably the diversity of the group and the rapidly diminishing area of annuals between 1984 and 1992. Phasing out of the subsidy system for basic grains after 1987 (Hansen-Kuhn, 1993) triggered almost complete disappearance of maize and rice.

Spatial dynamics

Differences in terms of contributing factors between resolutions were small (Table 2.4a). Typically the same factors were important at level 1 and level 3. However, regression coefficients belonging to the factors did change with resolution. Often consistent changes were present from level 1 to level 3, thus indicating the presence of a scale effect. Whether factors gained or lost importance varied greatly between the land uses.

Individual cases

Figure 2.4 depicts the relationship between actual cover and cover predicted by the multiple regression equations at level 3 in 1984 for the most important land uses. It shows that at this resolution the relationships between land use and its correlating variables were captured in a satisfactory manner. In Table 2.5 the main contributing variables in the multiple regression models at level 1 in 1984 are listed for the most important land uses.

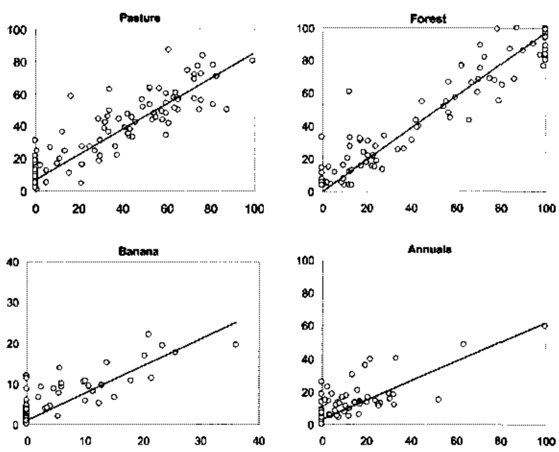

Figure 2.4. Relationship between actual cover (x-axis; % per grid cell) and cover calculated by multiple regression techniques (y-axis) at level 3 in 1984.

Table 2.5. Most important variables in the multiple regression models at level 1 in 1984 for selected land uses, grouped by variable type.

Variable group	Forest	Pasture	Annuals	Bananas
Soil	Shallow Poorly drained Sandy	Deep	Low fertility Leached but not: Poorly drained Shallow	Well drained High fertility but not: Leached Shallow
Other bio-geophysical	Steep slopes High altitude High rainfall	Steep slopes Stony surface		Low flooding risk Gentle slopes Higher altitude
Demographic		Near main roads	Higher rural density	
Policy	In natural parks In nature reserves	Outside national parks Inside old IDA settlements	Inside young and medium old IDA settlements	Not within IDA settlements

Forest is still one of the dominant vegetation types in the NAZ, despite the ongoing process of deforestation and agricultural expansion. Factors that explained the current distribution of forest clearly showed the effects of agricultural expansion (as described by *e.g.,* Sader and Joyce, 1988). Forest is restricted to poor soils (shallow and poorly drained) in the national parks or to biophysically unfavourable conditions (high rainfall, steep slopes) in mountainous areas (high altitude). To some extent, a similar pattern was found in the distribution of annuals. Their presence correlated with leached and low fertility soils. However, poorly drained soils that are very shallow were apparently unsuitable for annuals. Farmers in the recently founded IDA settlements cultivated more annuals than outside. The opposite could be observed in the case of bananas, that require well-drained, highly fertile soils that are not leached and not too shallow (Delvaux, 1995). Flooding risk has to be low and the crop is restricted to flat or almost flat areas. Altitude contributed positively to the cover of bananas, although the single correlation was a negative one. This suggests that *within* the area of gentle slopes with fertile soils, the higher areas (10 – 100 m) are preferred. The contributing biophysical factors display some characteristics of the distribution of pasture in the NAZ: on steep slopes with a stony surface. The positive contribution of deep soils may seem illogical, but deep soils in the area coincide with the areas that are flooded permanently, making any other agricultural land use improbable.

Multiple regression models seem to be able to adequately describe the land use distribution, as it is known to exist in the NAZ. Forest was largely restricted to the poor biogeophysical conditions, coinciding with the presence of national parks. Banana plantations have claimed the best soils in flat, non-flooded areas. Annuals were thus restricted to the somewhat poorer circumstances, while pasture remained in the steep, stony, wet areas. It is assumed that new driving forces will not become of great importance in the near future. It is thus justified to use the results of the multiple regression models in the allocation module of CLUE.

As no data were available for palm heart, but its area is predicted to expand rapidly in the coming years, an expert equation was constructed. Though only qualitative information on its current distribution and driving forces was available, an effort was made to quantify relations based on expert knowledge. Presence of palm heart is assumed to be correlated with soil drainage, surface stoniness, flooding risk, altitude, and distance to the nearest market. A summarising variable (PALMSUIT) was constructed with values ranging from 0 (all five variables unsuitable) to 4 (all suitable). The regression coefficient was set at 0.1 and the intercept at 40 (0.4%).

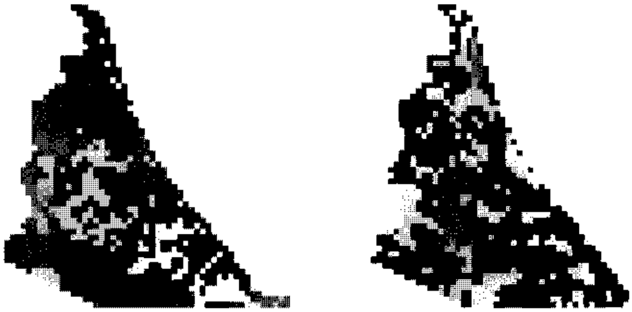

Figure 2.5. Regression hot spots maps for bananas and forest. Dark grey tones indicate areas where regression values exceed actual values and changes are to be expected. Light tones indicate areas where the opposite holds.

Regression hot spots

From the statistical analysis, so called regression hot spots maps were constructed by subtracting the observed cover of 1984 from the predicted regression cover of the same year. Basic assumption is that competition is an important factor, which is not incorporated in the regression analysis. Examining regression hot spot maps, it is possible to get an idea of the potential changes that could occur, before running the allocation module. Values deviating from zero, *i.e.,* where actual and predicted cover differ, indicate areas where changes are most likely to take place. In Figure 2.5, the regression hot spot maps for bananas and forest are given. Comparing both maps, it can be concluded that potential dynamics for bananas are much more geographically concentrated than forest dynamics. Resulting patterns after running the allocation module might differ considerably from regression hot spots, because neither competition among land uses nor changes in the value of driving forces and total supply are taken into account here.

2.3.2 Allocation under given scenarios

Results of the base scenario for 2005 are given in Figure 2.6, which includes a comparison with the initial 1984 situation.

Base scenario

In the base scenario, forest will become restricted entirely to remote and areas unsuitable for agriculture. Demand for agricultural land in potentially suitable areas for forest reduced natural cover in large areas to almost zero. Noteworthy is the persistence of forest in areas within the boundaries of national parks, even though these areas do not have a protected status in the base scenario.

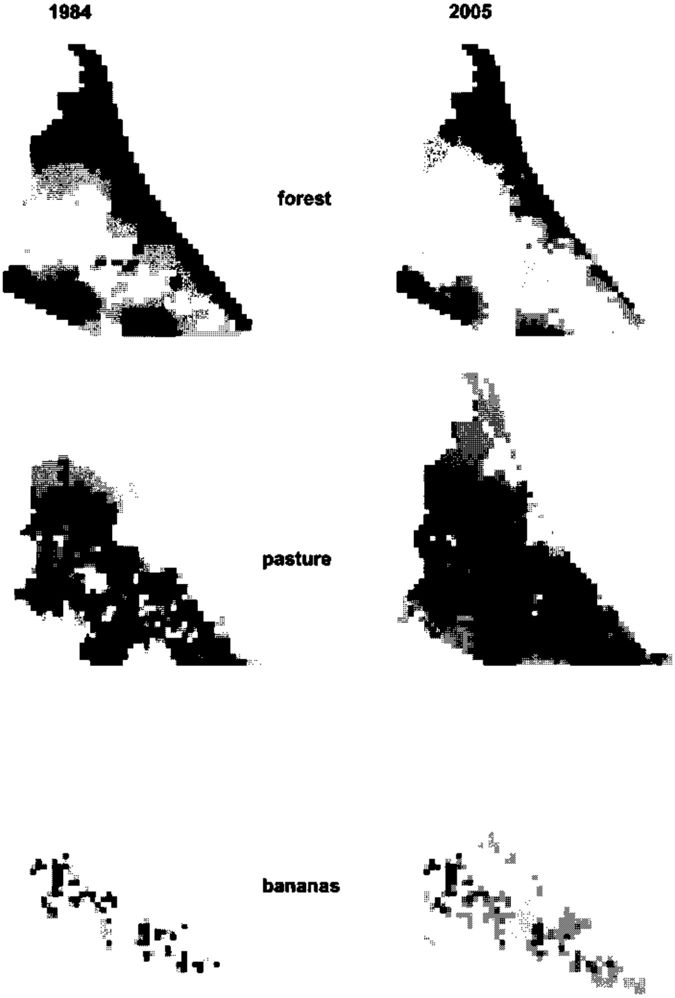

Figure 2.6. Input data and results of base scenario. Left side: situation in 1984; right side: situation after 21 years (2005). Top: forest; middle: pasture; bottom: bananas. Light grey tones indicate areas with a low cover percentage (<5% per grid cell); dark tones indicate a high cover percentage (>80% per grid cell).

Pasture increasingly becomes the dominant land use in the entire zone. Besides some isolated pixels with banana plantations and the already mentioned areas with forest, pasture becomes the dominant cover everywhere. Expansion of banana plantations will predominantly occur near areas where bananas were already present. In particular close to Limón (in the southeastern corner of the study area) new plantations are projected by the model. The location of annual crops will be restricted to a few well-defined areas. Those areas do not necessarily correspond to the original areas in 1984. Palm heart was not present in the zone in 1984, but its projected presence is in the area just south of the main banana zone in the slightly higher locations.

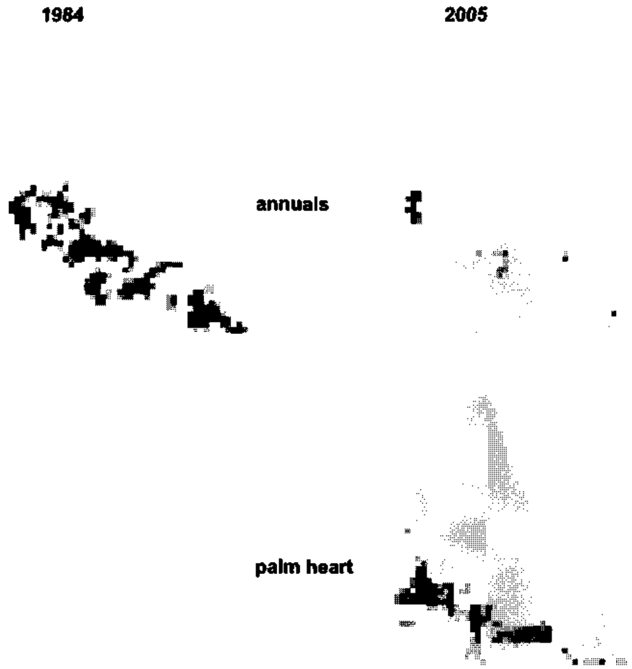

Figure 2.6. (continued). Input data and results of base scenario. Left side: situation in 1984; right side: situation after 21 years (2005). Top: Annuals; bottom: palm heart. Palm heart did not exist in 1984. Light grey tones indicate areas with a low cover percentage (<5% per grid cell); dark tones indicate a high cover percentage (>80% per grid cell).

Competition among land uses is an important factor in the allocation procedure. A comparison between Figure 2.5 (regression hot spots) and Figure 2.6 (changes between 1984 and 2005) illustrates that patterns can differ considerably. Forest is pushed away completely by agricultural land use. The matching patterns between regression hot spots and changes in banana area indicate that in general banana plantations are strong competitors. The same holds for pasture (not shown). The process of deforestation and replacement of forest by (mainly) pasture was modelled accurately with CLUE. Figure 2.7 shows the strong correlation between the disappearance of forest and the increase of pasture. This result confirms expert knowledge and is in agreement with conclusions drawn by Schipper *et al.* (1998).

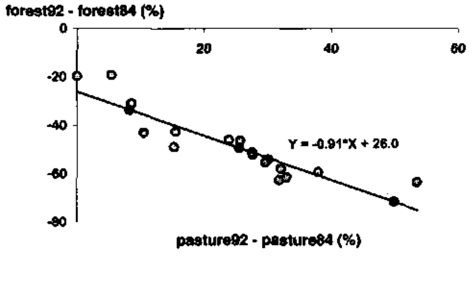

Figure 2.7. Relationship between disappearance of forest and increase of pasture area between 1984 and 1992, aggregated per administrative unit.

Figure 2.8. Differences in allocation of annuals between the liberalisation and base scenarios. Dark areas indicate location of annuals in the base scenario; light grey tones indicate presence of annuals in the liberalisation scenario; intermediate tones indicate areas without annuals.

Other scenarios

Differences in land use patterns between the three demand-controlled scenarios (base, protection, and liberalisation) were small. Despite large differences in changes in total area between the market protection and market liberalisation scenarios (Table 2.3), the overall patterns are very similar for most the important land uses. Forest is consistently pushed out of agriculturally favourable areas and becomes restricted to the northern part of the region. Pasture increases in various places but predominantly in areas with high deforestation rates, and bananas are present in the same areas in all scenarios. The location of areas with annual crops significantly differed between the various scenarios. In Figure 2.8, areas with annuals in the liberalisation and base scenarios almost completely exclude each other. Again, competition with other land uses is the reason for this difference. Annuals have a preference for the same areas as bananas and the stronger push of bananas in the liberalisation scenario causes the annuals to disappear completely from that area.

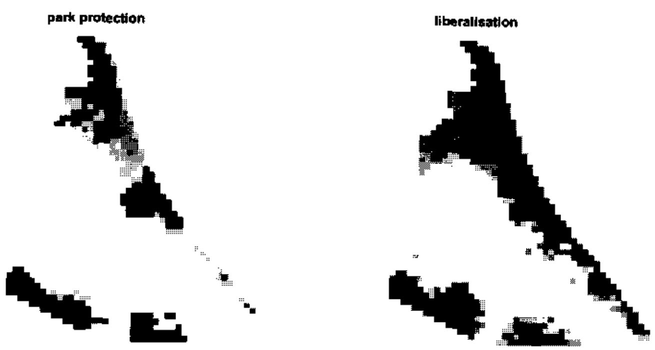

Figure 2.9. Distribution of forest in liberalisation scenario with (left) and without (right) protection of national parks. Percentages indicate forest cover after 21 years of simulation.

Park protection scenario
Restricting land use allocation through protecting parks considerably influences land use patterns. Figure 2.9 shows the distribution of forest with and without protection of national parks. Examining national aggregated numbers (Table 2.3), the pressure on forest *outside* parks is enhanced almost up to the point of complete disappearance. Only in the most remote area close to the border with Nicaragua, forest is still present in reasonable quantities; the remainder of the NAZ is almost exclusively devoted to agricultural uses.

2.3.3 Validation
Figure 2.10 shows the aggregated results of the validation run. CLUE proved to be capable of modelling land use patterns in 1992 from the 1984 situation. Especially the location of pasture and forest were modelled very well, with a correlation coefficient between actual and predicted land use of 0.87 and 0.95, respectively. For bananas, the corresponding correlation coefficient was 0.74. The modelling of location of annual crops was less successful, as reflected in a correlation coefficient of 0.36. For forest, pasture and annuals, the regression line between actual and predicted land use did not differ significantly from the 1:1 relationship. For bananas, cover was overestimated in districts with little banana area, and underestimated in districts with large banana plantations. From a visual comparison between modelled and actual cover of banana plantations (Figure 2.11), it can be concluded that the majority of the new plantations are located at or near areas where increases were modelled. However, the largest decreases in banana area were predicted incorrectly in areas where banana cover was close to 100% in both 1984 and 1992.

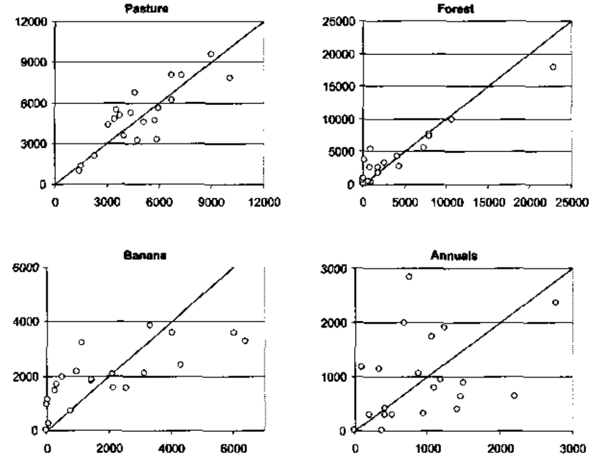

Figure 2.10. Modelled (y-axis) versus actual (x-axis) cover in hectares in 1992, aggregated per administrative unit. Lines are the 1: 1 relationship (y = x).

Figure 2.11. Comparison between modelled increase of banana cover of base scenario (cover in 1992 minus cover in year 1984) and location of banana plantations as observed in 1984 and 1992 (Based on Stoorvogel and Eppink, 1995).

2.4 Discussion and conclusions

2.4.1 General model performance

The spatial pattern of land use in the northern Atlantic Zone of Costa Rica was described in a satisfactory way using statistical techniques in the context of the CLUE framework. Both socioeconomic and biogeophysical factors proved necessary to describe land use patterns. Using the results of this analysis it was possible to satisfactorily simulate land use pattern dynamics over a period of 20 years. Resulting maps showed patterns that could be explained with processes that are known to take place in the region. Especially the competition for land among bananas, pasture and forest was modelled well. Results indicate that the CLUE modelling framework can be successfully used at sub-national level. Comparison with the land use study based on linear programming techniques presented in Schipper *et al.* (2000) reveals interesting similarities. Under a similar scenario of excluding and including protection of national parks, it was concluded that extending the agricultural area into existing protected areas brings only marginal benefits, which is confirmed by this study (see Figure 2.9). A more elaborate comparison between the CLUE methodology and optimisation techniques is given by Bessembinder (1997).

2.4.2 Model benefits and limitations

Two advantages of the CLUE methodology are its speed and data requirements. Although a relatively high amount of data is needed, data required to run CLUE are readily available for many parts of the world. Time consuming and costly fieldwork is not necessary, thus considerably speeding up the modelling procedure, which will typically not take more than 4-6 months.

One of the main points of criticism against statistical modelling is the lack of explanatory power. Obviously, it is necessary to evaluate empirical relationships with expert knowledge of the area. Given the available amount of expert knowledge on land use and land use change dynamics of the NAZ, the step from a statistical analysis to process-based rules is relatively small. It is not *lack of explanatory power* but rather the *lack of knowledge* that limits the application possibilities of a statistical analysis. Even though we do not wish to propagate careless use of statistical relationships, we do want to stress the application value of statistical models, especially in combination with models that use process-based relationships. A limitation of the CLUE modelling framework is its short time horizon, because it is founded on a system description of the (recent) past. Although a separate analysis of a second year enables a check on the stability of the relationships between land use and its driving forces estimated for the first year, uncertainty remains about future changes. Uncertainty is enhanced when incorporating economic variables like price changes or GDP growth. The current version of the CLUE modelling framework can therefore probably not be used for making reliable extrapolations for more than 15 - 20 years into the future.

The observed differences between modelled and actual location of bananas in the application for the NAZ touch upon a limitation of the CLUE allocation procedure. The allocation algorithm was not designed to deal with extremely 'clumpy' cover patterns. An inevitable effect of the large-scale production of bananas as present in the NAZ is that part of the area is located on less suitable soils, while better biophysical circumstances are present elsewhere in the region. Simulation of changes in allocation using CLUE will attempt to "correct" those apparent mis-allocations. Cells with high covers of bananas will be reduced and the thus remaining area will be allocated in cells with similar suitable biophysical conditions. The procedure works very well for covers that are omnipresent like pasture or covers of which the pattern was well described during the statistical analysis, like forest. Even though patterns of more local land uses (see Figure 2.11) might be captured reasonably, estimated cover percentages might not correspond to actually observed percentages.

2.4.3 Scale issues

The present study has demonstrated how multiple spatial resolutions can be incorporated in a quantitative modelling approach. Although the statistical analysis did not demonstrate great differences between resolutions, the CLUE modelling framework offers tools to deal with multi-scale data sets. Not only can local variability in soil properties and the influences of a city or road be captured, but long-term macro-economic changes and influences of policies of other countries can be accounted for as well. Top-down modelling ensures that at every resolution variability of all higher resolutions is included, while bottom-up feedbacks in turn ensure that local constraints are not considered less important than global economic changes. Ignoring one or more scale, *i.e.*, assuming a constant effect on other scales, may limit the valid domain of model results.

Combination of the CLUE model for the NAZ as presented here with the CLUE version for the whole of Costa Rica (Veldkamp and Fresco, 1996b) will allow interpretation over a range of spatial resolutions from 2 × 2 km to 45 × 45 km (see Chapter 7). A preliminary comparison between this study and national level scenario runs revealed similarities in the patterns of forest and differences for pasture which is allocated in another part of the country in the study of Veldkamp and Fresco (1996b).

2.4.4 Application domain

The aim of the CLUE modelling framework is to understand relationships between the environment and land use, and the general or recurrent changes that are observed. General conclusions like the rapid disappearance of forest in the southern part versus the slow deforestation rate in the north *under any given scenario* could be a useful piece of information for policy makers. CLUE furthermore demonstrates the spatially explicit effects of important processes: *e.g.*, the effects of accelerated deforestation, and the restriction of annual crops to poor soils by the strongly competing banana plantations are very convincingly shown in the presented maps. By analysing countries from different geographical locations and in different phases of the process of land use change, an attempt can be made to draw conclusions on issues of global importance.

Finally, erosion, nutrient fluxes, carbon fixation, and loss of biodiversity are just a few of the possible effects that land use or land cover change may have. Comprehension of the relationships between drivers and land use change and the scale at which they operate could prove a powerful tool in a range of scientific fields. Past applications of CLUE proved the feasibility of linking its results with the modelling of nutrient balances (De Koning *et al.*, 1997).

Appendix 1. Independent variables used as input in the statistical analysis.

Parameter abbreviation	Type	Description	Unit
DALF	Demographic	Average agricultural labor force	persons ha^{-1}
DRUR	Demographic	Average rural population density (districts)	persons ha^{-1}
DISDRUR	Demographic	Average rural population density (towns)	persons ha^{-1}
URBDEN	Demographic	Average urban density	persons ha^{-1}
URBDIS	Demographic	Average distance to nearest city	m
DSROAD	Demographic	Average distance to nearest primary or secondary road	m
BSATHI	Soil	Soils with high base saturation; > 50% (between 25 and 100 cm)	%
CECHIGH	Soil	High cation-exchange capacity; > 24 meq/100 g soil	%
CECLOW	Soil	Low cation-exchange capacity; ≤ 16 meq/100 g soil	%
DEPDEEP	Soil	Deep soils; > 125 cm	%
DEPSHAL	Soil	Shallow soils; 0-25 cm	%
DEVWELL	Soil	Well developed and moderately leached soils	%
DEVNO	Soil	Not or slightly developed soils	%
DRAIGOOD	Soil	Well drained soils	%
DRAIBAD	Soil	Very poorly or poorly drained soils	%
ECECHI	Soil	High acidity; > 2 meq/100 g soil and >2 meq KCl extraction Al+H/100 g soil	%
ECECLOW	Soil	Low acidity; < 2 meq/100 g soil	%
FERTHI	Soil	High fertile soils	%
FERTLOW	Soil	Infertile soils	%
PHHIGH	Soil	High pH; pH H_2O > 5.5	%
PHLOW	Soil	Low pH; pH H_2O < 4.5	%
TEXTCLAY	Soil	Clayey texture; SaCl, SiCl, Cl	%
TEXTSAND	Soil	Sandy texture; Sa, Lsa	%
TEXTWET	Soil	Wet texture; no texture (too wet)	%
SLOPSTEE	Other biogeophysical	Steep slopes; steepness > 13%	%
SLOPFLAT	Other biogeophysical	Flat area; steepness 0 - 2%	%
ALT	Other biogeophysical	Average altitude	m
RAIN	Other biogeophysical	Average yearly precipitation	mm
FLOODAL	Other biogeophysical	Always flooded areas	%
FLOODLO	Other biogeophysical	No flooding or low flooding risk	%
STONNO	Other biogeophysical	No stones to fairly stony on soil surface	%
STONYES	Other biogeophysical	Stony to very stony on soil surface	%
DISRIVP	Other biogeophysical	Average distance to nearest minor or major river	m
DISRIVS	Other biogeophysical	Average distance to nearest river or gully	m
PARKNAT	Policy	Area within national park	%
PARKOTH	Policy	Area with other type of protective status	%
IDAYOU	Policy	Area within IDA settlement established after 1980	%
IDAMED	Policy	Area within IDA settlement established between 1970 and 1979	%
IDAOLD	Policy	Area within IDA settlement established between 1960 and 1969	%
IDANOT	Policy	Area outside IDA settlements	%

CHAPTER 3[#]

Spatial determinants of Honduran land use: Empirical evidence for Malthus' theory

Abstract

Land use patterns are influenced by large variety of factors that act over a broad range of scales. International, national, and local factors are all important and need to be incorporated, when the existing composition and distribution of land use is to be understood. A statistical analysis of land use patterns in Honduras is conducted at six spatial resolutions for 1974 and 1993 to identify multi-scale spatial determinants of land use. Special reference is given to the influence of population (growth) and the implications for the theories of Boserup and Malthus. Multiple regression equations indicate the importance of soil-related, climatic and demographic factors for most of the ten land uses. Rural population density dominates as driver over the whole range of resolutions and both years, and especially for maize, where it explains up to 80% of the variation. The strong constant relationship between population and agricultural area hints at a lack of technological development. An analysis of yield development confirms that for most annual crops yield increases lags behind area growth. Land use changes in Honduras support the theory of Malthus, as population growth is coupled with ongoing environmental destruction (deforestation), while yield development largely stagnated over a period of 20 years. The confirmation of Malthus' theory contradicts the prevailing opinion of an ever-present endogenous technological development often assumed by policy makers and apparent at the national scale. The changing conclusions with scale of observation stress the need for multi-scale studies in the field of land use research.

3.1 Introduction

3.1.1 The complexity of land use patterns

Land use patterns are governed by a broad variety of potential driving forces and constraints (Turner II *et al.*, 1995; Nunes and Augé, 1999; Pfaff, 1999), that act over a large range of scales (Gibson *et al.*, 2000). International agreements induced by *e.g.* the United Nations, World Bank or GATT influence regional and national policies that in turn trickle down to local decision-makers and that will ultimately affect farmers' decision to change land use. Other broad-scale determinants of land use are, for instance, extreme weather events (Blaikie *et al.*, 1994; Rodgers *et al.*, 1994) or an international oil crisis (Diaz-Bonilla, 1990). Simultaneously, local changes, *e.g.*

[#] Based on: Kok, K., Bouma, J., submitted. Spatial determinants of Honduran land use: Empirical evidence for Malthus' theory. Submitted to Annals of the Association of American Geographers.

deforestation for fuelwood, in land use can influence higher levels in the hierarchy. Even over a limited range of scales, factors form a complex web of interactions and feedbacks that blur cause-effect relations and complicate interpretation between land use and its drivers (Conway, 1987; Musters *et al.*, 1998). For example, there is agreement, although not undisputed, that pasture expansion in Central America has been initiated by beef demand from the United States (Howard-Borjas, 1995; Thorpe, 1997a). Much more difficult to understand, however, are processes that influenced the location of this forest to pasture conversion. Presence of infrastructure (Ludeke *et al.*, 1990), population pressure (Rudel and Roper, 1997), timber demand (Humphries, 1998), and the general economic situation (May and Bonilla, 1997), to name a few, are factors that together influence patterns of deforestation and pasture development. The same holds for many other land uses, including maize, and banana and coffee plantations.

3.1.2 Scale effect

Which variables will emerge as spatial determinants of land use, depends largely on the adopted (spatial) scale of analysis. This scale dependency of spatially explicit research has long been noted by ecologists (Allen and Starr, 1982; O'Neill *et al.*, 1986; Meentemeyer, 1989; Peterson and Parker, 1998) and more recently by the land use/land cover change community (Turner II *et al.*, 1995; Nunes and Augé, 1999). The smallest discernible unit, or grain, and the size of the area, or extent, will influence which land use drivers contribute to the distribution of land use. Besides, the temporal scale (grain: interval between time steps; extent: time horizon) is of importance as well. Long-term investigations for large areas will often identify population pressure as main cause of land use change (*e.g.* Cuffaro, 1997), while short term, localised studies might highlight a completely different set of driving forces that act at that particular time and location (*e.g.* Chomitz and Gray, 1996). Any investigation that aims at understanding the complexity of land use and land use change should consider multiple temporal and spatial scales of observation. An analysis of multiple years provides a relatively straightforward test on the system's stability over time. The effects of a changing spatial scale are not yet well understood, and particularly the effect of a changing resolution is of a more complex nature (Gustafson, 1998).

3.1.3 Population as driving force of land use change

There is an ongoing debate on the role of population in the process of land use change in general and deforestation in particular (see Pender, 1998). Although nobody will question that humans ultimately induce the majority of all land use changes occurring at present, there is no agreement on causal relationships between population pressure, technological development, and land use change. Based on the theories of Boserup (1965, 1981) and Malthus (1967) contrasting opinions have been generated. Boserup argues that increasing population pressure will induce an, endogenous, technological development that will thus counteract land degradation (read: deforestation) and poverty. Malthus on the other hand claims that an endogenous population pressure will depress economic growth and will lead to food insecurity and accelerated deforestation. The viewpoint of both Boserup (Lele and Stone, 1989; Cuffaro, 1997; Tilman, 1999) and Malthus (Hardin, 1968; Stonich, 1993; Brown, 1994) have been advocated fervently. Others search for a compromise (Blaikie and Brookfield, 1987), recognising that both theories "may be more complementary on closer inspection" (Turner II and Ali, 1996). It is often noted that the observed role of population depends on the particular situation. Initial population density (Pender, 1998), land availability (Jones, 1988), and type of land use (Schelhas, 1996) influence the result. The most important influencing variable, however, might well be the scale of observation. Both temporal (Turner II and Ali, 1996) and spatial (Tilman, 1999) aspects are influential. The larger the temporal or spatial extent, the more evidence can normally be gathered in favour of Boserup. Besides scale-dependency, the relation between population and land use is most clearly related to the phase of the process of land use (change). Economically backward areas will have fewer possibilities than technologically advanced countries and the same holds for areas in the agriculture-forest fringe.

3.1.4 Study area

Honduras is selected as study area, because of its lack of economic prosperity and poor biophysical circumstances (Stonich, 1993; World Bank, 1998), a rare combination in Latin America. Although economic reform programs have recently been successfully implemented and executed (Thorpe, 1997b), this small Central American country continues to be one of the poorest countries of the Western Hemisphere. Its fast growing population has an extremely low purchasing power parity, 50% of the population lives in poverty, inflation rates are high, and the economy is still largely based on agricultural exports (World Bank, 1998). Prospects worsened yet after a major natural disaster, caused by the extreme rainfall that accompanied hurricane Mitch in 1998. What is more, natural resources are relatively scarce; shallow, often unfertile soils prevail, prolonged dry periods are present in most of the inhabited places, and large parts of agricultural production are found on slopes. As a result of these combined poor economic and biophysical circumstances, a subsistence farming system with maize, beans, and pasture is still very common, with little prospect for change. Large-scale land use changes took place over the last decades. The area of annual crop increased with 30%, permanents with 50%, and pasture with almost 15%. Likewise, land use patterns of especially rapidly expanding crops like beans, rice, and coffee, changed considerably. Deforestation predominantly took place in Olancho (see Figure 3.8) and in the north, coupled with some localised reforestation in the west and in the south.

3.1.5 Research framework

A general description of the CLUE modelling framework as well as previous research concerning the spatial determinants of land use at different spatial scales are given in

Chapter 1. In the context of this paper it suffices to know that for every application of the model, multiple regression equations at multiple resolutions need to be generated. Those equations are subsequently used to allocate changes. The empirical results obtained in this study will be used for the application of CLUE to Honduras. Consequently, part of the methodology employed is predefined by model requirements.

3.1.6 Objectives

The objective of the paper is to perform a multi-scale –spatial and temporal– analysis of land use patterns in Honduras, including demographic, soil, and other biogeophysical spatial determinants. Special attention is given to the importance of population density and agricultural yield development in respect to the theories of Boserup and Malthus.

3.2 Methods and material

3.2.1 Data issues

A grid-based data format is adopted, as data from many different sources have to be harmonised. Instead of using uniform grid cells with one dominant land use type and one average or dominant value for every explaining variable, sub-grid information is present for most of the driving forces and each land use type. In every cell, we use *e.g.* the percentage of highly fertile soils and the percentage of each land use. In this way, we do not lose any information when either gridding the data or scaling up, although spatial precision decreases. The size of the basic gridcell of 7.5 × 7.5 km is based on the average unit size (municipality) of the land use and population data, being the most important data sources. The Islas de la Bahia (see Figure 3.8) are excluded from the analysis, because of poor data quality of the soil map and absence of climate data.

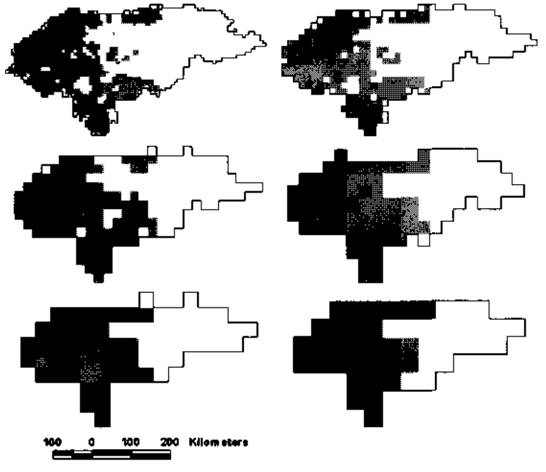

Figure 3.1. Six spatial resolutions with rural population density as an example. Light shades indicate a low density, dark shades a high density.

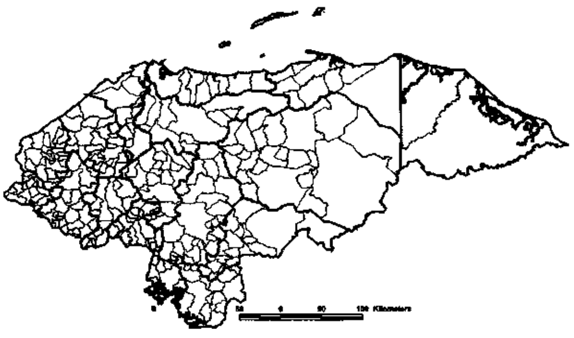

Figure 3.2. Second (thick lines) and third (thin lines) level administrative units of Honduras.

3.2.2 Spatial and temporal resolutions

In addition to the basic grid of 7.5 × 7.5 km (n=1973), five coarser spatial resolutions are created. Coarser resolutions include 15 × 15 km (n=486), 22.5 × 22.5 km (n=212), 30 × 30 km (n=115), 37.5 × 37.5 km (n=69), and 45× 45 km (n=50). The six spatial resolutions are presented in Figure 3.1, using the average rural population density as an example. Data are available for two points in time, 1974 and 1993.

3.2.3 Land use

Agricultural censuses are good sources of thematically detailed information on land use practices. In contrast to most other Central American countries, Honduras has regularly performed a detailed agricultural census, most recently in 1974 and 1993. Both contain information on a large amount of different agricultural products. Data are published at the municipality level, the third level administrative units (Figure 3.2), of which there are approximately 300. Based on total area coverage and economic importance, ten land use types are selected that together represent about 90% of Honduran land uses in terms of area. Citrus and African palm that rapidly increased in recent years are not included, because of their absence in 1974 and extremely localised presence in 1993. Included are:

1. Beans	5. Bananas	9. Pasture
2. Maize	6. Coffee	10. Natural vegetation
3. Rice	7. Sugar cane	
4. Sorghum	8. Plantains	

The category 'pasture' includes only grasslands within the agricultural area and thus excludes most of the natural grasslands. Natural vegetation mainly consists of tropical forest, but also includes secondary regrowth, long-term fallow, natural pastures, and built-up area. The latter covers less than two percent and is therefore not treated separately. Land-use patterns and areas in 1974 and 1993 are given in Figure 3.3 and 3.4.

Sources do not agree on the amount of natural vegetation present in Honduras. An existing forest map adds up to about 70,000 km^2 in 1990 (AFE-COHDEFOR, 1995), whereas the FAOSTAT databases report a constant 60,000 km^2 between 1961 and

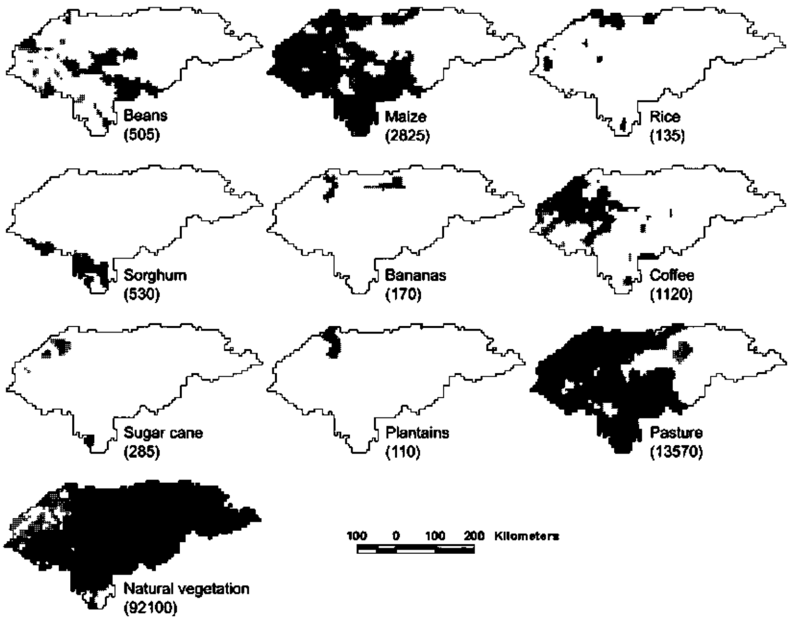

*Figure 3.3. Spatial distribution of all land use types in 1974. Light shades indicate a low cover percentage dark shades a high cover percentage. Numbers between brackets indicate total area in km². *

1996. Based on the agricultural censuses, the undisturbed area amounts up to almost 90,000 km^2, which could possibly be an overestimation of the actual cover of natural vegetation. Assuming a consistent error in space and time we use the quantities as reported by the censuses.

3.2.4 Explaining factors

From the wide variety of possible driving forces of land use, a limited, but broad group of variables is first pre-selected. Pre-selection is based on existing literature on driving forces of land use, an unpublished study concerning the population data base of Honduras, and opinions of local experts. All data are extracted from an existing database (CIAT, 1998). Table 3.1 lists the 22 possible explaining factors that are included in the statistical analysis. Grouping of categorical variables like FERTHIGH and FERTLOW reduces the 'real' number of variables to 17. Explaining factors are divided into three functional groups to facilitate interpretation.

Demographic factors are extracted from population censuses and include total and rural population density, percentage of population that is classified rural, and the average number of workers per farm. Two population censuses are available, the year

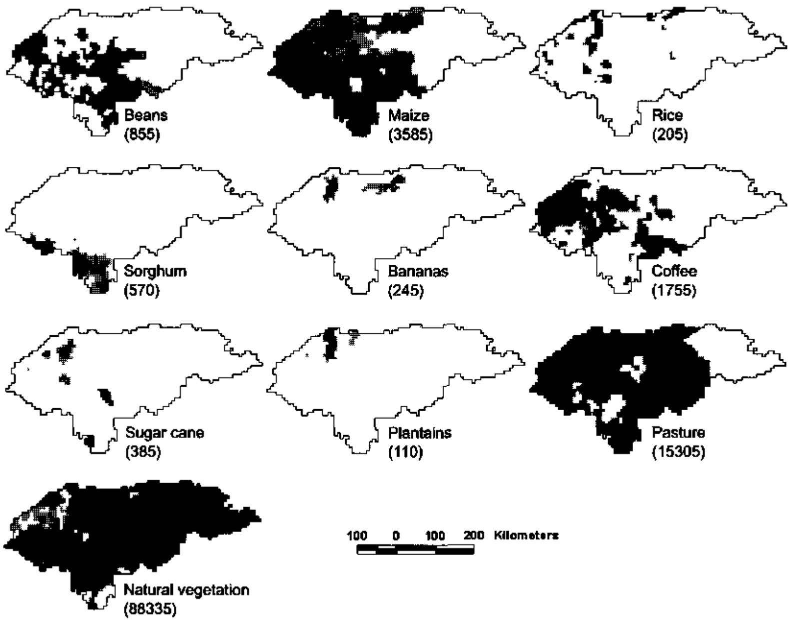

Figure 3.4. Spatial distribution of all land use types in 1993. Light shades indicate a low cover percentage dark shades a high cover percentage. Numbers between brackets indicate total area in km^2.

of the second census being 1988, which does not coincide with the date of the agricultural census. Because population density is dynamic, a 1993 map has to be constructed. A combination of spatially explicit growth rates that can be calculated from the two censuses and national growth rates (FAO, 1999) between 1988 and 1993 is used to update the 1988 population variables. A wealth of other variables, like agricultural labour force, level of education, illiteracy etc., are available, but are not considered because of their high correlation with rural or total population density. An existing soil map (Simons, 1977) is used to obtain information on various soil chemical and physical properties. Included in the analysis are fertility, texture, water retention capacity, pH of topsoil, rooting depth, drainage, and susceptibility for erosion. The latter two are not divided into subclasses. Every gridcell contains information on the dominant class, instead of a subclass percentage for those soil properties. Other biogeophysical data include altitude and slope, which are derived from a digital terrain model with a resolution of 100 m, and total annual rainfall and number of consecutive dry months (< 60 mm of rainfall), both derived from monthly rainfall maps. Distance to nearest river is based on a topographic map with all major rivers. Information on geological units is extracted from an existing geological map (IGN, 1991).

Table 3.1. Basic information of variables included in the multiple regression analysis.

Variable	Explanation	Unit	Source
Demographic			
DENRUR	rural population density	ind./ha	Population censuses 1974 and 1988
DENTOT	total population density	ind./ha	Population censuses 1974 and 1988
PERRUR	fraction of population classified rural	% of population	Population censuses 1974 and 1988
WORKER	number of workers per farm	number	Population censuses 1974 and 1988
Soil			
FERTLOW	non fertile or low fertility	% of gridcell	Soil map of Honduras, CIAT, Colombia
FERTHIGH	high fertility	% of gridcell	Soil map of Honduras, CIAT, Colombia
TEXTSAND	topsoil with sandy texture	% of gridcell	Soil map of Honduras, CIAT, Colombia
TEXTCLAY	topsoil with clayey texture	% of gridcell	Soil map of Honduras, CIAT, Colombia
WATRETL	low water retention	% of gridcell	Soil map of Honduras, CIAT, Colombia
WATRETH	high water retention	% of gridcell	Soil map of Honduras, CIAT, Colombia
ROOTSHAL	rooting depth < 20 cm	% of gridcell	Soil map of Honduras, CIAT, Colombia
ROOTDEEP	rooting depth > 50 cm	% of gridcell	Soil map of Honduras, CIAT, Colombia
PH	pH of topsoil	number	Soil map of Honduras, CIAT, Colombia
SOILDRAI	soil drainage, three classes (0 = poor)	classes	Soil map of Honduras, CIAT, Colombia
EROSRISK	erosion risk, five classes (0 = low)	classes	Soil map of Honduras, CIAT, Colombia
Other biogeophysical			
ALTITUDE	altitude	meters	Digital Elevation Model, CIAT, Colombia
SLOPE	slope steepness	degrees	Digital Elevation Model, CIAT, Colombia
RAINFALL	average total annual precipitation	mm	Monthly rainfall maps, CIAT, Colombia
DRYMONTH	consecutive months with <60 mm of precipitation	number	Monthly rainfall maps, CIAT, Colombia
DISTRIV	distance to nearest river	meters	Topographic map, CIAT, Colombia
GEOLT	rock at surface of tertiary origin	% of gridcell	Geologic map, CIAT, Colombia
GEOLQ	rock at surface of quaternary origin	% of gridcell	Geologic map, CIAT, Colombia

3.2.5 Statistical analysis

The relationships between land use and the selected set of potential explaining factors are quantified using multiple regression techniques. First, significantly ($P < 0.05$) contributing variables are selected by means of stepwise regression. Subsequently, this set of variables is used to construct multiple regression equations. The procedure is executed for every land use type, at six spatial resolutions, and for 1974 and 1993, resulting in a total of 120 equations. The adjusted coefficient of determination (R^2) serves as a measure for the amount of variation explained. The standardised regression coefficients (standardised betas) are used to indicate the relative importance of individual variables and variable groups. Before executing the multiple regression analysis, a couple of steps are taken to minimise the correlation between variables (multicollinearity effects) and between neighbouring grid cells within one variable (spatial autocorrelation).

Multicollinearity effects are considerable and several measures are taken to reduce it as much as possible. Of all classified variables (*e.g.* soil fertility) one categorical class (*e.g.* percentage of medium fertile soils) is omitted from the analysis. Of all pairs of variables with a correlation over 0.80, one is omitted from the analysis. Of all pairs of variables with a correlation over 0.50, only one is allowed to enter a regression equation. The use of a stepwise regression procedure solves most remaining problems. Omitted for reasons of redundancy are urban population density (obtainable from total and rural density) medium soil fertility, medium soil texture, medium water retention, and medium rooting depth. Excluded for reasons of high correlation are distance to nearest road (correlation with DENRUR), distance to nearest port (DENRUR), soil depth (rooting depth), temperature (ALTITUDE), and aspect (SLOPE). Not allowed together in one equation are DRYMONTH and RAINFALL; SLOPE and ALTITUDE; ROOTSHAL and WATRETL; TEXTSAND and FERTHIGH.

Spatial autocorrelation can change the results of a regression analysis. In particular standardised betas are sensitive for the presence of autocorrelation (Anselin and Griffith, 1988; Chou, 1991). Theoretically, methods exists that can correct for autocorrelation. However, in this alternative manner to derive multiple regression equations the use of a stepwise procedure becomes very time-consuming, which complicates the calculation of a high number of equations. A stepwise procedure, however, is considered indispensable in this study. At the country scale considered here, underlying processes are not completely understood and the complex web of interactions between the multitude of driving forces might change with the scale of analysis. A theoretical model of significantly contributing factors can therefore not be generated *a priori*. Overmars (2000) analysed the influence of spatial autocorrelation using a multi-resolution dataset from Ecuador, over a range of resolutions similar to this study. Results indicated the presence of spatial autocorrelation at the most detailed resolution (9.5 × 9.5 km) and a rapid decrease at coarser resolutions. Moreover, most multiple regression equations and standardised betas varied little when a spatial autoregressive model was used. The statistical analyses are therefore conducted without correcting for the influence of spatial autocorrelation.

3.2.6 Technological development

The strong correlation between population density and land use that was established after the initial analyses poses the question of the role of technological development. Yield development relative to area development between 1974 and 1993 is considered a good indicator of technological improvement within the agricultural sector. Changes in technological change are calculated at two distinct resolutions, national level and the basic grid of 7.5 × 7.5 km:

$$DIFNAT_i = AREAGROW_i - YIELDGROW_i \qquad (1)$$

$$DIFFCELL_i = AREAGROW_i - \sum_{0}^{n}(YIELDGROW_{xyi}) \qquad (2)$$

where DIFNAT is the difference at national level and DIFFCELL the difference at the basic grid. AREAGROW and YIELDGROW are the annual increases in area and yield between 1974 and 1993 (%). Indices are i for land use type, x for column number, y for row number; n is the number of cells in the analysis.

Main difference between the calculations is that for the spatially explicit analysis of technological change (DIFCELL), yield in all cells receives an equal weight irrespective of the area that a land use type occupies. It is thus assumed that a small area is as good an indication for yield potential as a large area. In the national calculation of yield difference (DIFNAT), the yield calculation is not area-weighted.

3.3 Results

3.3.1 Coefficients of determination

Adjusted coefficients of determination (R^2) of all 120 multiple regression equations are given in Table 3.2. In general, all individual land uses yield a R^2 of at least 0.25. Less satisfactory statistical models are found for sugar cane and plantains in 1974 and rice in 1993, all of which concern crops with a very localised distribution, partly in plantations. The coefficients of determination for the distribution of maize, sorghum, and natural vegetation are high in both years and over all resolutions. Especially patterns of maize cultivation are well described with the set of potential drivers. Coefficient of determination invariably increases with spatial resolution. On average, an increase of 0.25 between level 1 and level 6 is observed, again in both years. At the coarsest spatial resolution, the R^2 is usually at least 0.50. The majority of the land use types show a linear increase over the first three spatial resolutions. When resolution further coarsens, however, the R^2 of most of the smaller land uses continues to increase (*e.g.* plantains 1974 or bananas 1993), whereas the R^2 of particularly the large land uses tends to level off (*e.g.* pasture 1974 or natural vegetation 1993).

Table 3.2. Coefficients of determination (adjusted R^2) for all spatial resolutions and all crops.

Land use type	Level 1	Level 2	Level 3	Level 4	Level 5	Level 6
1974						
beans	0.28	0.30	0.31	0.49	0.46	0.44
maize	0.76	0.76	0.81	0.81	0.82	0.84
rice	0.27	0.32	0.31	0.41	0.38	0.57
sorghum	0.57	0.63	0.73	0.82	0.80	0.87
bananas	0.28	0.35	0.40	0.38	0.38	0.65
coffee	0.27	0.31	0.29	0.35	0.59	0.37
sugar cane	0.09	0.11	0.12	0.21	0.25	0.48
plantains	0.22	0.30	0.36	0.39	0.44	0.79
pasture	0.47	0.54	0.59	0.61	0.67	0.63
nat. vegetation	0.59	0.63	0.67	0.68	0.73	0.69
1993						
beans	0.43	0.50	0.59	0.61	0.70	0.76
maize	0.76	0.79	0.80	0.76	0.89	0.85
rice	0.18	0.20	0.27	0.31	0.26	0.49
sorghum	0.55	0.60	0.68	0.72	0.73	0.78
bananas	0.35	0.39	0.43	0.51	0.59	0.66
coffee	0.37	0.41	0.46	0.55	0.69	0.64
sugar cane	0.27	0.28	0.31	0.35	0.63	0.58
plantains	0.31	0.42	0.49	0.49	0.51	0.73
pasture	0.48	0.52	0.55	0.55	0.63	0.64
nat. vegetation	0.66	0.70	0.71	0.69	0.78	0.78

The partly linear increases contradict findings of earlier CLUE-related studies in Latin America over a broad range of resolutions. Veldkamp and Fresco (1997) report levelling off coefficients of determination for a number of land use types in Costa Rica, and De Koning *et al.* (1998) concludes that coefficients stop increasing after level 4 when describing land use patterns in Ecuador. Both studies applied a range of resolutions that was similar to this study. Using a much coarser resolution in China, Verburg and Chen (2001) report similar results for horticulture. Comparable methodologies have also been used on remote sensing images to quantify scale-dependencies. Malingreau and Belward (1992) report a large resolution effect "between the 16 and 25 pixel sample sizes" for NDVI time series in the Amazon

Table 3.3. Multiple regression equations at six spatial resolutions for spatial distribution of beans, maize, bananas, coffee, pasture and natural vegetation in 1974. All variables significant at the $P < 0.001$ level, unless noted otherwise.

Level 1 variable	stb	Level 2 variable	stb	Level 3 variable	stb	Level 4 variable	stb	Level 5 variable	stb	Level 6 variable	stb
beans											
DENRUR	0.38	DENRUR	0.34	DENRUR	0.34	DENRUR	0.47	WATRETH[2]	-0.27	DENTOT[2]	0.25
WORKER	0.15	WORKER	0.18	FERTLOW[1]	0.19	WORKER[2]	0.18	ROOTSHAL[2]	0.22	PH[2]	-0.28
FERTHIGH	-0.22	FERTLOW	0.18	SLOPE[2]	0.13	FERTHIGH	-0.60	DISTRIV[1]	0.33	DRYMONTH[1]	0.52
ROOTDEEP	-0.18	SOILDRAI[2]	0.09	DRYMONTH	0.29	ROOTDEEP	-0.36	GEOLQ[2]	-0.24		
DRYMONTH[2]	0.05	DRYMONTH[2]	0.15			PH[1]	0.24				
						DRYMONTH[2]	0.21				
maize											
DENRUR	0.80	DENRUR	0.80	DENRUR	0.81	DENRUR	0.83	DENRUR	0.70	DENRUR	0.87
WORKER	0.06	WORKER[2]	0.05	PERRUR	0.11	ALTITUDE[2]	-0.12	DISTRIV[2]	0.18	WORKER	0.45
FERTHIGH	-0.05	ALTITUDE	-0.08	WORKER	0.17	DRYMONTH	0.20			FERTHIGH[2]	-0.21
ALTITUDE	-0.11	DRYMONTH	0.17	ALTITUDE	-0.19					ALTITUDE	-0.32
DRYMONTH	0.18			DRYMONTH	0.23					RAIN	-0.41
DISTRIV	0.05			DISTRIV[2]	0.09						
				GEOLT	-0.15						
bananas											
DENRUR	0.25	DENRUR	0.29	DENRUR	0.33	DENRUR	0.29	PERRUR[2]	-0.29	DENRUR[1]	0.39
DENTOT	0.09	PERRUR	-0.08	FERTHIGH	0.34	PERRUR[2]	-0.16	FERTHIGH	0.49	FERTHIGH	0.53
FERTHIGH	0.21	FERTHIGH	0.28	TEXTCLAY	-0.21	FERTHIGH[2]	0.23	DRYMONTH	-0.79	ERORISK[1]	-0.28
TEXTCLAY	-0.15	TEXTCLAY	-0.19	ROOTSHAL[2]	0.28	DRYMONTH	-0.72			DRYMONTH[1]	-0.47
WATRETL	-0.20	ROOTSHAL[1]	0.22	SOILDRAI[2]	0.12	GEOLQ[2]	0.24				
DRYMONTH	-0.60	ALTITUDE[2]	-0.12	ALTITUDE[2]	-0.15						
GEOLQ	0.18	DRYMONTH	-0.51	DRYMONTH	-0.56						
		GEOLQ[1]	0.17	GEOLQ[1]	0.22						
coffee											
DENRUR	0.48	DENRUR	0.45	DENRUR	0.64	DENRUR	0.39	DENRUR	0.46	DENRUR[2]	0.40
DENTOT	-0.10	PERRUR[2]	0.09	DENTOT	-0.28	FERTLOW[2]	0.18	FERTHIGH	-0.45	FERTHIGH	-0.28
WORKER	-0.07	FERTHIGH	-0.19	FERTLOW[2]	0.15	SLOPE	0.39	TEXTCLAY	0.42	WATRETL[2]	-0.56
FERTHIGH	-0.14	WATRETL	-0.31	TEXTCLAY[2]	0.12			SLOPE	0.68	ROOTDEEP[1]	-0.72
WATRETL	-0.21	ROOTDEEP	-0.39	SLOPE	0.28			RAINFALL	0.38	SLOPE[1]	0.39
ROOTDEEP	-0.33	SOILDRAI	0.15								
SOILDRAI	0.14	SLOPE	0.20								
SLOPE	0.18										
pasture											
DENRUR	0.56	DENRUR	0.60	DENRUR	0.71	DENRUR	0.63	DENRUR	0.72	DENRUR	0.81
TEXTCLAY	-0.07	FERTHIGH[1]	-0.10	FERTHIGH[1]	-0.17	PERRUR[2]	-0.31	ALTITUDE[2]	-0.30	FERTLOW[1]	0.41
ALTITUDE	-0.19	ALTITUDE	-0.28	ALTITUDE	-0.29	FERTLOW[2]	0.12	DISTRIV[1]	0.25	WATRETH[1]	0.23
RAINFALL	-0.27	DRYMONTH[1]	0.16	RAINFALL	-0.30	TEXSAND[2]	-0.13	GEOLT[2]	-0.21	PH[2]	0.22
DISTRIV	0.13	DISTRIV	0.12	GEOLQ[1]	0.22					DISTRIV[2]	0.25
GEOLQ	0.13	GEOLQ	0.27								
natural vegetation											
DENRUR	-0.69	DENRUR	-0.71	DENRUR	-0.78	DENRUR	-0.71	DENRUR	-0.85	DENRUR	-0.71
TEXTCLAY	0.05	FERTHIGH[1]	0.09	FERTHIGH[2]	0.12	PERRUR[2]	0.28	FERTLOW[2]	-0.15	FERTLOW[2]	-0.21
ALTITUDE	0.16	ALTITUDE	0.24	ALTITUDE	0.28	FERTLOW[2]	-0.13	ROOTDEEP[1]	-0.17	ALTITUDE[1]	0.41
RAINFALL	0.19	DRYMONTH[2]	-0.12	DRYMONTH[1]	-0.17	TEXSAND[2]	0.11	DISTRIV[1]	-0.24	DISTRIV[2]	-0.23
DISTRIV	-0.10	DISTRIV[1]	-0.08	GEOLT[2]	0.13			GEOLT[2]	0.19		
GEOLQ	-0.10	GEOLQ	-0.14								

[1] $P < 0.01$
[2] $P < 0.05$

Basin, with a pixelsize of 1.1 kilometre. Walsh and his co-workers established linear increases of R^2 in Northern Thailand (Walsh *et al.*, 1999) in explaining the ratio between land and population, but levelling off R^2's when explaining NDVI-values in Montana (Walsh *et al.*, 1997), over a range from 30 m to 1000 meter.

3.3.2 Variable composition

Multiple regression equations in terms of standardised betas for the most important land use types in 1974 and 1993 are given in Table 3.3 and Table 3.4. The equations for the remaining land uses (rice, sorghum, plantains, and sugar cane) are not presented, as the results do not add to the conclusions from the presented equations. In general, variables that appear in an equation have the expected sign. For instance, a higher value for rural population density (DENRUR) results in more agricultural land and less natural vegetation. Beans are furthermore not cultivated on fertile soils (FERTHIGH -); maize prevails in the drier areas (DRYMONTH +); banana plantations need fertile soils (FERTHIGH +); coffee is cultivated at higher altitudes (SLOPE or ALTITUDE +); and pasture is predominant on slightly less suitable soils (WATRETL +) in lower areas (ALTITUDE -). The negative sign of FERTLOW in

Table 3.4. Multiple regression equations at six spatial resolutions for spatial distribution of beans, maize, bananas, coffee, pasture and natural vegetation in 1993. All variables significant at the P < 0.001 level, unless noted otherwise.

Level 1 variable	stb	Level 2 variable	stb	Level 3 variable	stb	Level 4 variable	stb	Level 5 variable	stb	Level 6 variable	stb
beans											
DENRUR	0.36	DENRUR	0.35	DENRUR	0.38	DENRUR	0.37	TEXTSAND[2]	0.16	DENRUR	0.37
DENTPOP	-0.13	DENTPOP	-0.15	DENTPOP[1]	-0.16	DENTPOP[2]	-0.18	ROOTDEEP	-0.45	WATRETL	0.42
FERTHIGH	-0.09	FERTHIGH	-0.07	FERTHIGH	-0.10	WORKER[2]	-0.14	DRYMONTH[2]	0.24	SOILDRAI[1]	0.27
ROOTDEEP	-0.21	ROOTDEEP	-0.27	ROOTDEEP	-0.26	TEXTSAND[1]	0.21	DISTRIV	0.32	DRYMONTH[2]	0.29
SOILDRAI	0.07	SOILDRAI	0.12	ALTITUDE	0.09	WATRETL[2]	0.19				
ALTITUDE	0.17	ALTITUDE[2]	0.11	DRYMONTH	0.23	DRYMONTH	0.41				
DRYMONTH	0.23	DRYMONTH	0.24	DISTRIV[2]	0.13						
DISTRIV	0.07	DISTRIV	0.12	GEOLQ[2]	-0.12						
maize											
DENRUR	0.86	DENRUR	0.87	DENRUR	0.85	DENRUR	0.91	DENRUR	0.86	DENRUR	0.76
PERRUR	-0.16	PERRUR	-0.18	WORKER[1]	-0.09	FERTHIGH[2]	-0.13	DRYMONTH[1]	0.15	DRYMONTH	0.28
WORKER	-0.09	WORKER	-0.11	DRYMONTH	0.19	DRYMONTH	0.23	DISTRIV[1]	0.20		
DRYMONTH	0.19	WATRETH	-0.06								
		DRYMONTH	0.16								
bananas											
DENRUR	0.47	DENRUR	0.55	DENRUR	0.67	DENRUR	0.71	DENRUR	0.55	DENRUR	0.59
PERRUR	-0.09	WORKER	0.40	WORKER	0.33	WORKER	0.41	FERTHIGH[1]	0.30	SOILDRAI[2]	-0.28
WORKER	0.40	FERTLOW[2]	-0.09	SOILDRAI[1]	0.15	WATRETH[2]	0.39	TEXTCLAY[1]	-0.29	DRYMONTH	-0.77
FERTLOW	-0.10	TEXTCLAY[2]	-0.09	DRYMONTH	-0.61	ROOTSHAL[1]	0.35	ROOTSHAL	0.29		
ROOTSHAL	0.09	EROSRISK[1]	0.13	GEOLQ[2]	0.18	DRYMONTH	-0.52	ALTITUDE	-0.56		
SLOPE	-0.09	DRYMONTH	-0.43					RAINFALL	-0.46		
DRYMONTH	-0.44	GEOLQ	0.24								
coffee											
DENRUR	0.43	DENRUR	0.40	DENRUR	0.49	DENRUR	0.51	DENRUR	0.58	DENRUR	0.52
WORKER	-0.17	WORKER	-0.17	WORKER[1]	-0.20	WORKER[1]	-0.20	WORKER[2]	-0.23	WORKER[1]	-0.40
FERTHIGH	-0.15	FERTHIGH[1]	-0.17	FERTHIGH[1]	-0.18	FERTHIGH[1]	-0.27	FERTHIGH[1]	-0.31	FERTLOW	0.54
WATRETL	-0.26	WATRETL	-0.29	WATRETL	-0.34	TEXTCLAY[1]	0.19	TEXTCLAY[1]	0.38	PH[2]	0.20
ROOTDEEP	-0.28	ROOTDEEP	-0.26	ROOTDEEP[1]	-0.30	ALTITUDE	0.32	ALTITUDE[1]	0.38	SOILDRAI[2]	0.26
ALTITUDE	0.26	ALTITUDE	0.30	ALTITUDE	0.31			RAINFALL	0.35	ALTITUDE[1]	0.23
GEOLT	-0.05										
pasture											
DENRUR	0.24	DENRUR	0.28	DENRUR	0.57	DENRUR	0.60	DENRUR	0.72	DENRUR	0.78
PERRUR	-0.33	PERRUR	-0.33	WATRETL	0.38	FERTLOW[2]	0.15	FERTLOW[2]	0.17	PERRUR[2]	-0.23
TEXTCLAY	-0.07	FERTLOW[1]	0.10	ROOTDEEP[1]	0.25	RAINFALL	-0.35	RAINFALL	-0.36	FERTLOW[2]	0.21
WATRETL	0.09	TEXTCLAY[2]	-0.07	RAINFALL	-0.29	GEOLT[1]	-0.25	GEOLT[1]	-0.29	SOILDRAI[2]	0.28
ALTITUDE	-0.10	RAINFALL	-0.23	GEOLT	-0.41					RAINFALL[2]	-0.21
RAINFALL	-0.28	DISTRIV	0.12							GEOLT[1]	-0.31
DISTRIV	0.11	GEOLT[1]	-0.12								
GEOLT	-0.15										
natural vegetation											
DENRUR	-0.47	DENRUR	-0.49	DENRUR	-0.76	DENRUR	-0.81	DENRUR	-0.85	DENRUR	-0.56
PERRUR	0.35	PERRUR	0.33	FERTLOW[2]	-0.08	FERTHIGH[2]	0.18	FERTHIGH[1]	0.20	PERRUR	0.49
FERTLOW	-0.07	ROOTSHAL	-0.17	TEXTCLAY[1]	0.12	RAINFALL	0.23	DRYMONTH[1]	0.23	FERTHIGH[2]	0.20
RAINFALL	0.18	RAINFALL	0.17	RAINFALL	0.27	GEOLT[1]	0.18				
DISTRIV	-0.06	DISTRIV[1]	-0.08	GEOLT	0.27						
GEOLT	0.10	GEOLT	0.13								

[1] $P < 0.01$
[2] $P < 0.05$

the explanation of the distribution of natural vegetation at many resolutions is one of the few factors with a counterintuitive sign. For the land uses that are not included in the table, DENRUR is usually the most important factor, followed by DRYMONTH (rice), and shallow rooting depth (ROOTSHAL, sorghum).

In almost every single equation (95%), DENRUR is present; in more than 75% of the equations it is the most important factor in terms of standardised beta. The other demographic variables also appear regularly. A second recurring variable is DRYMONTH, which is present in 50% of the cases, especially explaining the distribution of beans, maize, and bananas. Other important variables include a range of soil factors (FERTHIGH, TEXTCLAY, ROOTSHAL), ALTITUDE, quaternary mother material (GEOLQ). Erosion risk (EROSRISK) and soil pH (PH) are among the least important factors, probably due to remaining multicollinearity effects with other soil-related variables. In 80% of the equations at least one variable from all three categories (demographic, soil, and other biogeophysical) is present. A notable exception is maize, where soil variables are not important. For visualisation purposes, the average standardised betas of the three most common parameters, DENRUR,

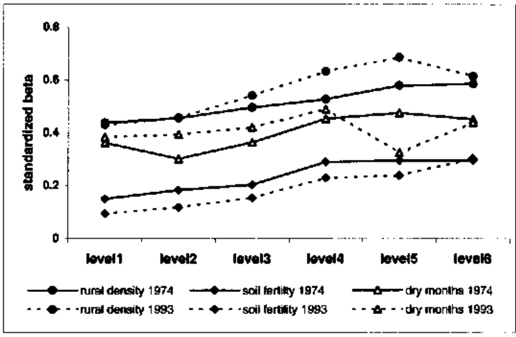

Figure 3.5. Standardised beta of rural population density, highly fertile soils, and number of dry months in 1974 and 1993. Values represent an average of all occurrences in ten multiple regression equations for all spatial resolutions and both years.

FERTHIGH, and DRYMONTH are depicted in Figure 3.5. In both years DENRUR is the most important variable, followed by DRYMONTH and FERTHIGH. DENRUR tends to be more important in 1993, while the importance of especially FERTHIGH diminishes. The effect of spatial resolution is, again, relatively small. All variables tend to have a higher standardised beta at coarser resolutions, but relative differences remain. Patterns of land use in Honduras are thus influenced heavily by rural population density, but explanations are not complete without taking into account climatic and soil-related factors.

3.3.3 Temporal and spatial changes

Although total quantities as well as patterns changed considerably between 1974 and 1993 (see Figure 3.3 and 3.4), composition of explaining variables remains relatively constant over this period of 20 years. Apparently, the land use system did not change, only its appearance did. Existing differences between years are usually attributable by the replacement of a variable by another from the same category. Interchangeable pairs of variables are, besides the ones mentioned in Section 2.5, TEXTCLAY and FERTLOW, FERTHIGH and ROOTDEEP, and GEOLT and DRYMONTH. When examining changes over the range of spatial resolutions, differences tend to increase and the number of variables that significantly contribute decreases to sometimes only 2 or 3 at coarser resolutions. Both observations can be explained by increasing effects of multicollinearity.

Like the development of the R^2, the stability over a range of resolutions contradicts some of the earlier studies. Veldkamp and Fresco (1997) report strong fluctuations and even changes of the sign for equations that describe land use in Costa Rica. According to De Koning *et al.* (1998) the importance of soil-related variables is systematically reduced and the importance of demographic variables increases in Ecuador. Verburg and Chen (2001) note that particularly the contribution of urban population density to the distribution of horticulture increases when resolution coarsens. Despite the results presented by Veldkamp and Fresco (1997), conclusions drawn by Kok and Veldkamp (2001) on the land use system in Costa Rica are confirmed: Changing the spatial resolution does not provoke major changes in the variable composition of equations that explain land use patterns in Central America.

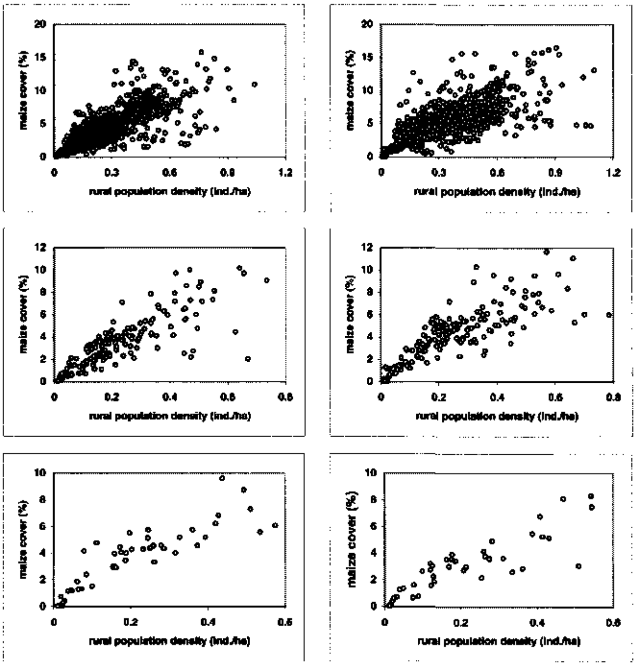

Figure 3.6. Relation between rural population density and the percentage of maize cover per gridcell. Depicted are the relations in 1974 (left) and 1993 (right) for level 1 (top), level 3 (middle), and level 6 (bottom).

3.3.4 Population

As concluded above, rural population density is of overriding influence in the explanation of land use patterns. Although of major importance for most land uses, maize stands out as a special case. DENRUR alone can explain up to 80% of the variation in the patterns of maize cultivation. Relations are visualised in Figure 3.6 for three resolutions and both years. A strong and linear relation exists between maize and rural population density. Best linear relationships are presented in Table 3.5, which shows that the relationship is stable in space and time. Because regression

Table 3.5. Equations and coefficient of determination of relationship between spatial distribution of maize and rural population density.

Scale	Slope	Intercept	Adjusted R^2
1974			
level 1	13.9	0.45	0.74
level 2	13.5	0.48	0.75
level 3	12.9	0.52	0.75
level 4	13.4	0.49	0.80
level 5	11.5	0.62	0.72
level 6	11.1	0.73	0.75
1993			
level 1	12.4	0.91	0.67
level 2	12.7	0.88	0.70
level 3	13.0	0.84	0.74
level 4	13.5	0.83	0.69
level 5	13.5	0.79	0.81
level 6	13.4	0.77	0.79
average	12.9	0.65	

coefficients and intercept did not differ significantly, one scale-independent, relation can be calculated by averaging the equations listed in Table 3.5:

$$\text{MAIZE} = 12.9 \times \text{DENRUR} + 0.65 \qquad (3)$$

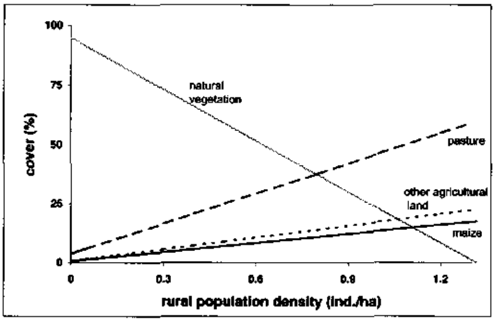

Figure 3.7. Scale-independent average relationships between rural population density and cover per gridcell of main land use types.

Similar equations can be constructed for natural vegetation and pasture. Figure 3.7 illustrates the (hypothetical) changes in a land use system of maize, other agricultural land, pasture, and natural vegetation. An initial mix of 95% natural vegetation and 5% pasture becomes a mix of 50% pasture, 10% maize, 15% other agricultural land, and 25% natural vegetation at one person per hectare. At a density of about 1.3 individuals/ha, the area is completely deforested and other agricultural products amount up to almost 20%. Although it is highly speculative to extrapolate knowledge from two points in time, the established relationships describe plausible changes of land use.

From the above it follows that in order to understand (changes in) land use patterns, an understanding of rural population growth and, more important, present and future migration flows is vital. Quantified information on past and present flows can be extracted from population census data, which contains information on the residential

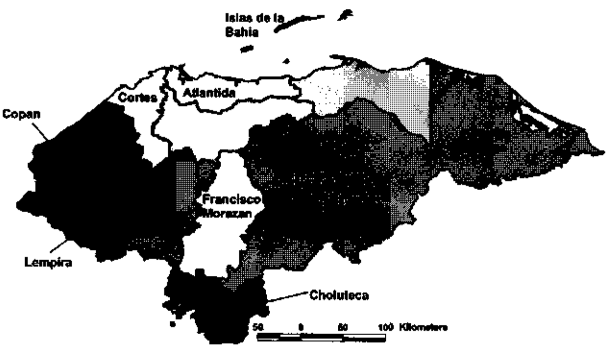

Figure 3.8. Migration patterns in Honduras between 1963 and 1988 at department level. Indicated are areas of inmigration (very light and light shades), areas of outmigration (dark and very dark shades), and areas without substantial migration flows (medium dark shades).

history of every individual. Figure 3.8 depicts migration flows of rural population between 1963 and 1988 aggregated to department level. During the last 25 years, a strong migration has taken place from Lempira, Copan, and Choluteca in the south and west to Cortes and Atlantida in the north. However, at present there is a strong migration to the south of Olancho near the agriculture-forest fringe, and migration is starting into Gracias a Dios in the east, where large areas of undisturbed forest are still present. Migration patterns are thus highly dynamic, and imposing past trends on future movements is arduous.

3.3.5 Yield versus area change

Figure 3.9 gives the relative difference between the annual area growth (%) and the annual yield change (%). Positive numbers indicate a predominant area expansion; negative numbers a yield increase. In some cases large differences exist between both scales. For beans and rice the national trend indicates an agricultural intensification with huge yield increases, while the opposite can be concluded from the spatially explicit calculation. This apparent contradiction can be explained by assuming that the small number of large and high producing farms did intensify, while the high number of small and more isolated farms opted for area expansion. Thus, in the majority of the cells area expansion prevailed. The opposite holds for plantains. Focusing on the spatially explicit analysis, the reaction to an increasing demand (compare Figure 3.3 and Figure 3.4) of annuals and pasture was an area expansion (dark columns positive), whereas permanent crops intensified their production (dark columns negative). Export-oriented permanents like coffee and bananas apparently had the means to intensify, unlike subsistence farming systems with annuals and pasture. The absence of suitable areas could also explain the intensification of permanent crops.

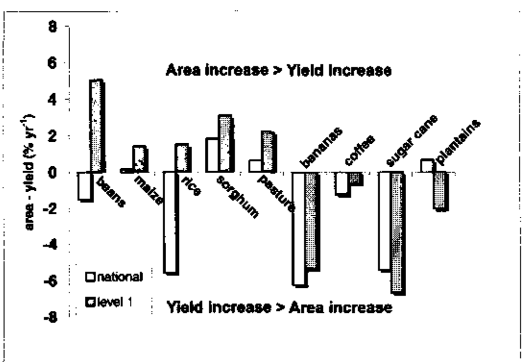

Figure 3.9. Difference between relative annual area development (%) and relative annual yield development (%). National numbers are based on total national area growth and average national yield development. Level 1 data are based on cell-specific area and yield development, averaged afterwards.

3.4 Discussion and conclusions

Land use patterns of ten land use types in 1974 and 1993 in Honduras are described satisfactorily over a range of spatial resolutions using empirical methods. The patterns of land uses that produce basic foodstuffs are very well explained, whereas distributions of crops that are export-oriented are less well captured. The set of selected demographic, soil-related, and biogeophysical factors suffices to describe the distribution of land uses like maize and pasture. The patterns of permanent crops are apparently also influenced by other variables. Economically oriented variables like land prices, or transportation costs are likely contributors. A second explanation of the poor model results for permanent crops lies in their clustered distribution, which calls for studies at a more local level, in order to unravel processes that act at the farm or household level.

The contradiction between findings of this study that concern the goodness-of-fit (R^2) and changes in variable composition and results of earlier CLUE-related studies is remarkable. Especially the stability of the variable composition in time and space is unexpected and questions the assumptions on scale-dependent behaviour of the land use system. The stability could be attributable to either the small size of Honduras as compared to *e.g.* China or to a fundamental different behaviour of underlying processes when scaling up. To investigate the latter, again, local case studies are needed. Numerous case studies on Honduras have been published (Godoy *et al.*, 1997; Sunderlin, 1997; Humphries, 1998; Kammerbauer and Ardon, 1999), but most are of a narrative nature and applied distinct methodologies. It has been suggested to link several modelling methodologies together to form a so-called modelling tool-box (Bouma, 1998). Root and Schneider (1995) have suggested the term Strategical Cyclical Scaling for a top-down, bottom-up cycle between models. These linkages could ensure methodological coherent investigations of spatial scale dependencies over a far larger range of spatial scales.

There are a number of possible causes for the observed extraordinary dominance of population in the explanation of maize cultivation patterns. Firstly, maize is cultivated as a subsistence crop. The traditionally large share of maize and beans in the diet composition directly influences the farmers' decision to cultivate maize and beans. Secondly, most people in Honduras, and especially those living in rural areas, lack the economic possibilities to either diversify their mix of cultivated crops or to improve yield. More people directly translate into more maize area. Thirdly, large parts of the area of Honduras are relatively unsuitable for cultivation of other crops. The relation between maize and population has not faded by processes of land use diversification, as they take place in for example Costa Rica. This conclusion is strengthened by the yield analysis, which indicates that only large farms that probably are economically more flexible intensified their farming system. The vast majority of small farmers is farming under poor biophysical and economical circumstances and did not have these possibilities.

The specific mix of unfavourable circumstances makes Honduras an apparent classic example of Malthus' rather pessimistic view on land use change. Its fast growing population translates into an ever-growing demand for agricultural products, which can theoretically be satisfied in different ways. Honduras, however, does not have the economic means to promote import. At the same time, large areas of Honduras are still unused for agricultural purposes. Thus, a high agricultural demand, poor economic situation and prospect, and high land availability come together. This resulting combination does not call for technological improvement, and indirectly drives farmers into virgin areas. Given the current economic outlook, no improvement is to be expected in the near future. These conclusions do not agree with the general representation of Latin and Central America, in which the region is seen as an example of the theory of Boserup (Schelhas, 1996; Tilman, 1999), whereas the theory of Malthus applies to Africa (*e.g.* Alcamo, 1994). In any case, classification depends to some extent on both the temporal and spatial scale of observation, like is demonstrated by the yield analysis at two resolutions. When taking into account only an analysis at national level, one could adopt the Boserupian view, particularly for permanent crops, noting that population growth has been accompanied by technological improvement. When refining the resolution, however, most land uses appear to have a stagnating yield in large parts of the country, which serves as an indication of environmental destruction and a confirmation of Malthus' theory.

Nevertheless, in this paper deforestation has been considered synonymous with environmental destruction and yield development with technological improvement. This generalisation does not do justice to environmental disasters like pollution, loss of biodiversity, erosion, and technological improvements like export/import changes, or replacement of agriculture by other types of land use not included in this study. Still, it seems justified to use the example of Honduras to state that uninhibited and unconditional destruction of the environment takes place in Central America. The prevailing opinion, especially at coarser scales, that Boserup's view is at least partly correct, should not be taking for granted.

CHAPTER 4[#]

Evaluating impact of spatial scales on land use pattern analysis in Central America

Abstract

The complexity of the relations between land use patterns and their spatial determinants causes the scale of analysis to influence the results. Often, focus is on one aspect of this scale effect, the spatial resolution. This study emphasises the influence of a varying spatial extent on the analysis of land use patterns in six countries in Central America. Statistical techniques are used to determine the relationship between six land uses and a number of potential determining factors, varying both resolution and extent. Results indicate that the effect of spatial resolution, by aggregating a basic grid to larger units, is small in comparison with other similar studies. The effect of a varying extent, by keeping either national boundaries or analysing the entire region at once, on the other hand, is substantial. An unrealistic redistribution of all major land use types, including a large-scale reforestation, is predicted using statistical analysis with the entire region as extent. When expanding the extent to a unit larger than a country, implicit assumptions concerning market mechanisms and national policies are adopted that do not correspond to the actual situation. Despite the existence of the Central American Common Market, it cannot be assumed that any agricultural land use will expand to satisfy an increasing demand in another country. Findings strongly suggest that any modelling effort at regional or global level should incorporate a thorough analysis of the effects of spatial scale on land use change predictions.

4.1 Introduction

4.1.1 Scale

It has been widely acknowledged in earth sciences, that the scale of observation can influence the outcome of an analysis (Cocklin *et al.*, 1997). A prime reason is the complex web of interactions and feedbacks formed by the underlying biophysical and socioeconomic processes (Turner *et al.*, 1995; Gibson *et al.*, 2000). At more detailed scales, the non-linear nature of many relationships inhibits translation from one hierarchical level to higher or lower levels (Rastetter, 1992; Hijmans and Van Ittersum, 1996). In particular landscape ecologists have made an effort to quantify the scale effect (O'Neill, 1988; Wiens, 1989; Levin, 1992), and the field of land use research is not lagging behind (Turner II *et al.*, 1995; Nunes and Augé, 1999). Following White and Running (1994), we define scale as "both the limit of *resolution*

[#] Based on: Kok, K., Veldkamp, A., 2001. Evaluating impact of spatial scales on land use pattern analysis in Central America. Agriculture, Ecosystems and Environment 00: 000-000.

where a phenomena is discernible and the *extent* that the phenomena is characterised over space and time". Most studies, however, are limited to the effect of spatial resolution (see Gibson *et al.*, 2000). The effect of changes in the spatial extent of the study area is probably the lesser-analysed dimension of the scale effect. Although extent and resolution are not completely independent for practical reasons, the effect on conclusions of an analysis can be different. A coarser resolution will reduce heterogeneity, while a larger extent will include more processes related to land use and land use change, and previously important processes may lose significance (King, 1991). Moreover, the same process might act at a different rate in different parts of the study area. The explaining factors of land use patterns will likewise change with changing resolution or extent. In this paper we quantify the specific problems of both a changing spatial extent and spatial resolution of the analysis.

4.1.2 Spatial scale in land use modelling

Models that relate land use, and more specifically land use patterns, to its determining factors cover a broad range of spatial scales. At spatially detailed scales, the direct actors of land use change can be identified and process-based relationships can be determined. With decreasing resolution and increasing extent, it becomes increasingly harder to identify key *processes*. It is at these coarser levels, that type of model and model assumptions have to change, as one can neither simply use nor extrapolate knowledge of local studies and employ it at another level. Yet, a large number of global change models exist (*e.g.* DICE (Nordhaus, 1992), PAGE (Hope *et al.*, 1993), and IMAGE (Alcamo *et al.*, 1998)), in which land use is usually incorporated. In IMAGE 2.1, for example, the earth is subdivided into a number of world regions, assuming a generally similar history (Zuidema *et al.*, 1994), without analysing the consequences of either the chosen spatial extent or resolution on resulting land use patterns. This study aims at an analysis of the feasibility of lumping together several countries into regions.

4.1.3 Study area

Central America (Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, and Panama) was chosen as study area. It is an area with large historical, political, and sociological differences, but with ample similarities between the individual countries as well (Jones, 1988; Diaz-Bonilla, 1990). Civil wars (Nicaragua, El Salvador), economic instability after the second oil crisis (all countries), and population pressure (Guatemala, El Salvador) were important factors in the recent history of Central America. In recent years existing differences are gradually disappearing by a continuing process of market liberalisation and formation of common markets (Bulmer-Thomas, 1998). Past dissimilarities, however, continue to have differentiating influences on the six countries. Even so, the dominant land uses are the same in all countries (FAO, 1999). Three permanent crops, bananas, coffee and sugar cane, dominate the agricultural export. Pasture is by far the largest land use in terms of area and is used for both beef (lowland) and cow milk (mountains) production. A substantial part of the agricultural area is used to produce a variety of annual crops, most important being maize, beans, rice, and sorghum. There is a shift from maize production in Guatemala and El Salvador to rice and bean cultivation in Costa Rica and Panama, related to a changing diet composition. A large part of most countries is still covered by some kind of natural vegetation, mostly forest. Extensive areas with tropical rainforest remain in Panama and Guatemala, and Honduras and Nicaragua share one of the largest continuous areas of forest in Latin America. El Salvador, on the other hand, is almost completely deforested.

4.1.4 Land-use determining factors

Land use in Central America is influenced by a great variety of factors that act at different scales. In this paper, the analysis is restricted to the spatial determinants of land use patterns, and includes potential proximate causes of land use patterns. Underlying driving forces like (inter)national policies or infrastructure development are not considered. In view of the mostly volcanic mountain ranges that shape the appearance of most countries, altitude and thus rainfall, temperature and slope, are important determinants of land use patterns. Soil chemical and physical characteristics are another important group of factors that influence land use in the region. Besides those environmental constraints, demographic and other socioeconomic variables, like location of cities, population density, or level of education, are main spatial determinants of land use. However, the relatively coarse spatial resolutions that are addressed here could obscure processes that influence land use. Apparent relationships will sometimes represent proxies of processes that are visible at the farm level. Population density, for instance, is often established as land use determinant, but is normally an indirect indicator of labour availability, accessibility, or presence of local markets. We therefore necessarily opted for an empirical, data-driven rather than a knowledge-based approach.

4.1.5 Research framework

A general description of the CLUE modelling framework as well as previous research concerning the spatial determinants of land use at different spatial scales are given in Section 1.5.3. In the context of this chapter it suffices to know that for every application of the model, multiple regression equations at multiple resolutions as described here are generated. Those equations are subsequently used in the allocation module. All previously published research focused primarily on the effects of spatial resolution. The effects of a varying extent have been touched upon (Verburg and Chen, 2001), but it always concerned a separation into different (agroecological) zones within one country. The effect of grouping different countries has not been investigated before. The results of the statistical analysis presented in this paper are used for the application of the CLUE modelling framework to Central America (see Chapter 5). Consequently, part of the methodologies employed, such as the type of statistical analysis, the basic resolution, and the number of land use types included, are predefined by model requirements of the allocation module.

4.1.6 Objectives

The objectives of this study are:

1. to quantify relationships between the distribution of land use and a set of potential demographic and biophysical explaining factors at the regional level
2. to specifically analyse both aspects of spatial scale, by varying resolution and extent
3. to analyse the effects of different extents on the input of the CLUE allocation module

4.2 Methods and material

4.2.1 Data format

Data format is in accordance with the data needs of the CLUE-CA allocation module. A grid-based approach is followed with a pixel size of 15 × 15 km as basic unit for analysis. Pixel size is based on the average size of the input units, as well as on the pixel size of other applications of CLUE in the region. Thus, a direct comparison is enabled with studies of the Atlantic Zone of Costa Rica (see Chapter 2), and Honduras (Chapter 3). Instead of using uniform grid cells with one dominant land use type and one average or dominant value for every explaining variable, sub-grid information is present for most of the spatial determinants and each land use type. In every cell, we use *e.g.* the percentage of highly fertile soils and the percentage of each land use. In this way, we do not lose any information when either gridding the data or scaling up, although spatial precision decreased.

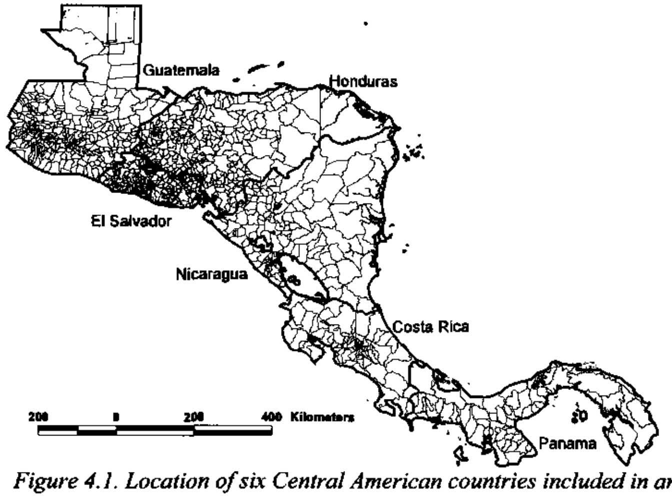

Figure 4.1. Location of six Central American countries included in analysis. Thick lines indicate country boundaries. Thin lines represent third level administrative boundaries.

Table 4.1. Date of most recent agricultural census and most recent land use map available for every country. Number of administrative units indicates the number of third level units (usually counties).

Country	Year of most recent agricultural census	Number of administrative units	Most recent land use map
Costa Rica	1984	82	forest map, 1996
El Salvador	not available	263	land use, 1993
Guatemala	1979	329	forest map, 1992
Honduras	1993	292	forest map, 1995
Nicaragua	1995, department level	144	land use, 1992
Panama	1990	68	not available

4.2.2 Dependent variable: Land use

The data of an agricultural census, the main data source within the CLUE framework, can be described best as 'land cover with aspects of land use'. In this paper, the term land use rather than land cover is adopted to refer to the above class description, although *e.g.* the class natural vegetation is more closely related to a cover. A land use map is obtained by combining data from two, basically different, sources: agricultural census data and existing land use maps. Agricultural censuses contain a wealth of information on a large number of annual and perennial crops. Because of this thematic detail, census data are used as main source of information. Existing land use maps, containing normally not more than a few broad classes, are used to update the census data, or to increase the spatial detail of the map. For Panama and Honduras no land use map is used, as recent, thematically and spatially detailed, census data is available. For El Salvador (not available) and Guatemala (outdated), the agricultural census is omitted. Table 4.1 summarises the employed information for the countries involved. Information is extracted from an existing database (CIAT, 2000), that was made available. In Figure 4.1, the spatial distribution of administrative units is visualised. Resulting national land use maps are subsequently updated to 1996, using temporally detailed, national statistics (FAO, 1999) on area development of all land uses since the most recent census. This polygon map is finally rasterised at various resolutions.

Every gridcell of the final map contains percentage information on six land use classes, which encompass the most important uses in terms of area and economic profit:

1. **Annuals** (mainly rice, maize, beans, and sorghum); 2. **Bananas** (including plantains); 3. **Coffee**; 4. **Sugar cane**; 5. **Pasture** (excluding natural pastures);

Table 4.2. Relative area coverage (% of total area) of the most important land use types in individual countries and entire region (Central America) in 1996.

Spatial extent	Annuals	Bananas	Coffee	Sugar cane	Pasture	Natural vegetation
Costa Rica	6	1	2	1	29	61
El Salvador	19	<1	11	2	46	21
Guatemala	16	<1	3	1	32	49
Honduras	6	<1	2	<1	14	78
Nicaragua	9	<1	<1	1	20	70
Panama	7	<1	<1	<1	21	71
Central America	9	<1	2	1	24	64

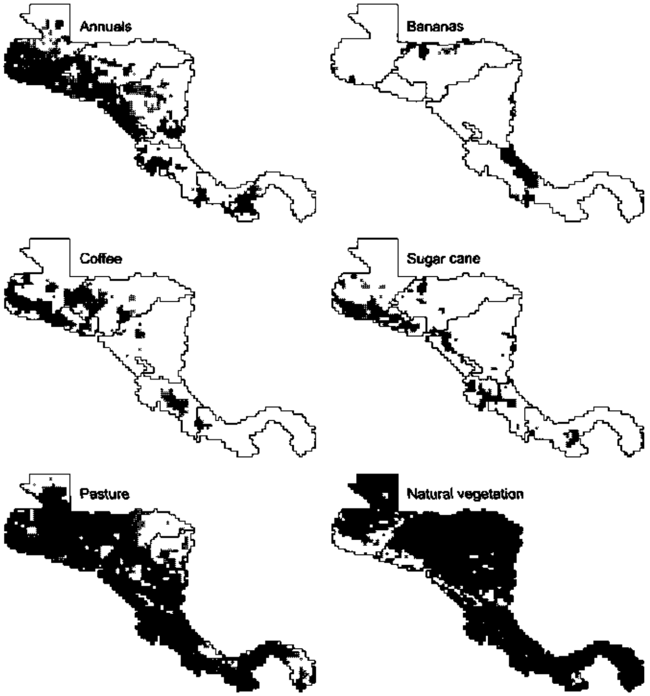

Figure 4.2. Land use patterns in 1996. Light colours indicate a low cover percentage; dark colours a high cover percentage.

6. **Natural vegetation.** This last group mainly consists of tropical forest, but also includes *e.g.* secondary regrowth, natural pastures, and built-up area. Urban area covers maximally five percent of any country and is therefore not treated as a separate land use type. In Table 4.2, the relative area coverage of all land use types is given at national level; Figure 4.2 visualises land use patterns in 1996.

4.2.3 Independent variables

From the enormous variety of possible spatial determinants of land use, a pre-selection is made. Table 4.3 lists the limited but broad selection of possible determinants that are used in the statistical analysis. Grouping of categorical variables like FERTHIGH and FERTLOW reduces the number from 22 to 16, labelled as 'groups' in Table 4.3. All information is extracted from an existing database (CIAT, 2000). Explaining factors are divided into four functional groups to facilitate interpretation.

- Demographic factors include population density (rural and urban), percentage of rural population, and two measures of accessibility. Population density is a dynamic variable and, much like for land use, a 1996 map needed to be constructed from various national sources. For every country at least two population censuses are available, of which the most recent was invariably conducted in the 1990s. National growth rates (FAO, 1999) of subsequent years are combined with spatial explicit growth rates derived from the two censuses to obtain a 1996 population map for the entire region.

- Soil variables include information on soil fertility, pH, drainage, depth, and texture of topsoil.
- Other bio-geophysical factors include altitude, precipitation, number of consecutive dry months, and slope steepness.
- The only factor related to land use policies, for which consistent spatially explicit information was available for all countries, was the location of national parks and other protected areas.

Table 4.3. Basic information of variables included in the multiple regression analysis.

Variable	Explanation	Unit	Source
Demographic (5 variables; 5 groups)			
DENRUR	rural population density	ind./ha	Population censuses of various years
DENURB	urban population density	ind./ha	
PERRUR	fraction of population classified rural	% of pop.	
ACCPORT	access to port; measured as weighted distance to port	meters	Accessibility map CIAT, Colombia
ACCMARK	access to market; measured as weighted distance to market	meters	
Soil (10 variables; 5 groups)			
DEPSHAL	shallow soils: normally < 50 cm	% of gridcell	FAO soil map of the world
DEPDEEP	deep soils: > 120 cm	% of gridcell	
DRAIBAD	poorly drained: water stagnation during a substantial part of the year	% of gridcell	
DRAIGOOD	well drained: no water stagnation	% of gridcell	
FERTHIGH	high fertility: high yields, suitable	% of gridcell	
FERTLOW	low fertility: low yields, not suitable	% of gridcell	
PHHIGH	pH > 6	% of gridcell	
PHLOW	pH normally lower than 4.5	% of gridcell	
TEXTCLAY	topsoil with clayey texture	% of gridcell	
TEXTSAND	topsoil with sandy texture	% of gridcell	
Other bio-geophysical (5 variables; 4 groups)			
SLOPFLAT	flat terrain: slope < 1%	% of gridcell	Digital Elevation Model
SLOPSTEEP	steep slopes: slope > 5%	% of gridcell	
ALT	altitude	meters	
RAINTOT	average annual total precipitation	mm	Monthly rainfall maps CIAT, Colombia
DRYMONTH	consecutive months with < 60 mm precipitation	number	
Park presence (2 variables; 2 groups)			
PARKALL	area within any type of protected area	% of gridcell	Map with parks and description, CIAT, Colombia
PARKNAT	area within national park	% of gridcell	
Omitted variables			
DENTOT	total population density	ind./ha	Population censuses
DISTROAD	distance to nearest road	meters	Topographic map, CIAT, Colombia
DEPMED	medium soil depth: normally 50-120 cm	% of gridcell	FAO soil map of the world
DRAIMED	moderately drained: some water stagnation	% of gridcell	
FERTMED	medium fertility: moderate yields	% of gridcell	
PHMED	pH between 4.5 and 6	% of gridcell	
TEXTMED	topsoil with silty texture	% of gridcell	
SLOPMED	moderate slopes: 1- 5% slope	% of gridcell	Digital Elevation Model

4.2.4 Spatial scales

Previous research within the CLUE framework on the effect of an decreasing resolution has indicated that the highest explaining power of multiple regression equations is obtained using a grid that is 9 to 36 times larger than the basic resolution. Based on this information, a second aggregation level of 75 × 75 km is selected, an aggregation of 5 × 5 cells of the basic level. The analysis is thus restricted to two aggregation levels, the minimum input of the CLUE allocation module. A third, intermediate, resolution of 45 × 45 km was initially included, but results varied little from the 75 × 75 km resolution. To vary the extent, the statistical analysis is executed for the entire region as a whole and for every country separately. Grouping countries together implies that the region is treated as one organisational unit, with *e.g.* one completely open market. The underlying assumption of the country extent is that differences in national policies and biogeophysical circumstances are such that land use distribution should be analysed at country level. At the coarse resolution, the analysis of Costa Rica includes the cells of Panama and El Salvador is analysed including Guatemala, as the number of data points is insufficient for separate analysis. Consequently, comparison between resolutions is difficult for Costa Rica and El Salvador. In Figure 4.3, resolutions are visualised for all countries.

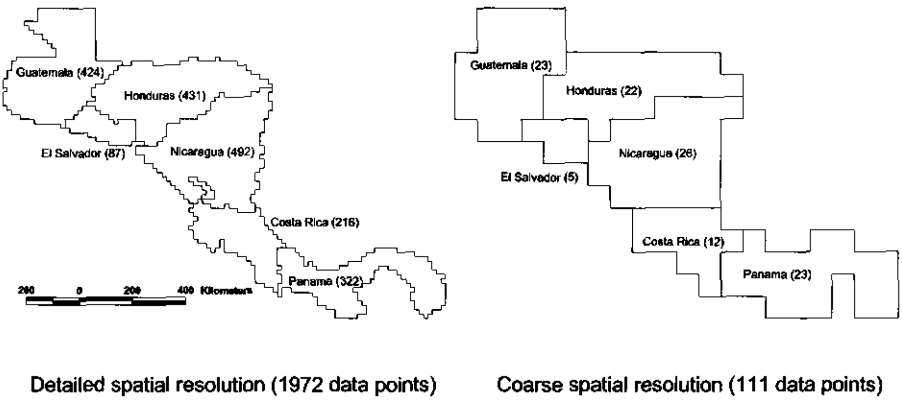

Figure 4.3. Spatial resolution of input data. Left side: 15 × 15 km resolution; right side: 75 × 75 km resolution. Numbers between brackets indicate the number of grid cells.

Before executing the multiple regression analysis, a couple of steps are taken to minimise the correlation between variables (multicollinearity effects) and between neighbouring grid cells within one variable (spatial autocorrelation).

4.2.5 Multicollinearity

Independency between variables is a prerequisite of the statistical method employed and several measures were taken to reduce the effects of multicollinearity as much as possible. Of all classified variables (*e.g.* soil fertility) one categorical sub-class (*e.g.* percentage of medium fertile soils) is omitted from the analysis for reasons of data redundancy. Subsequently, of all pairs of variables with a correlation over 0.80, one is omitted from the analysis. Of all pairs of variables with a correlation over 0.50, only one is allowed to enter a regression equation. The use of a stepwise regression procedure solves remaining multicollinearity problems. Omitted variables are listed in Table 4.3. Pairs of correlated variables (> 0.50) are number of dry months and total precipitation (DRYMONTH and RAINTOT); percentage of population classified rural and rural population density (PERRUR and DENRUR); presence of national park and presence of any type of protected area (PARKNAT and PARKALL); high soil pH and high soil fertility (PHHIGH and FERTHIGH); altitude and steep slopes (ALT and SLOPSTEEP).

4.2.6 Spatial autocorrelation

Spatial autocorrelation can obscure the results of a regression analysis (Anselin and Griffith, 1988; Chou, 1991). The regression coefficient and significance of the contribution of individual variables are sensitive for the presence of autocorrelation. Unfortunately, with this alternative manner to calculate multiple regression equations it would be far too time consuming to use a stepwise procedure, especially considering the high number of equations that need to be calculated. Consequently, either a theoretical combination of explaining variables has to be available in advance, or methods that correct for autocorrelation have to be abandoned. Alternatively, a check on the presence of spatial autocorrelation in the residuals of a regression equation can be performed. Overmars (2000) analysed the influence of spatial autocorrelation using a multi-resolution dataset from Ecuador, over a range of resolutions similar to this study. Results indicated the presence of spatial autocorrelation at the most detailed resolution (9.5 × 9.5 km) and a rapid decrease at coarser resolutions. Moreover, most multiple regression equations varied little when a spatial autoregressive model was used. The three most important spatial determinants were identical in most cases. We therefore opt to 'disregard' the effects of spatial autocorrelation and limit the interpretation of the equations to the three most important variables in terms of standardised betas.

4.2.7 Statistical analysis

The relationships between land use and the selected set of variables are quantified in a two-step procedure, using multiple regression techniques. First, significantly contributing variables are selected with a stepwise regression procedure, using the 0.05 significance criterion. Subsequently, this set of variables is used to construct multiple regression equations. The procedure is repeated for every land use type, for both resolutions, and for the various extents. The adjusted coefficient of determination (R^2) serves as a measure for the amount of variation explained. The standardised regression coefficients (standardised betas or β_{st}) are used to indicate the relative importance of individual variables in a given equation. When multiple regression equations are applied, the results can be used as a prediction of the cell-specific land use distribution. This so-called 'regression cover' is a key input in the CLUE allocation module. The effect of a changing extent on the resulting regression covers is analysed.

4.3 Results

4.3.1 Coefficient of determination

In Table 4.4, adjusted coefficients of determination (R^2) are given for 84 statistical models. The average of the six national analyses is weighted by country size, the average for land use by total area. With the exception of sugar cane in Panama at the coarse resolution, a statistically significant model is always established. Coefficients of determination vary between 0.11 for the explanation of the distribution of sugar cane in the whole region at the fine resolution, and 0.96 for the distribution of natural vegetation in Honduras at the coarse resolution. In the majority of the cases, the R^2 is satisfactory, but large differences exist between land use type, extent, and resolution. The distributions of land use types that cover large areas (annuals, pasture, and natural vegetation, see Table 4.2) are explained best. The R^2 of annuals (weighted average 0.51 at detailed resolution), pasture (0.45) and natural vegetation (0.53) are relatively high. At the coarse resolution, differences with the three permanent land uses are less pronounced, but present. The distribution of sugar cane is poorly described by the set of potential spatial determinants. Part of the explanation for the difficulties in explaining the distribution of low covering land uses is found in the high number of cells that have a very low cover (0-5%), but with a high variation. Location of large plantations is normally correctly predicted, but the variability in the low range is hard to capture with linear regression methods.

The R^2 increases substantially, when the extent is reduced from regional to national. Comparing the model performance of regional and average country analyses (bold numbers in Table 4.4) at the detailed resolution, an increase between 0.09 (sugar cane) and 0.23 (annuals) is obtained using country extent. At the coarse resolution, the increase is about twice that amount. The same applies for the analyses of most

Table 4.4. Adjusted coefficients of determination (R^2) of all multiple regression equations.

land use type	CAM	GUA	ELS[1]	NIC	HON	COS[2]	PAN	average[3] countries
Fine resolution								
annuals	**0.28**	0.47	0.48	0.36	0.79	0.30	0.53	**0.51**
bananas	**0.15**	0.18	0.12	0.14	0.49	0.50	0.23	**0.28**
coffee	**0.25**	0.42	0.43	0.18	0.39	0.76	0.42	**0.39**
sugar cane	**0.11**	0.25	0.17	0.12	0.24	0.26	0.17	**0.20**
pasture	**0.28**	0.58	0.35	0.23	0.59	0.23	0.60	**0.45**
natural vegetation	**0.40**	0.69	0.32	0.27	0.74	0.33	0.63	**0.53**
Coarse resolution								
annuals	**0.49**	0.91	0.85	0.78	0.94	0.56	0.87	**0.84**
bananas	**0.32**	0.80	0.36	0.83	0.86	0.50	0.83	**0.78**
coffee	**0.81**	0.83	0.27	0.76	0.77	0.86	0.86	**0.78**
sugar cane	**0.25**	0.40	0.41	0.68	0.61	0.30	n.s.	**0.45**
pasture	**0.57**	0.91	0.90	0.89	0.90	0.55	0.82	**0.85**
natural vegetation	**0.65**	0.94	0.95	0.83	0.96	0.73	0.85	**0.88**

1: At the coarse resolution, the analysis of El Salvador included the cells of both Ecuador and Guatemala
2: At the coarse resolution, the analysis of Costa Rica included the cells of both Costa Rica and Panama
3: Weighted by country size
CAM = Central America; GUA = Guatemala; ELS = El Salvador; NIC = Nicaragua; HON = Honduras; COS = Costa Rica; PAN = Panama.

individual countries at both resolutions and for all land uses. Exceptions are the poor explanation of banana cover in El Salvador, which relates to the extremely low area covered by bananas (about 1 km^2), and the generally poor results for Nicaragua at the detailed resolution, which can probably be attributed to poor data quality. The consistently lower explanatory power at the supra-national level demonstrates the importance of underlying driving forces, which are more difficult to quantify. Differences in national policies, history, and tradition account for *e.g.* large areas of coffee in El Salvador, though only 5% of the country is suitable, while 30% of the neighbouring Guatemala (3.5 million hectares) could be used for coffee plantations but is not. All models have a higher explanatory power at the coarse than at the detailed resolution. In general, the R^2 roughly doubles when using a 25-fold larger resolution. Equations of the most important land uses in terms of area have coefficients of determination at the coarse resolution generally above 0.80 as opposed to about 0.50 at the detailed resolution. The increase of explanatory power of models

Table 4.5. Three most important explaining factors in terms of standardised beta for all multiple regression equations. Variables are listed in order of importance.

Land use type	CAM	GUA	ELS[1]	NIC	HON	COS[2]	PAN
Fine resolution							
Annuals	drymonth +	drymonth +	altitude +	accport –	denrur +	drymonth +	accport –
	denrur +	accport –	accmark –	depshal +	accport –	fertlow +	drymonth +
	phhigh +	perrur +	slopsteep +	ferthigh +	drymonth +	draigood +	ferthigh +
Bananas	drymonth –	accport –	perrur +	parkall –	denrur +	drymonth –	denrur +
	accport –	slopflat +	raintot –	accport +	draigood –	depdeep +	ferthigh +
	textsand +	draigood –	draigood +	raintot +	drymonth –	ferthigh –	phlow –
Coffee	textsand +	slopsteep +	altitude +	altitude +	denrur +	denrur +	altitude +
	drymonth +	drymonth +	accport –	denrur +	fertlow +	draigood –	textsand +
	denrur +	ferthigh +	draibad +	drymonth –	altitude +	altitude +	denrur +
Sugar cane	phhigh +	drymonth +	ferthigh +	phhigh +	denrur +	phhigh +	drymonth +
	raintot +	denrur –	textsand +	accmark –	phhigh +	denurb –	ferthigh +
	accport –	accport –	drymonth –	raintot +	draigood –	drymonth +	draibed –
Pasture	accport –	altitude –	slopflat –	accport –	denrur +	phlow –	accmark –
	phhigh +	accport –	accport +	depshal +	ferthigh –	accport –	drymonth +
	draibad +	parkall –	depdeep –	slopflat –	raintot –	draigood +	depshal +
Natural vegetation	accport +	accport +	ferthigh –	accport +	denrur –	phlow +	drymonth –
	phlow +	altitude +	accmark +	perrur +	draibad –	altitude –	accmark +
	raintot –	drymonth –	drymonth –	depshal –	phhigh –	accport +	ferthigh –
Coarse resolution							
Annuals	drymonth +	slopsteep +	slopsteep +	accport –	denrur +	drymonth +	drymonth +
	altitude +	denrur –	denrur –	altitude –	drymonth +	depdeep –	slopsteep +
	ferthigh +	fertlow –	fertlow –	depdeep +	accport –	accport –	accport –
Bananas	drymonth –	slopflat +	accport –	depdeep +	denurb +	textclay –	ferthigh +
	accport –	accmark –	slopflat +	perrur +	drymonth +	raintot +	drymonth +
	textclay –	ferthigh –	drymonth –	phlow –	textclay –	phlow –	depdeep +
Coffee	denrur +	draigood +	denrur +	altitude +	fertlow –	denrur +	altitude +
	altitude +	depdeep +	depdeep +	denrur +	denrur +	altitude +	ferthigh +
	depdeep +	altitude +	altitude +	accport +	depdeep –	slopsteep +	denrur +
Sugar cane	phhigh +	depshal –	draibad –	phhigh +	denrur +	ferthigh +	no
	accport –	phlow –	depshal –	accmark –	depshal –	drymonth +	significant
	slopflat +	draibad –	raintot +	denrur –	n.s.	denurb –	model
Pasture	phhigh +	depdeep +	depdeep +	accport –	denrur +	accmark –	depdeep –
	drymonth +	altitude –	altitude –	accmark +	drymonth –	drymonth +	accmark –
	draibad +	parkall –	parkall –	depdeep +	accport +	draibad +	perrur –
Natural vegetation	phhigh –	slopsteep –	depdeep –	accport +	denrur –	fertlow –	drymonth –
	accport +	depdeep –	slopsteep –	ferthigh +	drymonth +	drymonth –	depdeep +
	drymonth –	parkall +	parkall +	altitude +	phlow +	denurb +	accmark +

1: At the coarse resolution, the analysis of El Salvador included the cells of both Ecuador and Guatemala
2: At the coarse resolution, the analysis of Costa Rica included the cells of both Costa Rica and Panama
CAM = Central America; GUA = Guatemala; ELS = El Salvador; NIC = Nicaragua; HON = Honduras; COS = Costa Rica; PAN = Panama.

for the three permanent crops is generally less. Because the analysis uses only two resolutions, conclusions on the effect of resolution are limited.

4.3.2 Variable importance

In Table 4.5, the three most important variables in terms of β_{st} of all equations are listed. Non of the equations included more than ten variables and the variables listed in Table 4.5 generally accounted for at least 75% of the total explaining power. Table 4.6 is a quantification of Table 4.5, by counting the number of occurrences of (groups of) variables, both for the entire region and for the six individual countries. All groups of variables, except park presence, contribute substantially to the explanation of the distribution of land use. A remarkable small range of 22% (demography at coarse level) to 40% (soil at coarse level) is found in the relative importance of demographic, soil, and other bio-geophysical variables in the regression equations (Table 4.6).

There are no apparent effects of changing resolution on the importance of the three variable groups (Table 4.6). Examining the composition within the groups, however, reveals interesting shifts. When scaling up, soil depth (DEPDEEP) becomes more important and soil fertility (mostly FERTHIGH) loses importance. It could indicate that farmers generally prefer areas with deep soils, and within those areas look for the most fertile soils. A second change is the lower participation of climate seasonality (DRYMONTH) at the coarse resolution. This seems in contradiction with the intuitive tendency to perceive climate variables as being more important at coarser resolutions, and spatial changes in DRYMONTH and precipitation (RAINTOT) are indeed gradual. Most likely, it is the increasing importance of other variables that causes the decreasing participation of this climatic variable.

Table 4.6. Variable importance in multiple regression models. Numbers are a count (no.) and percentage (%) of the three most important variables. 'CAM' represents the model run for the entire region; in the column 'countries', six national analyses are grouped.

Variable group	CAM (no.)	Countries (no.)	CAM (%)	Countries (%)	CAM (no.)	Countries (no.)	CAM (%)	Countries (%)
	Fine resolution				*Coarse resolution*			
Perrur/denrur	2	14	11	13	1	13	6	13
Denurb	-	1	-	< 1	-	4	-	4
Accmark	-	5	-	5	-	5	-	5
Accport	4	15	22	14	3	10	16	10
POPULATION	**6**	**35**	**33**	**32**	**4**	**32**	**22**	**32**
Depshal/depdeep	-	5	-	5	1	17	6	16
Fertlow/ferthigh and phlow/phhigh	4	19	22	18	4	14	22	13
Draibad/draigood	1	10	6	9	1	3	6	3
Textclay/textsand	2	2	11	2	1	3	6	3
SOIL	**7**	**36**	**39**	**34**	**7**	**37**	**40**	**35**
Alt	-	9	-	8	2	9	11	9
Raintot/drymonth	5	21	28	19	4	14	22	13
Slopsteep/slopflat	-	5	-	5	1	8	6	7
CLIMATE	**5**	**35**	**28**	**32**	**7**	**31**	**39**	**29**
Parknat/parkall	-	2	-	2	-	4	-	4
PARK	**0**	**2**	**0**	**2**	**0**	**4**	**0**	**4**
Total	18	108	100	100	18	104	~100	100

When analysing the results at the highly aggregated level of four variables groups, the effect of changes in extent is marginal as well. At the coarse resolution the effect is somewhat larger, considering the difference between the contribution of soil (22% and 32% for the regional and national analyses respectively) and other bio-geophysical (39% and 29%) variables. However, substantial differences surface when examining the importance of single variables. A good example is the relation between altitude and coffee at the fine resolution: In the national analyses, altitude (ALT) or the related steep slopes (SLOPSTEEP) are always amongst the three most explaining variables, and in three countries (El Salvador, Nicaragua, and Panama) altitude is the most important one. Analysis at the regional extent fails to recognise altitude as important determinant of the location of coffee, and selects sandy soils (TEXTSAND) and rural population density (DENRUR) instead.

In all countries, annuals are cultivated preferably in areas with a pronounced dry period (Table 4.5, high importance DRYMONTH+), which is consistent with the reported need of annual crops for a dry period to complete ripening of the grain (Schelhas, 1992). The unimportance of access to ports (ACCPORT) in explaining the distribution of bananas seems remarkable. However, although banana plantations are never located far from a port (Hallam, 1995), not all ports have nearby banana plantations, which weakens the relationship. Coffee is typically cultivated above 1000 meter, which is reflected by the presence of altitude, as well as correlated variables rural population density and steep slopes in the equations. The distribution of sugar cane is strongly related to indicators of good soils (positive correlation with high pH, high fertility, or deep soils), which also reflects the preference for locations close to water. Determinants of the distribution of pasture are often associated with low quality soils (positive correlation with poorly drained soils, low pH, or shallow soils), indicating that grassland is found at places unsuitable for other, more profitable, crops. The distribution of natural vegetation depends on a number of variables. Most important are associated with poor soils (low pH, low fertility) or demography (low rural population density, large distance to ports). Various variables that explain the distribution of natural vegetation have a counterintuitive sign (*e.g.* FERTLOW- in Costa Rica, and SLOPSTEEP- in Guatemala). The most likely cause is the diverse nature of the natural vegetation class. Furthermore, the overwhelming influence of rural population density in Honduras is noteworthy. Solely the variable rural population density explains about 50% of the variation in annual cover at the fine resolution and almost 80% at the coarse resolution, and it is the variable with the highest explanatory power in almost every equation. A separate study the importance of population density in Honduras is forthcoming (Kok and Bouma, submitted; see Chapter 3).

Table 4.7. Relative area coverage (% of total area) of most important land use types as predicted by multiple regression equations for entire region (Central America) and for individual countries (countries). Bold (countries <) and underlined (countries >) numbers show most conspicuous differences.

Country	Annuals		Pasture		Natural vegetation	
	Central America	Countries	Central America	Countries	Central America	Countries
Costa Rica	10	6	31	29	52	61
El Salvador	21	19	38	46	**31**	**21**
Guatemala	10	16	23	32	**64**	**49**
Honduras	9	6	**21**	**14**	68	78
Nicaragua	8	9	22	20	68	70
Panama	7	7	22	21	70	71

4.3.3 Spatial considerations

In Table 4.7, the relative area of three land use types as predicted by the regression equations is given, aggregated at country level. When aggregating a regression cover to the level at which the regression analysis is carried out, by definition the input situation (in this case, the actual land use in 1996) is approximated. Consequently, the aggregated cover percentage of an analysis at country level equals the 1996 actual situation (see Table 4.2). When aggregating to a more detailed level, like the summation of the supra-national analysis to country level, the actual situation is not necessarily approached. Increasing the extent from national to regional provokes substantial changes all countries, but Panama and Nicaragua. The regional analysis predicts large-scale redistributions of annuals, pasture, and consequently natural vegetation. A 10% to 15% reduction of the agricultural land (mainly pasture) would take place in Guatemala and El Salvador, countries where population pressure has historically been high, and forest is scarce. This area (about 300,000 hectares) would be taken into production in Costa Rica and Honduras. When the statistical models would be used to predict land use changes, a strong reforestation in Guatemala and El Salvador would take place, coupled with an accelerated deforestation in Honduras and Costa Rica. Changes are visualised in Figure 4.4, depicting the difference between the regression covers based on the regional analysis and the regression covers as calculated by using the national regression equations. Dark areas indicate places where a higher cover percentage is projected by the national analyses; the light areas indicate a higher percentage in the regional analysis. Apart from aforementioned examples, which are stressed again, the regional analysis predicts a shift of banana plantations from Costa Rica and Honduras (dark areas) to Panama and Nicaragua (white areas). When applying the regional instead of national regression equations, the recurrent pattern is a decreasing area of any agricultural land use of which the total cover percentage is relatively high. This decrease is accompanied by an increase in countries with abundant forested areas that are suitable for that land use type. An interesting detail is an area in the Southwest of Costa Rica that is predicted to be deforested (dark grey areas) in the regional analysis, as it is the same area that has been reforested between 1975 and 1985, a period of large-scale population outmigration (Edelman, 1992).

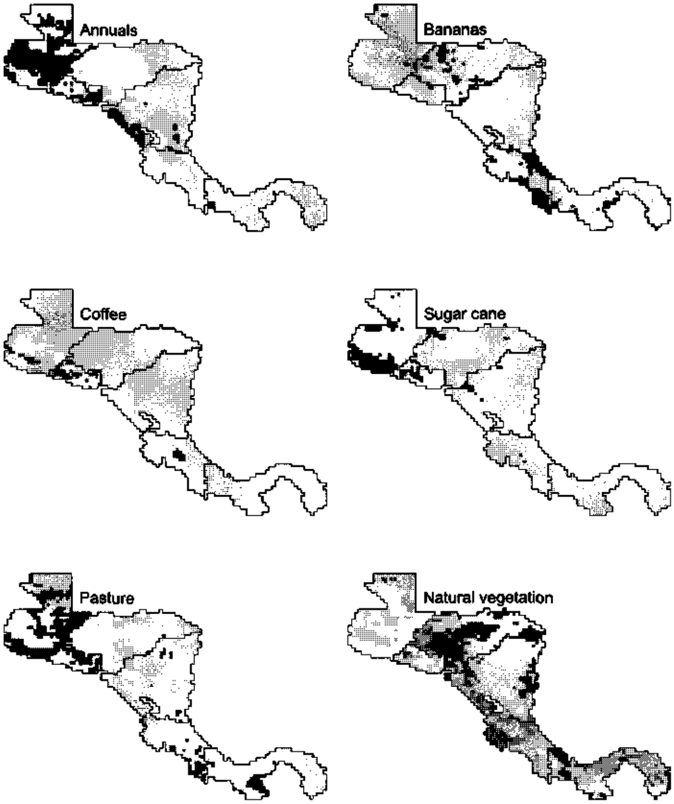

Figure 4.4. Differences between cover percentage based on regional and national multiple regression equations. (Very) dark areas indicate places where a (much) higher cover percentage is projected by the national analyses; light shaded areas indicate a higher percentage in the regional analysis. Medium grey tones indicate similar percentages.

4.4 Discussion and conclusions

The overall results of the multiple regression analysis are satisfactory. Generally, coefficients of determination are (very) high, although at the fine resolution some equations yield a relatively low coefficient. Moreover, most of the spatial determinants included in the equations have the expected sign. This performance strongly suggests that for most land uses, the set of explanatory variables used includes the most important spatial determinants of land use in Central America. Soil, biogeophysical, and demographic factors are equally important in the explanation of land use patterns, and need to be included in any analysis of the distribution of land use at the (supra-)national scale. Rural population density, rainfall seasonality, and soil fertility are of highest importance.

Changing the spatial resolution from 15 × 15 km to 75 × 75 km in Central America does not greatly influence the analysis. Land use patterns are described by approximately the same set of spatial determinants. Findings contradict conclusions drawn by De Koning *et al.* (1998) for Ecuador, using a resolution range from 9 × 9 km to 55 × 55 km, and Verburg *et al.* (1999b) for Java, with a range from 20 × 20 to 40 × 40 km, who employed the same methodology. Both studies indicate significant changes in variable composition and standardised betas with changing resolution. In the light of the previous work, the effect of resolution found here is remarkably small. The stability could be attributable to the coarse basic resolution relative to the total area, which may inhibit detection of scale-dependent relations at finer resolutions.

The effect of changing the extent is substantial. A redistribution of land uses is predicted to take place when using the supra-national extent. Countries with a relatively low pressure on the land will be deforested more rapidly, while in countries with a high agricultural output reforestation will take place. When analysing at the supra-national extent, the key underlying assumption becomes that the agricultural markets are completely open and products can be freely redistributed. A free market would boost import and export quantities in all countries and would thus facilitate *e.g.* cultivation of annuals in Costa Rica to meet the domestic demand in Guatemala. This hypothetical situation that is implicitly assumed, is far from realistic. Although trade within the Central American Common Market has grown recently, it remains highly concentrated with exchanges between El Salvador and Guatemala (Bulmer-Thomas, 1998). Average intraregional trade of beef can be as high as 20%, but trade of annuals is normally less than 5% of the total production (Rueda-Juquera, 1998). As long as a large federation of states is not established and as long as agricultural land use remains based on subsistence farming in some countries, intraregional trade is not expected to rise in the near future. Deforestation will continue throughout the region with little or no regrowth outside of well-protected national parks. This study thus demonstrates that in Central America, and possibly in other regions as well, the nation is the largest extent that can be analysed. The extent of the analysis has to be determined by existing organisational units, and not by data availability or computing time.

Figure 4.5 depicts the relations between model performance, spatial extent, and spatial resolution as established in this study. There is an apparent paradox between the decrease of explanatory power when enlarging the spatial extent and the increase of model fits when coarsening the spatial resolution, as the effect of both changes in spatial scale is a potential inclusion of more land use change processes. The observed changes in model performance nicely illustrate the difference between varying extent and resolution. By enlarging the extent from country to region in Central America, a border of a level of organisation is crossed. In the regional analysis, six differently organised units are combined in one analysis, which explains the lower model fits. By increasing spatial resolution borders between levels of organisation might be crossed also, but those sub-national levels apparently do not have a significant influence in Central America. Aggregation effects (see Rastetter *et al.*, 1992) and changes in variance within one level of organisation becomes major differentiators, which results

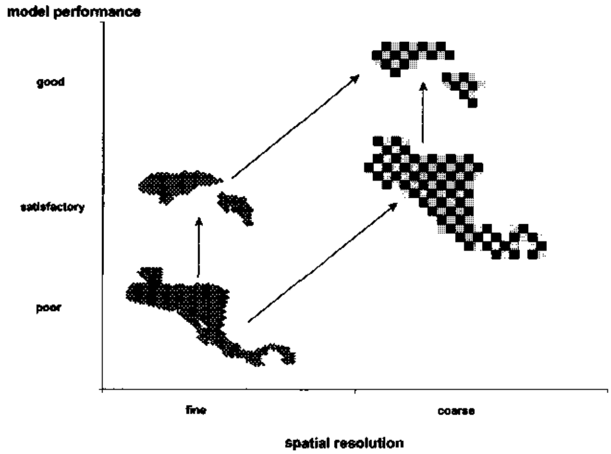

Figure 4.5. Schematic representation of model performance as a function of spatial extent (region versus country, represented by Costa Rica and Honduras) and spatial resolution (represented by differently sized checkerboards).

in a model performance increase. Extrapolation of findings to other regions is very difficult, as information on the presence of supra-national or sub-national levels of organisation is lacking.

Our findings have implications for modelling efforts at regional or global level. In the first place, it has to be investigated whether it is necessary to create separate uniform units within a country, based on agroecological zones or planning regions, like exist in *e.g.* Costa Rica. Secondly, this chapter should be a warning for global change modellers, especially those that choose to incorporate a spatially explicit analysis of land use changes, but do so in a simplified and highly aggregate manner due to data limitations. One must realise that the adoption of a limited number of world regions (*e.g.* IMAGE 2.1) as modelling extents will result in assumptions that could violate the actual situation. Before a realistic simulation of land use changes can be claimed (see Leemans, 1999), a thorough analysis of the effects of spatial scale on their predictions of spatial explicit land use changes needs to be included.

CHAPTER 5[#]

Scenario building and model results for Central America

Abstract

Land use systems are highly complex, and any modelling effort of land use change should fully account for the complexity of the system. Furthermore, when the aim is to produce realistic scenarios, land use models should be both spatially and temporally explicit. Using an example of such a model, the CLUE modelling framework, we explore near-future land use changes in Central America. Besides a base and a sustainable scenario, that assumes increasing yields and increasing export and import, focus is on projection of the long-term effects of an extreme event. Scenario assumptions are partly based on actual data that became available after hurricane Mitch struck the continent. Resulting maps of the Base as well as a Sustainable scenario demonstrate how slow and gradual changes at the national level translate into highly dynamic patterns of land use change when allocated spatially. Hot-spots of change prove relatively insensitive to changes in income. Compared to the Base scenario, the impact of sustainability measurements is more substantial, although the effect on distribution of pasture, annual crops, and natural vegetation is far larger than on patterns of bananas, coffee, and sugar cane. Results of the Natural Hazard scenario for Honduras separately as well as for Central America as a whole clearly indicate that the effects of a hurricane on land use patterns, though initially strong, are likely to largely disappear within a period of 10 year. Concepts from ecology are used to illustrate the behaviour of a complex system. Implications for policy makers are indicated, although similar studies and spatially explicit models are needed from sociology and economy to complete our understanding of the long-term effects of an extreme event.

5.1 Introduction

There is a growing demand for quantitative information on actual land use/land cover and their future changes in space and time, particularly since the formulation of the Kyoto protocol. The influence of land use (change) on climate, particularly in relation with carbon sequestration, has become an important issue. In order to quantify changes, understanding of the functioning of the land use system is needed. System's theory, however, is not yet very well developed for land use systems. Fortunately, the properties of a land use system are in many ways comparable to those of an ecosystem and the way it functions (Hart, 1985; Conway, 1987), and ecosystem theory has a long history. Especially the theory of complex systems is well evolved. Ecologists discern two types of complexity (Allen and Starr, 1982; Jørgensen, 1994) that both apply to

---

[#] Based on: Kok, K., Winograd, M., submitted. Spatially explicit modelling of the Central American land-use system. Submitted to Ecological Modelling.

land use systems as well. Firstly, land use systems are *functionally complex*, *i.e.* many factors influence the manner the land is used (Loucks, 1977). Biophysical, climatic, demographic, economic, and political variables all directly or indirectly influence land use practices (Turner *et al.*, 1995). Moreover, factors do not act independently, but form a web of interactions and feedbacks. A second, probably more important, type of complexity is *structural complexity*, indicating that factors act on different temporal and spatial scales (Peterson and Parker, 1998). For ecosystems, the so-called hierarchy theory has been developed (O'Neill, 1988) that states that to understand any complex system, one needs study at least three levels in the spatio-temporal hierarchy. There is a growing body of evidence of the importance of the scale effect in many scientific disciplines (Gibson *et al.*, 2000).

Models are crucial tools to help understand the dynamics and complexity of a land use system. In accordance with the above, land use models should be exhaustive in the factors that are considered, and should be based on an analysis of the system at various levels. Yet, when examining existing models, particularly at the regional and higher levels, this is usually not the case. Recognising the excessive complexity of the system, land use modellers often confine themselves to either a single process (*e.g.* deforestation, see Lambin, 1994), a single discipline (*e.g.* economic models, see Bockstael, 1996), or a limited area. Models that opt to incorporate a larger number of factors for a large area (*e.g.* global circulation models, see Zuidema *et al.*, 1994) are forced to severely simplify the land use system. While specialised models that isolate part of the system serve to gain detailed understanding of the process studied, they fall short when the aim is at a realistic projection of possible future pathways of the land use system in a temporally and spatially detailed way. Mostly an optimal future without a specific temporal dimension is presented, sometimes accompanied by an indication of the possible direction of change (*e.g.* linear programming models, see Van Ittersum *et al.*, 1998) or an indication is given of the possible directions of change. Some models do incorporate a space and time dimension and also address the question of structural complexity. Cellular automata (see Balzter *et al.*, 1998), LAND USE SCANNER (Hilferink and Rietveld, 1999), and GEOMOD (Pontius *et al.*, 2001) are good examples. However, the scale dependency of relationships is not considered. The CLUE (Conversion of Land Use and its Effects; Veldkamp and Fresco, 1996b; Schoorl *et al.*, 1997) modelling framework is one of the few examples of a land use model that incorporates both structural and functional complexity. Because of these characteristics CLUE was selected as an appropriate means for the analysis proposed here.

Main objective is to develop various plausible near-future pathways (1996 until 2010) of land use change at the national level and to analyse the consequences on spatial patterns in Central America. Besides various non-spatial scenarios, special attention was given to the construction of a natural hazard scenario, based on actual data, in order to examine realistically the effects of an extreme event on properties of the land use system.

5.2 The CLUE modelling framework

5.2.1 General structure

A general description of the CLUE modelling framework as well as a list of previous model applications are given in Section 1.5.3. Kok *et al.* (2001), see Chapter 6, performed a calibration and multi-scale validation of the CLUE application described here for Costa Rica and Honduras. In most applications until now, special attention was given to either differences at the non-spatial level (export/import, domestic intake etc.), or on restriction of allocation (exclude degraded areas or national parks). They served to demonstrate the feasibility of the model application. The current application was a first attempt to define a realistic scenario based on actual data.

5.2.2 Drivers of land use change in Central America

Within the framework of CLUE, Kok and Veldkamp (2001) performed a multi-scale empirical analysis on the drivers of land use in Central America patterns (see Chapter 4). Results serve as a main input for the allocation module of the CLUE application for Central America described in this chapter. Main conclusion of the statistical analysis was that invariably a mix of demographic, soil-related, and climatic variables determines land use. The mix of variables varies with land use type, country, and spatial resolution, but all groups are always of substantial importance. Important variables include rural population density, access to nearest port, soil fertility, soil drainage, and climate seasonality. Pattern of land use change as described here can mostly be attributed those factors.

5.2.3 Spatial scale considerations

The spatial resolution and spatial extent at which the model is executed are of essential importance. To account for scale dependencies, multiple resolutions are used in the CLUE methodology. Resolutions that need to be incorporated in the allocation module are determined during the statistical analysis. For the present application, a base grid of 15 × 15 km and a coarser resolution of 75 × 75 km were adopted. Instead of using uniform grid cells with one dominant land use type, sub-grid information is present; *i.e.* every cell contains percentage information on each land use type and for most of the driving forces. Kok and Veldkamp (2001) elaborated on the effects of a varying modelling extent. They concluded that a country is the largest organisational unit that should be modelled in Central America. Substantial and non-realistic land use changes could be introduced when scenarios would be developed for the whole region at once. Consequently, all scenarios were developed separately for the six countries involved, and model runs involved one country at the time. Countries were treated as separate units, linked only by intraregional export and import quantities.

5.2.4 Study area

Central America (Guatemala, El Salvador, Honduras, Nicaragua, Costa Rica, and Panama) was selected as study area. It offers the possibility to study various countries simultaneously, because of their small sizes. Although largely similar in climatic and biophysical land use potential and recent political history (Schumann and Partridge, 1989), the six countries display large economic (World Bank, 1998) and political (Brockett, 1988; Pelupessy and Weeks, 1993) differences. Besides, biophysical, climatic, and socioeconomic gradients (mountain ranges, rainfall, and population density) are steep over small distances within the countries, which induces strong variation in land use over relatively small areas. Furthermore, natural hazards in general and hurricanes in particular are a real threat to especially the northern and eastern parts of the region. In October 1998 the powerful hurricane Mitch struck above all Honduras and Nicaragua. Because of the extreme rainfall (up to 50% of the yearly total within a week (INETER, 1999)) large lowland areas were flooded. Numerous bridges and roads were washed away, hundreds of thousands of people became homeless, and harvests and herds were lost. Total losses are estimated at almost seven billion dollars, which equals 15% of the region's GDP. The devastating power of Mitch stressed the need to investigate the aftermath of this type of extreme events.

5.3 Scenario development

Scenarios were defined and developed in collaboration with members of the World Bank, UNEP, CIAT, and ministries of the various countries in Central America. Scenarios were developed for every country and for every land use type separately. National data were largely extracted from the FAOSTAT databases (FAO, 1999). Economic variables were obtained from World Bank (World Bank, 1998). Scenarios were calculated for the period 1997 until 2010. Analysis of historical changes was restricted to the period between 1975 and 1996.

Scenarios were developed for ten commodities that translate into five agricultural land uses. Together with natural vegetation, for which no specific demand was calculated, those six land use types were used as input in the allocation module of CLUE. The ten commodities included 1. maize, 2. beans, 3. rice, 4. sorghum, 5. bananas, 6. plantains, 7. coffee, 8. sugar/sugar cane, 9. cow milk, and 10. beef. The six land uses for which spatial information was available were annuals (commodity 1-4) bananas (5 and 6), coffee (7), sugar cane (8), pasture (9 and 10), and natural vegetation (remaining area). The latter mainly consisted of tropical forest, but also included *e.g.* secondary regrowth, natural pastures, and built-up area. Urban area covered maximally five percent of any country and was therefore not treated as a separate land use type.

A total of three scenarios were developed:

- Base scenario. Historical trends continue until 2010. In some cases, the period 1975-1985 (influenced by international oil crises) was excluded from the analysis. Three sub-scenarios were discerned, differing in GDP growth at national level. Base3% assumes a 3% GDP growth, which is in line with the average recent development. Base1% and Base5% assume 1% and 5% GDP growth respectively.
- Sustainable scenario. Sustainability is defined as a higher agricultural output per hectare, thus decreasing the -unsustainable- destruction of natural vegetation to meet agricultural demand. Yields are projected to increase to the maximum attained in 1996 anywhere in the region; export and import will increase to ensure cultivation of more 'appropriate' crops; waste losses are reduced to the minimum reported in 1996. Furthermore, GDP growth will be 5%, under the assumption that sustainability measures will only be executed in a combination with a high income growth.
- Natural Hazard scenario. A hurricane like Mitch is assumed to strike Central America in 1998. The effects will depress economic development. Consequently, export is reduced; import is temporarily increased (international aid); waste losses are increased; GDP growth is set at 1%. The effects are assumed to be temporal and to end in 2005, after which assumptions of the Base1% scenario apply. Additional assumptions are explained below.

Scenarios can be grouped in two types. In the first type, only the total area to be allocated is variable (demand-controlled scenarios). Changes in land use at the national level depend on (macro-)economic and crop specific factors. All variants of the Base scenario and the Sustainable scenario belong to this type. In the second type, the focus is on the realistic integration of location specific and total area changes. Land use changes largely depend on spatially specific changes (allocation-controlled scenario). The Natural Hazard scenario is an example of this type.

5.3.1 Demand-controlled scenarios

The analysis of area development focused on changes in demand, under the assumption that demand equals supply, following assumptions of the FAOSTAT databases. Yearly demand (in hectares) was calculated for every commodity (Area) between 1997 and 2010 and is a function of the commodity specific production (Production, kg) and commodity specific yield (Yield, kg/ha):

$$\text{Area} = \text{Production} \,/\, \text{Yield} \qquad (1)$$

Future yield developments varied depending on the scenario. In the Base scenario yield largely developed following past trends. In the Sustainable scenario, it was assumed that all yields approach the highest average national yield attained in Central America in 1996. Changes in commodity specific production depend on a number of factors, largely those that are present in the FAOSTAT databases:

$$\text{Production} = (FO + EX - IM + PR + FE + OU) \times (1 + FWA + FSE) \quad (2)$$

FO	= Food quantity	FE	= Feed quantity
EX	= Exported quantity	OU	= Other uses quantity
IM	= Imported quantity	FWA	= fraction that is wasted
PR	= Processed quantity	FSE	= fraction used for seed

Base-scenario projections for all categories except FOOD were based on a combination of extrapolating past developments, expert knowledge, and existing scenario studies (*e.g.* USDA, 1999). For example, the feed quantity of maize is expected to increase dramatically over the next decade, in sharp contrast with past trends. The increase is caused by an expected rising demand for chicken meat in all Central American countries. In Table 5.1, an example is given of the data used to calculate the production of maize.

Table 5.1. Base-scenario assumptions used to calculate maize production between 1996 and 2010 for six Central American countries. Plus sign indicates an annual increase.

Category	Costa Rica	El Salvador	Guatemala	Honduras	Nicaragua	Panama
Feed (ton)	+10,000	+10,000	+10,000	+1,500	+5,000	+1,500
Processed (ton)	0	0	0	0	0	0
Export (ton)	10,000	5,000	30,000	5,000	5,000	0
Import (ton)	+12,000	+12,000	+12,000	+1,500	+5,000	+5000
Other uses (ton)	4000	3000	4000	3000	4000	2000
Waste (%)	5.0	5.0	4.5	7.5	8.0	2.5
Seed (%)	1.0	1.0	1.5	1.3	1.5	1.0

The Sustainable scenario assumed an increased intraregional export and import, based on the reasoning that the process of market liberalisation will eventually ensure land use to be more 'appropriate', and thus more sustainable. Additionally, waste losses are assumed to decrease substantially.

Changes in the FOOD category, for most commodities the most important factor, were given special attention:

$$\text{FOOD} = \text{CONSCAP} \times \text{POP} \quad (3)$$

FOOD	= Quantity used for food (kg)
CONSCAP	= Consumption per capita (kg/capita)
POP	= Total population (capita)

Population growth rates between 1997 and 2010 were based on existing projections (US Census Bureau, 1998) and were in accordance with the medium variant of the UN (UN, 1997). The development of CONSCAP was considered to be a function of three parameters, GDP per capita (proxy for income), the percentage of GDP used for consumption, and a time dummy. Due to lack of consistent information for all countries, price information was not considered. Multiple regression techniques were used to describe the development of CONSCAP between 1975 and 1996. Resulting equations were used to predict future consumption per capita.

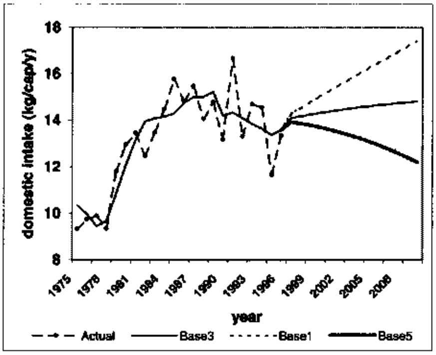

Figure 5.1. Actual (1975-1998) and modelled (1999-2010) rice consumption (kg capita^{-1}) in El Salvador for three variants of the Base scenario.

Figure 5.1 illustrates the predictive power of the multiple regression equation and the possible future developments for rice consumption in El Salvador. Rice apparently is considered an inferior foodstuff, as its share in the food basket will decrease with increasing income. In the majority of the countries the consumption of beans, maize, sorghum, and plantains decreased with increasing income. The consumption of particularly beef, milk, and coffee increased with income. Thus we can calculate changes in production (ten commodities) and area (six land use types) for every country separately, and for Central America. Summarising data are given in Table 5.2.

Table 5.2. Area (km^2) and relative differences (annual change percentage) of six land use types in Central America in different scenarios.

	Annuals	Bananas	Coffee	Sugar Cane	Pasture	Natural vegetation
Area 1996	41,600	1,600	7,700	3,300	104,700	284,800
Area 2010 Base 1%	51,950	1,800	8,500	4,050	103,100	274,300
Area 2010 Base 3%	49,300	1,800	8,600	4,100	107,800	272,100
Area 2010 Base 5%	45,900	1,850	8,850	4,200	120,500	262,400
Area 2010 Sustainable	35,950	1,950	8,800	3,900	92,500	300,600
Difference Base 1%	+1.7	+0.9	+0.7	+1.5	-0.1	-0.2
Difference Base 3%	+1.3	+0.9	+0.8	+1.6	+0.2	-0.3
Difference Base 5%	+0.7	+1.1	+1.0	+1.8	+1.0	-0.5
Difference Sustainable	-0.9	+1.5	+0.9	+1.2	-0.8	+0.4

In Figure 5.2, actual and projected area development of natural vegetation and annuals is given between 1975 and 2010 for the demand-controlled (sub-)scenarios. Higher GDP growth rates result in higher deforestation rates, although demand for annuals decreases with GDP growth. Following the assumptions behind a sustainable

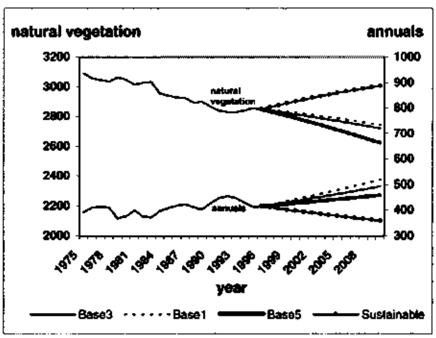

Figure 5.2. Actual (1975-1996) and modelled (1997-2010) Central American area development (km^2/100) of natural vegetation and annuals in various scenarios.

development, a relatively strong reforestation will take place in this scenario.

5.3.2 Natural Hazard scenario

Because of the rapidly expanded possibilities of Internet, within days after Mitch struck Central America the first images became available on the exact path of the hurricane, total rainfall, damaged roads and bridges, etc. (CINDI, 1998), together with additional information like production losses of *e.g.* banana plantations (Internet, various sources). This wealth of information and, more important, the speed with which it became available, provided an excellent opportunity to apply the CLUE model to Honduras and predict, based on the additional datasets, the long-term effects of hurricane Mitch. Data analysis and model runs were comparable to the methodology described for Central America. Most important differences were the basic grid size, which was set at 7.5 × 7.5 km and the temporal extent, set at 1993 - 2005 for Honduras. Accessibility maps for Honduras were altered conform information on damaged roads and bridges (CIAT, 1999).

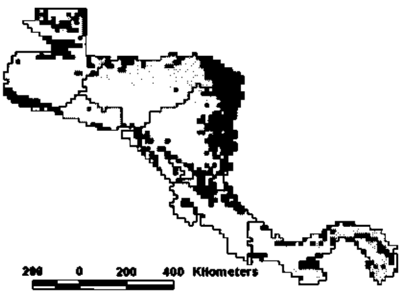

Figure 5.3. Areas vulnerable to flooding in Central America in the Natural Hazard scenario.

The Natural Hazard scenario that was used for Central America was based on the results from the Mitch scenario in Honduras. A similar scenario was developed, simulating the effects of a major hurricane. The basic assumptions were the following:

- A hurricane of strength equal to Mitch will hit Central America, passing over all six countries.
- Areas vulnerable to flooding will be affected and production from those areas will be lost in the first year and restored gradually over the course of five years. A grid cell was considered vulnerable when two of the following four criteria were met: a> at least 75% flat, b> at least 75% poorly drained, c> altitude maximally 200 m, d> located at the Atlantic side, within 60 kilometres of the coast.
- GDP growth will be at 1% from 1999 onwards.
- Export will be reduced and import will increase strongly in the first five years and remain slightly higher in the years after. Rates of change were land use type specific.
- Accessibility of affected areas will be reduced, thus extending the effect to areas that were not flooded, where accessibility was unaffected.
- Part of the population in the affected areas (10%) will migrate to the nearest city and growth rates in the vulnerable areas will remain 1% yr^{-1} lower.

The vulnerable areas are presented in Figure 5.3. About 25% of the area (509 out of 1972 cells) was projected to be affected. Coffee plantations were hardly affected, whereas almost half of the area under bananas and sugar cane was located in the flooded area. Forty percent of the area of Nicaragua was classified vulnerable, while only 9% of El Salvador would be affected in case of a hurricane.

5.4 Model results

5.4.1 Demand-controlled scenarios

Base scenario

Maps of land use distribution in 1996 are presented in Figure 5.4. Maps of hot-spots of change (1996 to 2010) under the Base3% scenario are given in Figure 5.5. The spatial pattern of land use is projected to change considerably, even though changes at the national level are relatively small and largely follow historic developments. Besides, changes within a country are rarely unidirectional. Strong increases and decreases often occur within a short range.

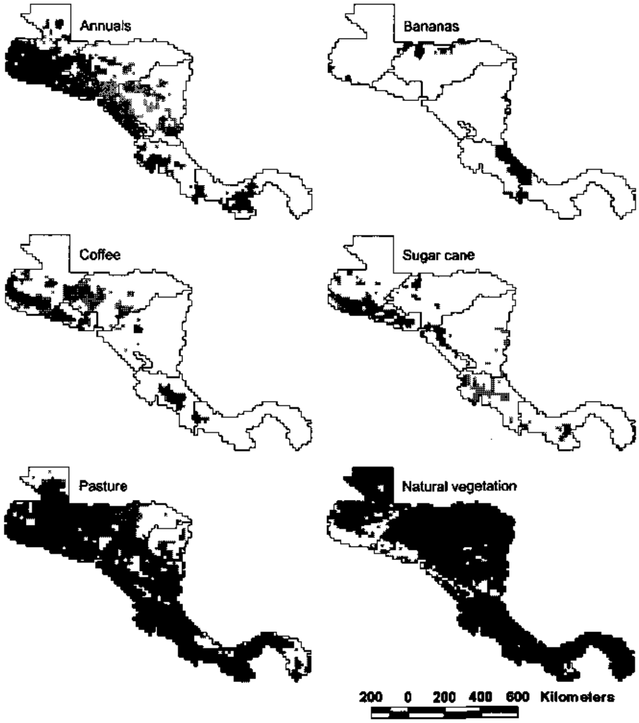

Figure 5.4. Land use patterns in 1996. Light colours indicate a low cover percentage; dark colours a high cover percentage.

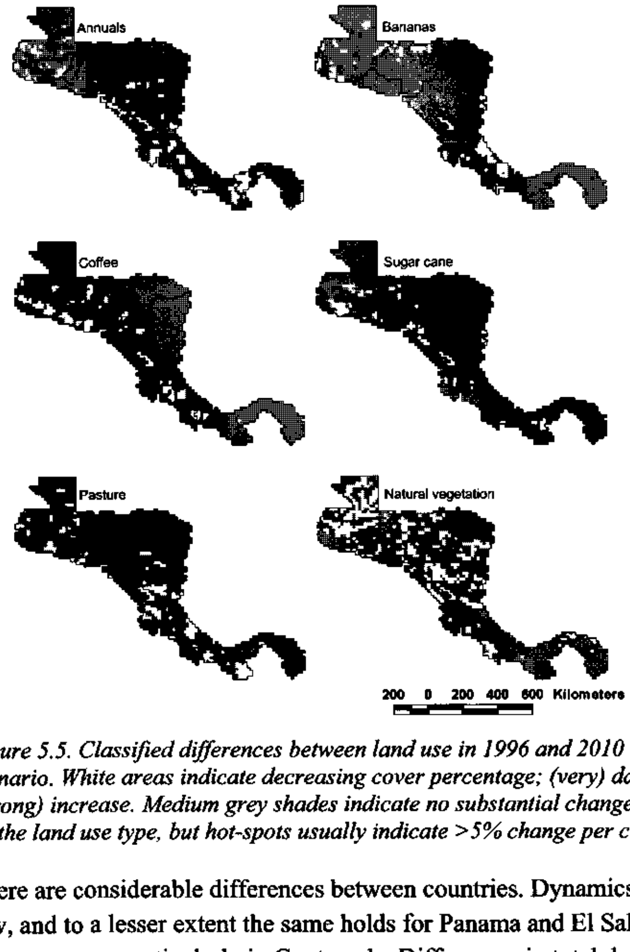

Figure 5.5. Classified differences between land use in 1996 and 2010 under the Base3% scenario. White areas indicate decreasing cover percentage; (very) dark shades indicate a (strong) increase. Medium grey shades indicate no substantial change. Classification depends on the land use type, but hot-spots usually indicate >5% change per cell.

There are considerable differences between countries. Dynamics in Honduras are very low, and to a lesser extent the same holds for Panama and El Salvador. Dynamic changes occur particularly in Guatemala. Differences in total demand changes between countries account for part of the observed variation. Demand for bananas in Costa Rica for example, is projected to rise 25%, which explains hot-spots of change to be concentrated in that country. On the other hand, annuals in Honduras increase at the same rate and comparable quantity as annuals in Nicaragua, but dynamics in the latter country are far larger. Of all land use types, annuals show most vigorous changes. Often, (very) strong increases are coupled with strong decreases. This highly dynamic modelled behaviour of annual crops is in line with the temporal character of the main crops classified as annuals, namely maize, beans, and rice. Unlike permanent crops, their location can potentially be changed within a year. The spatial pattern of bananas shows remarkable changes in Costa Rica. Plantations are shifted from the Atlantic to the pacific side. Those projected new locations coincide with prior locations of banana plantations in the 1960s and 1970s (Goluboay and Vega, 1988), when cultivation in the Atlantic zone was temporarily ceased due to a fungus infection. However, the projected shift to the south is not very realistic. An omission from the set of land use drivers that was used (see Kok and Veldkamp, 2001) is the transportation from port to final destinations in Europe and the US. In this case, particularly the costs to pass through the Panama Canal make banana cultivation in the south unprofitable, despite the proximity of a port. The spatial patterns of coffee and sugar cane change substantially. Especially in Guatemala and El Salvador, present plantations are projected to shift to various other spots spread out over the countries. Whether such shifts of land uses with a permanent character are to be expected, depends on variables like the existence of local corporations, and should be analysed using more detailed models. Anyhow, model results indicate a strong potential for sugar cane and coffee cultivation outside present locations. There are clear hot-spots of increase and of decrease of pasture. Areas of high increase are present in the south of Costa Rica and in the central highlands of Guatemala. Both are areas with a relatively high forest cover in the proximity of roads and people. Areas of pasture decrease are found in most countries, and are mostly located on poor soils, in relatively remote areas. Hot-spots of deforestation are scattered over all countries, except Panama. Remarkably, the three large continuous forested areas in the south of Panama, the north of Guatemala and the east of Honduras (see Figure 5.4) remain largely intact. Some deforestation takes place in the north of Guatemala, but deforestation elsewhere in the country is more severe. This tendency is even stronger in Honduras. The general trend is one of deforestation of remaining small forest stands.

Hot-spots of land use changes in the Base1% and Base5% scenario were insufficiently different from the Base3% results to justify separate evaluation. Distributions of the three permanent land uses, that are generally influenced stronger by export and import than by changes in domestic intake, were virtually identical in all variants of the base scenario. Patterns of annual crops and pasture are influenced stronger by changes in income and domestic consumption, but most important hot-spots of change remained. Deforestation hot-spots likewise did not change, except for a slight acceleration in the eastern part of Honduras.

Sustainable scenario

Hot-spots of land use change between 1996 and 2010 under the Sustainable scenario are given in Figure 5.6. Again, land use changes are highly dynamic, but there are differences with the Base3% scenario. Annuals decrease especially in Nicaragua and Guatemala. The overall lower cover is caused by assumed yield increases of annuals. Because Nicaraguan yields are the lowest in the region, the effects of sustainable management are largest in this country. In Costa Rica hot-spots of annuals become more dynamic, probably caused by a competition for land with bananas and pasture. Hot-spots of change in banana plantations are predominantly found in Costa Rica, similar to Base3%. The location of increasing cover, however, is different. New plantations are projected in the northern part instead of the South. Projected changes are unlikely to happen in such short term, mainly due to the lack of proper

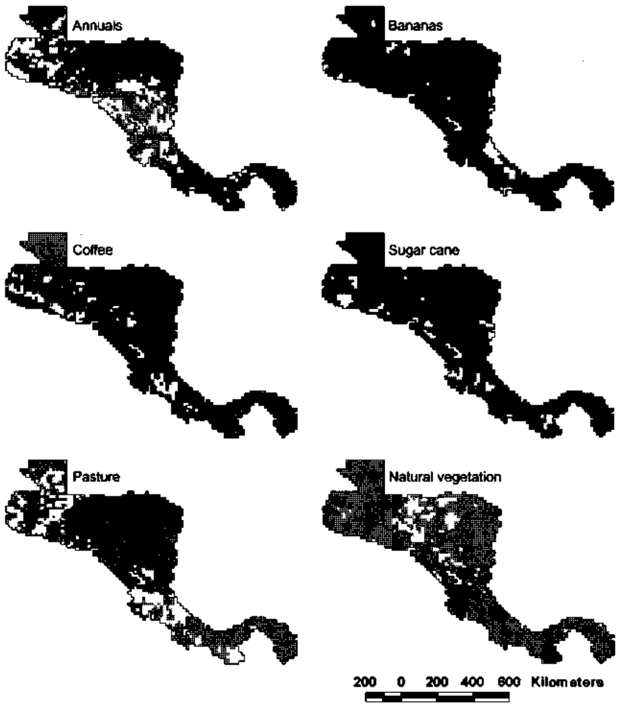

Figure 5.6. Classified differences between land use in 1996 and 2010 under the Sustainable scenario. White areas indicate decreasing cover percentage; (very) dark shades indicate a (strong) increase. Medium grey shades indicate no substantial change. Classification is crop-dependent, but hot-spots usually indicate >5% change per cell.

infrastructure on this side of the country, but the potential for banana expansion in Costa Rica is indicated. Sugar cane and coffee both display hot-spots of change that are very comparable to the Base3% scenario. Yields were already very high and other measures that are assumed in the Sustainable scenario did not strongly affect the total area of both land uses (see Table 5.2). Because of projected increasing stocking rates and decreasing demand, large areas of grassland are afforested in Costa Rica, Guatemala, and to a lesser extent in Nicaragua. The opposite process of increased deforestation to satisfy the demand for pasture (mainly beef) can be observed in Honduras. In all countries, changes are almost unidirectional, indicating that new pasturelands are developed where no strong competition with other land uses takes place, and that abandoned pastures are almost always converted to secondary forest.

5.4.2 Natural Hazard scenario

Before discussing the results of the Natural Hazard scenario in Central America, the application of CLUE to actual data that became available after Mitch struck Honduras is given. The model was executed for the period 1993 until 2005. In Figure 5.7 the short-term (1999) and long-term (2005) effects of hurricane Mitch are illustrated with the hot-spots of change for maize.

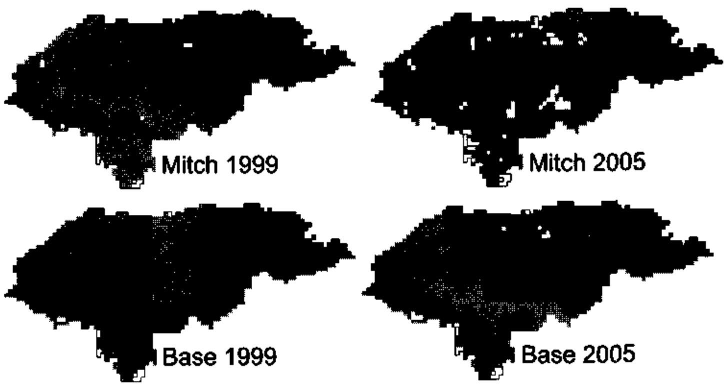

Figure 5.7. Short-term and long-term effects of hurricane Mitch on cover percentage of maize in Honduras. Depicted are changes in cover in between 1993 and 1999, one year after the hurricane (left) and between 1993 and 2005 (right), for Base1% scenario (bottom) and Mitch scenario (top). Changes are classified in decreasing cover (white), increasing cover (dark grey and black), and no change (medium grey). Lines indicate the flooded area.

In 1999, one year after the hurricane, the intensity of land use change is clearly higher in the Mitch scenario than in the Base1% scenario. In large parts outside the area that was flooded, the maize area increased substantially (> 2% per grid cell), while hot-spots of increase in the Base1% scenario are scattered and less pronounced (usually < 1% per grid cell). However, when we compare maps of 2005, seven years after Mitch, differences between the two scenarios are less clear. Although the dynamics in the Mitch scenario are somewhat higher, the overall patterns are similar to those of the Base scenario. One specific area where maize showed a lasting stronger increase in the Mitch scenario is located in the south-southeast, in the forest-agriculture fringe. Reactions of other land use types were less strong, but similar.

Results of the Natural Hazard scenario for entire Central America were largely comparable to the results for Honduras. Final hot-spots of change in 2010 were similar to patterns after the Base3% scenario (see Figure 5.5). Temporal dynamics are illustrated in Figure 5.8, displaying the time path of the changes of annuals in non-flooded area of Central America. After the hurricane passes, the average percentage of annuals in a cell in the non-flooded area rises sharply from 10.5% to more than 13%. While annual cover in the Base1% scenario continues to increase gradually until 2010, the average annual cover in the Natural Hazard scenario decreases. Eventually about 10 years after the hurricane, the area (as well as patterns) become very similar. Although differences are generally small and main hot-spots do not change position, consistent tendencies are revealed when considering the aggregated reaction of all land use types. In Figure 5.9 the percentage of cells that have an equal cover percentage (difference < 1% per grid cell) in the Base1% and the Natural Hazard scenario is given for the flooded and the non-flooded area. Two points stand out. First, differences between Base1% and Natural Hazard scenario are largest for land uses with a non-permanent character, annuals and sugar cane. The area of those land uses

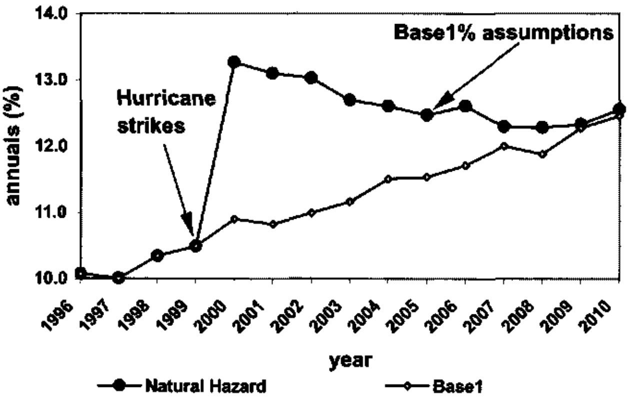

Figure 5.8. Changes of average cover percentage of annuals in the non-flooded area in Central America between 1996 and 2010 in the Base1% and Natural Hazard scenario.

differs substantially in about 25% of the grid cells. Especially pasture and banana plantations show much smaller differences between the scenarios. Given the permanent character of these types of land use this was to be expected, although no *a priori* assumptions were made on the land use specific rates of change. Secondly, the percentage of cells that have an equal cover is consistently higher in the flooded area. For all land use types, the off-site effects of a hurricane are projected to be larger than the direct effects of flooding. The chain of events that takes place after the strike of a hurricane serves to explain the observed effects. In the flooded area, annuals are washed away (Base1% >> Natural Hazard), while the unabated demand for food triggers new areas of cultivation in the non-flooded area (Base1% << Natural Hazard). The same holds for sugar cane. In the case of bananas, the model projects a return of plantations at the same locations (Base1% equals Natural Hazard), which seems realistic given the economic power of the multinationals that own the majority of the banana plantations. The location of pasture is similarly little influenced by the flooding, as most of the grasslands will have remained after the flooding. As a result, deforestation in flooded areas decreases relative to the Base1% scenario.

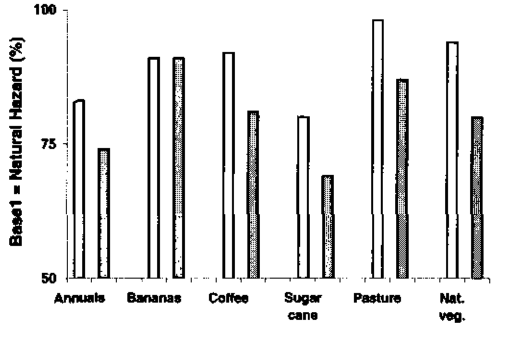

Figure 5.9. Percentage of cells that have a similar cover in Base1% and Natural Hazard scenario in both the flooded (white) and non-flooded (grey) area.

5.5 Discussion and conclusions

Application of the CLUE modelling framework to Central America proved that the model is able to realistically mimic various aspects of the complexity of a land use system simultaneously. The integration of a multitude of biogeophysical and socioeconomic land use change drivers, the explicit incorporation of competition between land use types, and the dynamic modelling at various spatial resolutions, are examples of characteristics that explain the model's capacity to produce spatially and temporally dynamic results. Differences between the slow and gradual changes projected at national level (Figure 5.2) and the spatially explicit hot-spots of strong increases and decreases (Figure 5.5) demonstrate the added value of a spatially explicit component to a land use model.

There is a remarkable lack of differences between results of the various demand-controlled scenarios. Differences in income (GDP) are seemingly not enough to generate major shifts in the land use system. A radically different and hardly plausible pathway of land use change had to be assumed in the Sustainable scenario, to generate different patterns of change. This apparent persistence of local circumstances and preferences as compared to national trends again stresses the importance of spatially explicit models in order to account for processes at different spatial scales. Results from the Natural Hazard scenario for Central America as well as for Honduras showed that an extreme event like a hurricane induces rapid and strong changes. Nevertheless, the model projects those changes to be temporal and to almost complete disappear over a relatively short period of time. Despite long-lasting effects through population migration and reduced income, export, and accessibility, final maps resemble the Base scenario output. The development of land use patterns in Central America on the short and medium term are remarkably balanced and seem independent of macroeconomic changes. Disturbances, no matter how strong, are smoothed and disappear over the course of ten year. Findings contrast with the prevailing opinion of a recovery period of at least 20 years.

The persistence of local circumstances and preferences under varying national trends is partly a result of model assumptions. The system description at one point in time (in this case 1996) is used to define spatial explicit circumstances. Besides population growth, these circumstances remain constant throughout the entire model run, thus generating recurring similar patterns. The validity of the assumptions on the constancy of the land use system can be illustrated by drawing from ecosystem theory, in particular the work of Holling (1973, 1992). He proposed to use two properties to describe the system's reaction to a disturbance, resilience and stability. A system is stable, when after a temporal disturbance, it can return to exactly the same equilibrium, whereas resilience refers to the ability to absorb changes of state variables, and still persist after a disturbance. Figure 5.10 illustrates the concept of resilience (Holling, 1992).

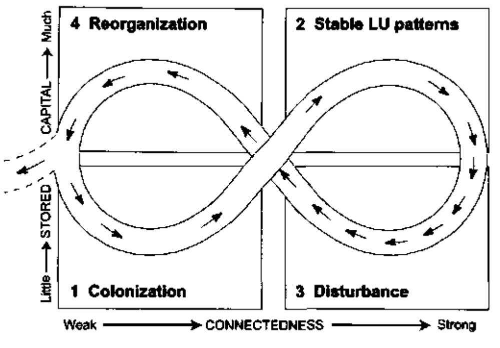

Figure 5.10. Four land use system functions and the flow of events between them. Adapted from figure 23, p. 481, Holling (1992).

When a hurricane strikes, stable land use patterns will rapidly be changed, during the short disturbance phase. Loss of capital and connectedness (complexity) describe the reorganisation phase that is initialised afterwards. Subsequently, the system returns to its former equilibrium, although key variables will certainly have changed, and a new (re)colonisation phase will start, which will result in stable land use patterns. Those patterns are not equal to the starting position; *i.e.* the land use system is unstable, but driven by the same set of variables, and thus resilient. The land use system in Central America appears to be very resilient though not necessarily stable.

Model findings, especially conclusions drawn based on the Mitch scenario, are useful for policy makers at various levels. International organisations, like the World Bank or the United Nations, can gain insight on the severity of spatially explicit changes as a reaction of macro-economic developments and *e.g.* compare the impact on and reaction of different countries. National authorities and institutes can potentially directly use the model and evaluate scenario results. The Natural Hazard scenario and particularly the accessibility maps offer excellent possibilities to assess *e.g.* the effects of repairing a particular road or bridge after Mitch. Provided the data are available, CLUE could be used in a recovery plan after an extreme event.

Evidently, land use is not the only system that is severely affected after an extreme event. Crops and herds are lost, which could be followed by a famine, hundreds of thousands of people can become homeless etc. From a sociological and probably also from an economical perspective, the aftermaths of a hurricane will be stronger and could last for much longer than the ten-year period modelled here. Eventually permanent changes in those systems might affect the land use system. To fortify conclusions drawn here, results from other disciplines are needed. In any case, extreme events will become neither less extreme nor more predictable, but modelling efforts as described here offer a flexible framework with a large number of changeable variables to rapidly react to events when they happen. Thus insights are offered that might help counteract some of the consequences before they happen.

CHAPTER 6[#]
Multi-scale validation of the CLUE allocation module using data from Costa Rica and Honduras

Abstract

The majority of the large number of existing land use models lack a proper validation, often because of data problems. Moreover, despite recognition of the necessity to incorporate a multi-scale analysis, scale dependencies are normally not considered during validation. In this paper, a multi-scale land use change modelling framework, CLUE (Conversion of Land Use and its Effects), is calibrated for Costa Rica and validated at five spatial resolutions for Honduras and Costa Rica. Both countries experienced locally very strong actual land use changes. Calibration runs show that the model is very sensitive to changes in the autonomous development parameter, which defines the influence of the finest resolution. Validation results are very satisfactory for both countries. Especially changes in major land use types are reproduced with the model. Changes in localised land use types are more difficult to project. The magnitude of gains and magnitude of losses are slightly underestimated in all cases. The multi-scale validation demonstrates that results improve strongly, and exponentially, with decreasing spatial resolution. Strong reduction of the number of observations results in a correlation between actual and modelled changes that approximates the perfect value of one. The study demonstrates that the CLUE modelling framework can reproduce changes as they took place in Central America in the 1970s and 1980s, and shows how conclusions can differ depending on the scale at which validation is performed.

6.1 Introduction

6.1.1 Land use models and validation

Use of models in land use research is almost universal (Beck, 1999). Extensive overviews are given by Kaimowitz and Angelsen (1998) and Lambin (1994), while both studies only consider deforestation. The number of spatially explicit land use models is much smaller (Sklar and Costanza, 1991), but rapidly increasing. In spite of the large number of models and in spite of a general agreement that validation should be an essential part of any model (Borenstein, 1998), the majority lack a validity check. An analysis of error propagation and parameter sensitivity is usually conducted, but for various reasons a full-fledged model validation is hindered in most spatially explicit land use models. Particularly models that operate on a higher scale

---

[#] Based on: Kok, K., Farrow, A., Veldkamp, A., Verburg, P.H., 2001. A method and application of multi-scale validation in spatial land use models. Agriculture, Ecosystems and Environment 00: 000-000.

lack an independent second data set (*e.g.*, Leemans and Van den Born, 1994; Heuvelink and Pebesma 1999), and because of the large extent, controlled experiments cannot be run. Besides, many models seek to explore future scenarios of land use change, and are therefore impossible to validate completely. A proper validation not only requires a second independent data set, it should be preceded by model calibration, which calls for an additional data set.

6.1.2 Scale issues

Besides practical difficulties to validate land use models, there is another complicating factor, which is referred to as the scale problem, or the fact that processes and relationships change both with the (spatial and temporal) *resolution* and *extent* at which they are observed. The problem was first recognised by ecologists (O'Neill, 1988; Meentemeyer, 1989), and recent awareness is growing in a number of other disciplines (Wagenet, 1998; Jansen and Stoorvogel, 1998; Becker *et al.*, 1999). With one notable exception (Costanza, 1989), this growing interest in multi-scale analysis is not accompanied by special interest in multi-scale model validation, even though most modellers do not claim that their models are valid at the scale of analysis (Jansen, 1998). There is no reason to assume that the scale effect is less influential in model validation and the results of a multi-scale model could therefore potentially be mis-used if not coupled with a multi-scale validation. This paper offers a first step towards such a validation, by a systematic study of the effects of spatial resolution with a constant extent on the validity of model results.

6.1.3 The CLUE modelling framework

The CLUE modelling framework, which is validated in this study, is one of the few spatially explicit land use models that analyses land use change at multiple scales. A general description of the CLUE modelling framework and a list of previous applications are given in Section 1.5.3. Recently, CLUE has been applied to Central America (see Chapter 5; Farrow and Winograd, 2001). The six most important land use types in terms of area and economic revenue were incorporated: annual crops (mainly maize, beans, rice, and sorghum); bananas; coffee; sugar cane (representing the permanent crops); pasture; and natural vegetation. Scenarios are developed that explore a number of different possible future pathways of land use changes between 1996 and 2010. Scenarios include a natural hazard, a sustainable future, and various future pathways of economic growth. The finest resolution is a gridcell of 15 × 15 km, which is not treated as a homogeneous unit. More than one land use type is usually present within a cell. CLUE-CA includes two spatial resolutions, and special emphasis is put on the effects of a varying spatial extent. The temporal resolution is one year, with a time span of 15 years.

6.1.4 Objectives

The main objective is to analyse the performance of CLUE-CA, using two independent data sets for both Costa Rica and Honduras. In order to achieve this, the model is calibrated for Costa Rica at the finest resolution and a sensitivity analysis of key parameters is performed. Subsequently the model is validated at four coarser resolutions for Costa Rica and at five resolutions for Honduras. The validation concerns changes in the past and the quantity of change was therefore known. Validation was consequently restricted to the location of change and assumed correct total quantities. As it is the first time the model is used to project land use changes at supra-national level, particular interest is given to the question how the CLUE allocation procedure copes with dynamics of several countries at the same time. An analysis of the temporal dynamics is made to gain understanding of the temporal realisation of spatial land use change patterns. Finally, a comparison with the statistical input of CLUE-CA is included to relate the performance of the model to the quality of that input.

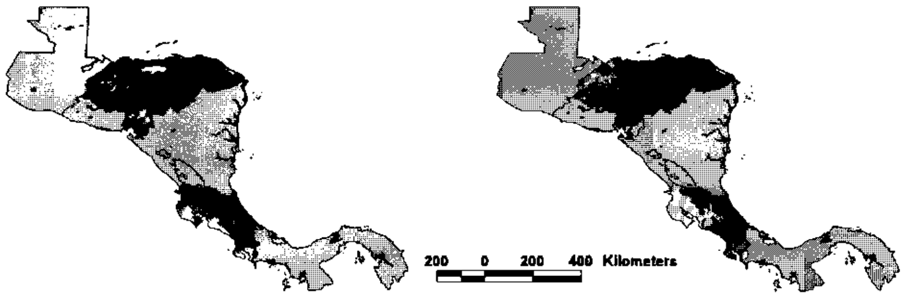

Figure 6.1. Left side: Distribution of natural vegetation in Costa Rica (1973) and Honduras (1974). white: 0%-20%; light grey: 20%-40%; medium grey: 40%-60%; dark grey: >60% cover percentage. Right side: Yearly total population growth rates for Honduras (average between 1974 and 1993) and Costa Rica (1973-1984). White: population decrease (<0% growth); light grey: stable population (0-0.5%); medium grey: slight population increase (0.5%-2%); dark grey: strong population increase (> 2%).

6.1.5 Actual land use changes

In both Costa Rica and Honduras, agricultural expansion at the expense of natural vegetation (forest) was the main process in the 1970s and 1980s. Land use dynamics were steered by strong and sometimes rapid changes that took place at local, national, and regional scales. At the regional level, civil wars and the second oil crisis in 1979 and its aftermath strongly influenced development of land use in Central America (Brockett, 1988; Diaz-Bonilla, 1990). Of all Central American countries, Honduras had the lowest per capita income, the highest population growth rate, and largest influence from the US market, whereas Costa Rica was, and continues to be, the richest country with the lowest population growth rates (World Bank, 1998). These national differences were reflected in the rates of land use change. At the local level, most conspicuous changes were related to large-scale land redistribution programs formulated to deal with increasing poverty in the 1970s (CCE, 1990). The result was a massive migration of rural population, especially in Costa Rica, where the programs were more successful (Jones, 1988). Figure 6.1 shows the yearly population growth rates between 1973 and 1984 for Costa Rica and 1974 and 1993 for Honduras and the distribution of natural vegetation in 1973 (Costa Rica) and 1974 (Honduras). Note the negative population growth in parts of both countries, and the high positive correlation between population growth and presence of natural vegetation. The observed (dis-)similarities offer a good opportunity to test the robustness of the CLUE allocation module.

Land use changes of the six land use types included in CLUE-CA are given in Table 6.1. Relative annual changes varied between -0.2% for natural vegetation in both countries and +2.8% per year for sugar cane in Costa Rica and were of similar magnitude for both countries. This annual deforestation rate of 0.2% was very low compared to a rate of at least 2% generally reported in literature (Stonich, 1993; Becker, 1998). The rates calculated here are net rates of changes and include development of secondary vegetation and other types of regrowth, whereas reported rates normally indicate gross deforestation of primary forest. Absolute changes were normally larger for Honduras as the country is twice the size of Costa Rica and the period of change was twice as long.

Table 6.1. Approximate area and area changes for six land use types in Costa Rica and Honduras between 1973 and 1984, and 1974 and 1993 respectively.

Country	Variable	Annuals	Bananas	Coffee	Sugar cane	Pasture	Natural vegetation
Costa Rica	Area 1973 (km^2)	2,700	350	790	330	14,500	29,900
	Area 1984 (km^2)	3,500	300	850	450	14,200	29,300
	Total change (km^2)	800	-50	60	120	-300	-600
	Total change (%)	30	-11	8	40	-2	-2
	Annual change (%)	2.4	-1.0	0.7	2.8	-0.2	-0.2
Honduras	Area 1974 (km^2)	4,500	240	1,000	250	12,000	79,300
	Area 1993 (km^2)	5,500	300	1,500	330	13,500	76,000
	Total change (km^2)	1,000	60	500	80	1,500	-3,300
	Total change (%)	23	28	56	35	13	-4
	Annual change (%)	1.1	1.2	2.4	1.6	0.6	-0.2

6.2 Methods and material

6.2.1 Data

Validation of CLUE-CA is restricted to Honduras and Costa Rica, being the countries for which two independent, high-quality data sets of land use are available. Land use data are derived from agricultural censuses, which contain detailed information on land use distribution at the crop level. In Costa Rica agricultural censuses were conducted in 1973 and 1984 (DGEC, 1976; DGEC 1987) and contain information for more than 400 districts; Honduran agricultural censuses are available for 1974 and 1993 (DGEC, 1978; SECPLAN, 1994) and include close to 300 administrative units.

Within the range of scales considered here, population density was and continues to be one of the key driving forces of land use change in Latin America (Rudel and Roper, 1997; De Koning, 1998). Given the population migration within the countries, spatially explicit information of at least two dates is necessary to calibrate and validate the model. For Costa Rica as well as Honduras, population censuses were conducted close to the years of the agricultural censuses.

6.2.2 Model calibration and sensitivity analysis

In this paper, sensitivity analysis refers to parameters within the CLUE allocation procedure. Parameters in the demand module that regulate the total quantity of change, like GDP per capita or consumption per capita, are not included. For model calibration the data sets of Costa Rica are used, as lack of a third data set for either Costa Rica or Honduras prevents the execution of an independent calibration. Because processes in Costa Rica and Honduras were largely similar over the time period that was considered and rates of changes were in the same order of magnitude, calibration for Costa Rica with subsequent validation for Honduras is justified. The validation for Costa Rica has to be evaluated carefully, since the basic grid level was used to calibrate the model.

Within the CLUE allocation module, there are two key input parameters, which need to be calibrated: SCALE_FACT and AUTODEV.

1. Scale parameter, SCALE_FACT. Determines to what extent the elasticity for changes as calculated at the coarse resolution will influence elasticity for changes at the fine resolution. This is its most important use:

$$REL\_CHANGE_t = (REL\_CHANGE_{t-1} / SCALE\_FACT) + 1 - (1 / SCALE\_FACT) \quad (1)$$

$$ELAS1 = ELAS0 \times REL\_CHANGE_t \quad (2)$$

REL_CHANGE: cell specific relative change in area for each land use type (unitless)
ELAS1: cell and land use specific elasticity to changes at fine resolution (fraction of total change)
ELAS0: land use specific elasticity to changes at coarse resolution (fraction of total change)
t: year index

SCALE_FACT changes the value of REL_CHANGE, which in turn influences the elasticity to change at the fine resolution. The higher SCALE_FACT, the closer REL_CHANGE will be to 1, the more elastic changes at the fine resolution will be, and the less the influence of the coarse resolution. At higher values of SCALE_FACT than approximately 10, the influence of the coarse resolution on the final output at the fine resolution becomes negligible.

2. Autonomous development parameter, AUTODEV. Determines the relative importance of national quantity of change and changes at the finest resolution. This is one of the key uses:

$$ACTCOV_t = ACTCOV_{t-1} + (REGCOV_t - ACTCOV_{t-1}) \times AUTODEV \quad (3)$$

$ACTCOV_t$: actual cell and land use specific area (ha/grid); $REGCOV_t$: cell and land use specific area as calculated by statistical analyses (ha/grid); t: year index

The unitless AUTODEV (value between 0 and 1) determines to what extent cell specific changes will be governed by local preferences (REGCOV - ACTCOV) instead of by national changes. The higher the value of AUTODEV, the stronger the local effect. At values above 0.50, the effect of further augmentation of AUTODEV becomes very small. At a value of 1, all changes are autonomous and the influence of national demand is negligible.

Model sensitivity for changes in the two key parameters mentioned is assessed by repeating model runs, varying the values of SCALE_FACT or of AUTODEV. Used values include 0.05, 0.10, 0.25, and 0.50 for AUTODEV and 1, 2, 5, and 10 for SCALE_FACT. The range of values is based on results of previous model calibrations for Ecuador and China. After preliminary analysis of the results, values of 2 for SCALE_FACT and of 0.25 for AUTODEV were adopted to validate the model. The influence of the coarser resolution is thus somewhat reduced and the influence of local preferences as compared to the national trend is substantially increased. A summary of the characteristics of SCALE_FACT and AUTODEV is given in Table 6.2.

Table 6.2. Range of values of SCALE_FACT and AUTODEV, two key parameters in CLUE allocation module.

Parameter	SCALE_FACT	AUTODEV
Minimum	1	0
Fine resolution dominates	< 2	> 0.20
Coarse resolution dominates	> 5	< 0.05
Maximum	∞	1
Adopted value after calibration	2	0.25

6.2.3 Multi-scale validation

In this paper, validation includes only the projection of the location of change. The quantity of change is set to be correct at the country level. For both countries the same validation procedure is followed. Within the framework of CLUE-CA, a set of multiple regression equations was previously created, that describe the relationship between patterns of land use and a set of explanatory variables at two different resolutions (15 × 15 km and 75 × 75 km) for the oldest of the two data sets available. A complete description of the methods and results of the statistical analysis is given in Chapter 4. Using this set of equations, the CLUE allocation module is run, starting at the oldest year until the most recent year. Results are annual maps of land use between 1973 and 1984 for Costa Rica, and between 1974 and 1993 for Honduras. Validation is quantified by comparing the modelled and actual land use *changes* between calibration date and validation date, as opposed to comparing resulting maps of 1984 and 1993 without accounting specifically for the change that occurred. Thus, the validation becomes independent from the total quantity of change at national level between start and end date and from the time span.

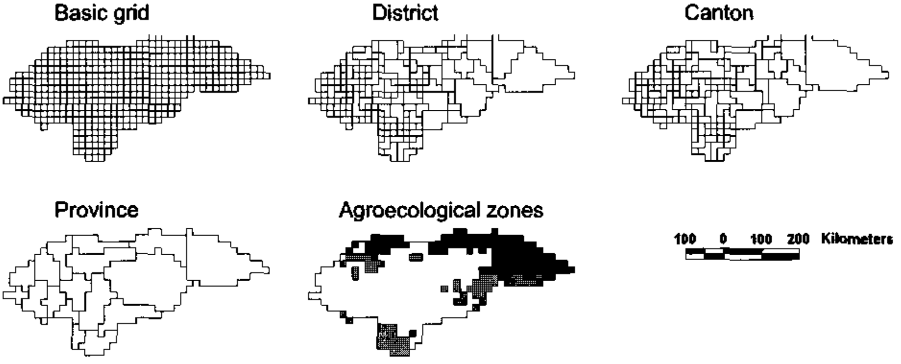

Figure 6.2. Five resolutions used for validation of Honduran data.

Besides the basic grid resolution (15 × 15 km), four additional coarser resolutions for validation are created (Table 6.3). A visual representation of the various resolutions in Honduras is given in Figure 6.2. To facilitate interpretation of results for potential stakeholders, resolutions are based on existing administrative divisions rather than artificial scales that could be created by averaging gridcells into larger grids. Three resolutions are created by grouping cells of the basic grid according to different administrative levels (districts, cantons, and provinces). The number of administrative units defined the number of observations. A fourth, most coarse, level is created by grouping cells to three agroecological zones: 1. Altitude < 500 meters and at least two consecutive dry months; 2. Altitude < 500 meters and no consecutive dry months; 3. Altitude ≥ 500.

Table 6.3. Basic information of five resolutions used for multi-scale validation and entire country. Number of observations and average unit size (km²) are given for Honduras (HON) and Costa Rica (COS).

Resolution	Number of observations		Average size of unit (km²)		Comments
HON and COS	HON	COS	HON	COS	HON and COS
Basic grid	431	216	225	225	15 × 15 km, level of analysis
District	118	50	822	972	lowest administrative level
Canton	72	31	1347	1568	intermediate administrative level
Province	17	7	5704	6943	highest sub-national administrative level
Agroecological zones	3	3	32325	16200	low and dry; low and wet; high
Country	1	1	96975	48600	total area is based on gridded data

In order to quantify relationships between actual and modelled land use changes, the correlation coefficient (r) and the slope of the best linear relationship (β_b) are calculated, using the ordinary least squares method, at every resolution and for every land use type. Additional analyses include a t-test on the significance of the intercept and a t-test on whether β_b is significantly different from one. The adopted manner to quantify validation results is, strictly spoken, a mis-use of the regression tool (Mitchell, 1997), and could pose interpretational problems. For example, results from testing the null hypothesis that the slope of the line does not differ significantly from one are difficult to interpret unambiguously, and the modelled and actual values cannot be treated as dependent and independent sets. We therefore utilise it mostly as a relative measure, to detect differences among spatial resolutions.

6.2.4 Temporal dynamics

The CLUE allocation module produces yearly land use maps. To analyse land use dynamics through time for the 11-year validation run for Costa Rica and the 20-year run for Honduras, cell-specific changes during every two-year period are calculated, by averaging year to year changes that proved relatively unstable. Land use specific changes are classified into three classes: cells with a decreasing land use percentage, cells with an increasing land use percentage, and cells where land use did not change substantially over any period of two years. Besides, for the decreasing and increasing class the average magnitude of change is calculated. By grouping cells in three classes, the spatial component is largely lost, but temporal detail is maintained. Only the basic grid resolution is analysed.

6.2.5 Comparison with statistical analysis

An important input of the CLUE allocation module is a set of multiple regression equations that describe land use patterns in a given year. For CLUE-CA, multiple regression analyses were performed at two resolutions. The finest resolution equalled the basic grid of this paper (15 × 15 km), a second resolution was created by aggregating 25 cells (75 × 75 km). From the results, so-called regression covers can be calculated. Subsequently, the correlation coefficients between the actual land use distribution in a given year and the 'prediction' by the statistical model for that same year can be calculated. Those correlation coefficients can be compared to the correlation coefficients of the validation described above. The former correlation coefficients represent the quality of the equations that are the core input of the allocation procedure. The latter are the results of the validation and represent the quality of the output of the CLUE model. Thus we can evaluate to what extent the success of allocation depends on the goodness-of-fit of the input equations.

6.3 Results

6.3.1 Model sensitivity

The model is not very sensitive for changes in SCALE_FACT, which regulates the influence of the coarse resolution on the fine resolution. The correlation coefficients (r's) and slope of the regression line (β_b's) between actual and modelled changes in area, obtained using higher (5 or 10) or lower (1) values for SCALE_FACT do not differ greatly from the results obtained in the validation run with a SCALE_FACT of 2. At higher values, the model performance is slightly different in the sense that hot-spots of change are more clustered, due to the larger influence of the coarse resolution.

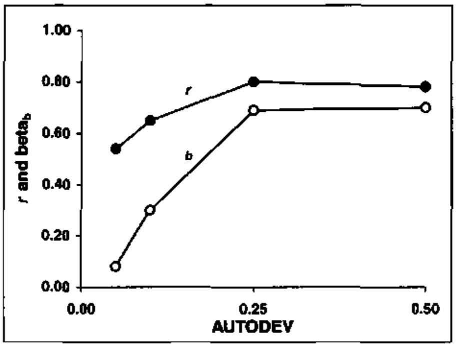

Figure 6.3. Sensitivity of correlation coefficients (r, P < 0.01) and slope of the best linear relationship (β_b) between modelled and actual changes in pasture area in Costa Rica at the basic grid to changes in the value of AUTODEV.

The model proves very sensitive to changes in the value of AUTODEV, which regulates the influence of national changes on the fine resolution. In Figure 6.3, r's and β_b's of the relationship between actual and modelled changes in pasture area are given at different values of AUTODEV. Correlation coefficients gradually increase up to a value of 0.25 for AUTODEV, after which r stabilises. At all values of AUTODEV, the r is reasonably high. The reaction of the β_b's on a changing AUTODEV is very strong. Augmentation of the value of AUTODEV from 0.05 to 0.25 results in an immediate and substantial improvement of the β_b's. Further increase to 0.50 has no effect on the model results. The low β_b's indicate that there is an underestimation of both the strong decreases in pasture in the southwest and increases in the northeast of Costa Rica. At low values of AUTODEV, the model cannot simulate the strong local changes that took place. The allocation module is apparently very sensitive for changes of AUTODEV between 0.05 and 0.25.

6.3.2 Validation

The results for Costa Rica at the basic grid are included, although this data set is used to calibrate the model and can strictly speaking not be used for validation purposes.

Qualitative comparison: hot-spots of change

In Figure 6.4, maps are presented that depict hot-spots of actual and modelled change at the basic grid level for four land use types. The CLUE allocation procedure captures the areas of major changes in a more than satisfactory way. Especially for pasture and natural vegetation, modelled and actual hot-spots of change coincide. Both the gradual deforestation in large areas in Honduras, and the reforestation in the southwestern part coupled with a rapid deforestation in the east and northeast of Costa Rica are reproduced with the model. An apparent mismatch is an area in the extreme south of Costa Rica where deforestation is modelled but did not occur. Low values for distance to market and the presence of high quality soils are among the reasons for the modelled deforestation. The initialisation of large-scale migration programs in the east and to a much lesser extent in the south that occurred in reality (Brockett, 1988), but was not included as a potential driving force during the statistical analysis, could explain the mis-match. The locations of change in area of annuals are reasonably well modelled, although the exact location of hot-spots in

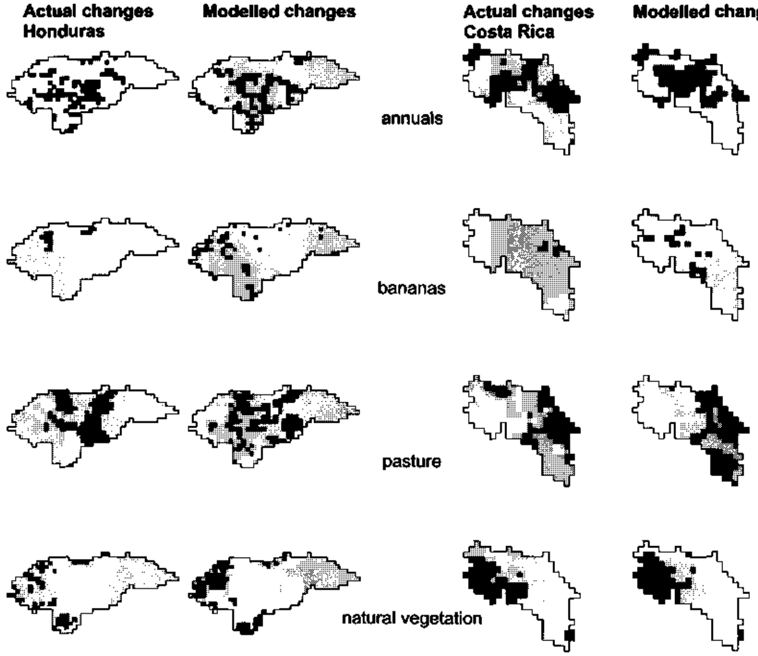

Figure 6.4. Visual comparison between modelled and actual changes of the four most important land use types in Costa Rica and Honduras. (Very) dark grey tones depict areas of an (strongly) increasing cover percentage; medium grey tones are areas without major changes and white areas depict a decreasing cover percentage.

Honduras not always matches. The model performance considering bananas is less satisfying. Areas of decrease generally coincide, but hot-spots of increase in banana area are not always in the correct places. The model is unable to project the highly clustered distribution of new banana plantations. The same conclusion can be drawn concerning the likewise clustered distributed coffee and sugar cane plantations (not shown).

Quantitative comparison

In the majority of the cases, the intercept of the linear relationship does not differ significantly from zero. The analysis of the effect of setting the intercept to zero is therefore small and is not treated separately. The remainder of the quantitative comparison focuses on the correlation coefficients and slope of the regression line.

Correlation coefficients

All correlation coefficients between modelled and actual land use distribution are given in Table 6.4. In Figure 6.5, the relationships between actual and modelled changes in the area of pasture are visualised for five resolutions. The statistical

Table 6.4. Significant correlation coefficients (P < 0.01) of relations between actual and modelled land use distribution for six land use types and five resolutions for Costa Rica and Honduras. The average value did not include bananas and sugar cane.

Country	Land use type	Data resolution				
		Basic grid	District	Canton	Province	AEZ[1]
Costa Rica	Annuals	0.72	0.71	0.73	0.80	0.90
	Bananas	0.15	n.s.[2]	n.s.	n.s.	0.97
	Coffee	0.86	0.73	0.77	0.89	0.97
	Sugar cane	n.s.	n.s.	n.s.	n.s.	-0.97
	Pasture	0.80	0.80	0.78	0.92	0.99
	Natural vegetation	0.81	0.81	0.76	0.93	1.00
	Average	**0.80**	**0.76**	**0.76**	**0.89**	**0.97**
Honduras	Annuals	0.69	0.72	0.74	0.80	1.00
	Bananas	n.s.	0.35	n.s.	n.s.	0.87
	Coffee	n.s.	n.s.	n.s.	n.s.	0.91
	Sugar cane	n.s.	n.s.	n.s.	n.s.	n.s.
	Pasture	0.57	0.59	0.60	0.73	1.00
	Natural vegetation	0.59	0.62	0.64	0.73	1.00
	Average	**0.62**	**0.64**	**0.66**	**0.75**	**1.00**

[1] agroecological zone
[2] not significant

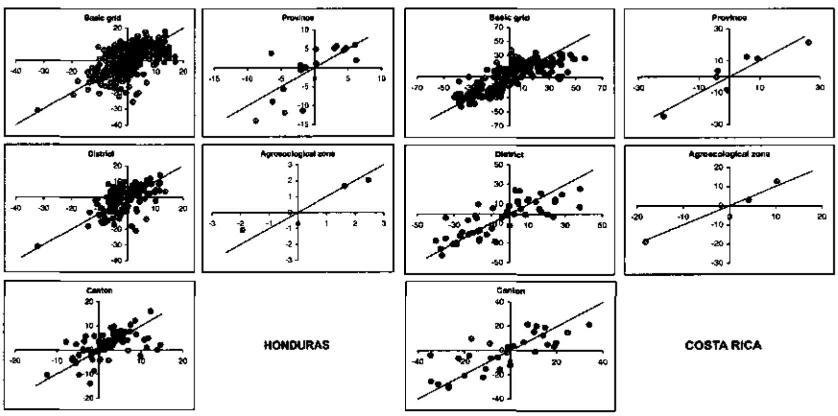

Figure 6.5. Relation between actual (X-axis) and modelled (Y-axis) changes in pasture area (ha) for five resolutions. Lines indicate the hypothetical 1:1 relationship.

significance generally decreases at the two coarsest resolutions although the *r* further increases, which is due to the low number of observations.

Important observation are:

- For most land use types, *r*-values are high (Table 6.4). At the basic grid level, the average *r* for the largest four land use types is 0.80 for Costa Rica and 0.62 for Honduras. A consistent and highly significant relation between actual and modelled changes exists at all levels of resolution.
- The model performance is better for Costa Rica than for Honduras. Especially changes in area of natural vegetation (0.81 versus 0.59 at the basic grid level),

pasture (0.80 versus 0.57) and coffee plantations (no significant correlation in Honduras) are better modelled. From Figure 6.5 it can be concluded that for pasture neither high correlations nor differences between both countries are caused by outliers or lack of normal distribution. Graphs for natural vegetation and annuals support the conclusion. The fact that the allocation module is calibrated using the Costa Rican data set, is a probable cause of the better model performance.

- The correlation between actual and modelled changes almost invariably increases with spatial resolution, which can be partly attributed to the loss of variance at coarser resolutions.
- The relation between loss of resolution and gain of model performance is exponential rather than linear. Reducing resolution from the basic grid to the canton level, thus reducing the number of observations to roughly 20%, has no beneficial effects on the r. A substantial gain in explanatory power is obtained when aggregating to the province level or AEZ level. All relationships approach the perfect fit at the agroecological zone level ($r = 1.0$ in Table 6.4), which is partly caused by the fact that national quantities are set to be correct.
- The performance of the model when addressing the permanent crops is poor. Often the r is not significant, and even negative values (sugar cane in Costa Rica) occur. Changes in banana and coffee area, on the other hand, can be successfully modelled when aggregated to AEZ level.

Table 6.5. Slopes of regression lines significantly different from zero ($P < 0.01$) of relation between actual and modelled land use distribution for six land use types and five resolutions for Costa Rica and Honduras. T-tests were not performed at AEZ level.

Country	Land use type	Data resolution				
		Basic grid	District	Canton	Province	AEZ[1]
Costa Rica	Annuals	[#]0.51	[#]0.55	[#]0.54	[#]0.63	0.71
	Bananas	[#]0.32	n.s.[2]	n.s.	n.s.	0.64
	Coffee	[#]0.81	[#]0.67	[#]0.67	[#]0.64	0.73
	Sugar cane	n.s.	n.s.	n.s.	n.s.	0.81
	Pasture	[#]0.64	[#]0.67	0.67	0.96	0.99
	Natural vegetation	[#]0.72	[#]0.65	0.64	0.87	0.91
Honduras	Annuals	[#]0.70	[#]0.71	0.70	1.03	1.04
	Bananas	n.s.	[#]0.55	n.s.	n.s.	0.72
	Coffee	n.s.	n.s.	n.s.	n.s.	0.55
	Sugar cane	n.s.	n.s.	n.s.	n.s.	n.s.
	Pasture	[#]0.66	0.73	0.56	1.08	1.10
	Natural vegetation	[#]0.68	0.80	0.59	0.99	1.05

[1] agroecological zone
[2] not significantly different from zero
[#] significantly lower than one

Regression coefficients

The slope of the best possible linear relation (β_b) of the majority of the regressions differs significantly from zero ($P < 0.01$). Results are given in Table 6.5. The minimum value for the individual models is 0.32 (bananas at basic grid in Costa Rica); the maximum value is 1.10 (pasture at AEZ level in Honduras). The test whether the β_b differed from the ideal value of one, however, results in many significantly lower values. In Figure 6.6, the development of β_b is depicted for averages of the most important land use types. It shows the clearly exponential improvement of the β_b's. The model systematically, and over all scales, underestimates sometimes locally severe land use changes as they occurred, particularly in Costa Rica. Nevertheless, model performance again improves when resolution is reduced. Similar to the changes in *r*, the improvement becomes substantial at the coarsest resolutions and is mostly exponential.

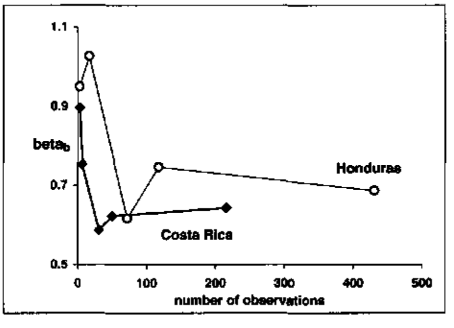

Figure 6.6. Slope of the best possible linear relationship between actual and modelled changes at five resolutions (β_b), indicated by the number of observations, for Costa Rica and Honduras. Values are averages for annuals, pasture, natural vegetation and coffee.

6.3.3 Temporal dynamics

In Figure 6.7, temporal changes of two typical cases are presented; pasture in Costa Rica and bananas in Honduras. Depicted are the percentage of cells that decrease or increase (stable when change < 0.10%), and the average change of those groups of cells. Temporal changes within a cell are highly non-linear. Pasture in Costa Rica represents a typical example of the functioning of the three large land use types: annuals, pasture, and natural vegetation. In the first couple of years, annual changes are highly dynamic (top left Figure 6.7). About 50% of the cells show a decreasing cover, the other 50% increase, and the average change (Figure 6.7, top right) is almost 5% $cell^{-1}$ yr^{-1}. After about six to eight years, the number of cells that stabilise their cover increases rapidly and the average change reduces sharply. During the last years, stability is reached in more than 75% of the cells, and the average change is smaller than 0.5% yr^{-1}. Bananas in Honduras represent a typical case of the three minor land use types in terms of area, and display a different pattern of change. Both the percentage of cells that change (about 50%) and the magnitude of change (less than 0.5% yr^{-1}) are far below the numbers for the large land use types. Given the large number of cells without banana cover and small total area coverage, this is to be expected. Again, changes in the first years are highly dynamic, but unlike the large land use types, an initial diminishing change is followed by a second period of

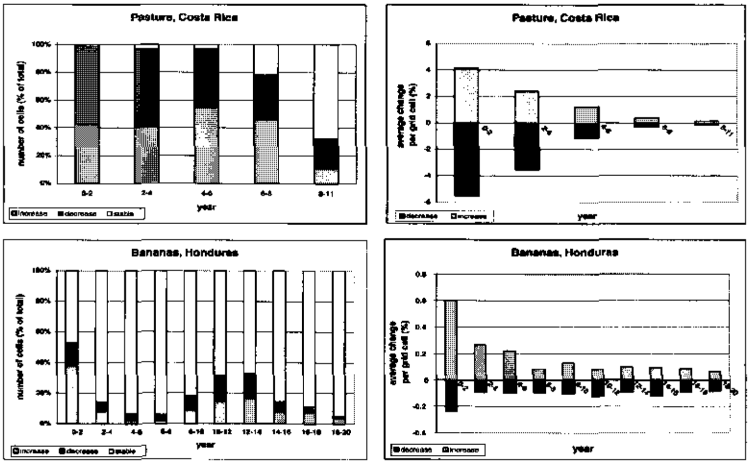

Figure 6.7. Temporal characteristics of changes in pasture area in Costa Rica (top) and bananas in Honduras (bottom). On the left-hand side, the percentage cells that is classified stable, increasing or decreasing over time is depicted. On the right-hand side, the average change in area (% of a cell) for cells classified as decreasing or increasing is given. Every column represents the average dynamics of a two-year period.

enhanced dynamics. Usually dynamics decrease again towards the final year of the simulation.

6.3.4 Comparison with input data

The results for the multiple regression analyses of 1993 for Honduras and 1984 for Costa Rica are given in Table 6.6. From the statistical analysis it was concluded that neither the explaining factors nor the goodness-of-fit change significantly over time (see Chapter 4). The validation results are therefore compared with the most recent and complete data set available and not with the input data of the model. The values in Table 6.6 can be compared with the *r*'s in Table 6.4. The data at the basic grid (15 × 15 km) can be compared directly; the coarser scale of Table 6.6 (75 × 75 km) is best compared with the validation results at the province level, which has approximately the same number of observations. Results vary between land use type, country, and resolution. The overall model performance for Costa Rica is better than could be expected based on the statistical relations. For Honduras, where the statistical relations are very strong, the opposite holds. At the coarser resolution the *r*'s of the statistical models are invariably higher. When examining individual land use types, the same division into two groups surfaces. The distribution of permanent crops, which gives the poorest results in the validation, also gives the lowest values of *r* of the statistical models. The difference between large covering land uses and permanent crops is far less in the statistical relations than after the model runs. It is thus possible to explain reasonably well the static distribution of permanent crops, but it is difficult to subsequently use these relationships to model changes over time. For large

Table 6.6. Correlation coefficients between land use distribution as calculated by multiple regression techniques and actual land use area for six land use types at two spatial resolutions.

Land use type	Costa Rica (1984)		Honduras (1993)	
	15 × 15 km	75 × 75 km	15 × 15 km	75 × 75 km
Number of observations	216	10	431	22
Annuals	0.58	0.80	0.89	0.98
Bananas	0.72	0.77	0.71	0.95
Coffee	0.88	0.94	0.63	0.92
Sugar cane	0.53	0.62	0.51	0.80
Pasture	0.51	0.79	0.78	0.96
Natural vegetation	0.60	0.90	0.87	0.99
Average[1]	**0.64**	**0.86**	**0.79**	**0.96**

[1] includes natural vegetation, pasture, annuals, and coffee

covering land uses, CLUE-CA in some cases performs better than was expected based on the multiple regression analyses. Especially the allocation of pasture and natural vegetation in Costa Rica during validation runs is more successful than the pattern description (0.60 and 0.51 as compared to 0.80 and 0.81 for natural vegetation and pasture at the basic grid respectively).

6.4 Discussion

The sensitivity analysis includes two key parameters of the CLUE allocation procedure, that both regulate the influence of the coarse resolution on the fine resolution in the CLUE allocation module. The model proves to be especially sensitive to changes in AUTODEV, the parameter that controls the influence of autonomous development at grid cell level as compared to national demand changes. Model performance for Costa Rica increases when using relatively high values of AUTODEV, leading to a large influence of local dynamics. This finding is in accordance with the highly dynamic local changes as they took place in Costa Rica in the 1970s and 1980s. With a single model parameter, slow and steady changes governed by national demand fluctuations, as well as dynamic local changes are simulated.

The most important changes in land use are captured for both Honduras and Costa Rica, two countries in which similar processes but with a different intensity took place. The overall model performance is slightly better for Costa Rica, for which the model is calibrated. Particularly good results are obtained for annuals, pasture and natural vegetation. It is especially noteworthy that CLUE is able to reproduce the large-scale forest regrowth in the southwestern part of Costa Rica, although the net process between 1973 and 1984 was one of deforestation. It proves that the CLUE modelling framework successfully synthesises interacting local and regional processes.

The scale of validation strongly influences the conclusions that can be drawn. Correlation coefficients and regression coefficients change exponentially with spatial resolution. When reducing resolution, the regression line rapidly approaches the 1:1 line and the correlation coefficient approaches one. For both countries, the model performance is nearly perfect when results are aggregated to the level of agroecological zones. The underestimation of the β_b's indicates that the CLUE allocation module tends to smooth the results too much, but the rapid increase at high aggregation levels strongly suggests that modelled changes are in the vicinity of actual changes. Additional proof is found in the visual comparison (Figure 6.4), where *e.g.* the allocation of annuals is modelled in generally the correct area. To combine resolution and validity in an optimal way, it seems best to perform validation at least at two scales: the scale of analysis (high resolution) and a very high aggregation level (high validity).

The validation described in this paper concerns only land use patterns and does not include an analysis on varying quantities at national level. Because those quantities are assumed correct, regression lines will by definition be perfect at the national level. The fact that lines approach the 1:1 line at the AEZ level can partly be attributed to the fact that quantities are fixed. The exponential rather than linear curve when scaling up cannot be explained by this 'cheating on quantities'.

Changes in land use types that are omnipresent or that do not change abruptly are reproduced successfully. Much less satisfying results are obtained for permanent crops, that are cultivated on highly clustered, large plantations. An exception is the cultivation of coffee in Costa Rica, which is controlled by smallholders in small corporations, and which is reflected in better validation results (Table 6.4). The apparent problem with smaller land use types can be partly explained by examining the temporal dynamics. The competitive power of large land use types is relatively high (see Figure 6.7). The initially high dynamics indicate that unfavourable conditions are abandoned and favourable cells occupied. After the new situation is established, those large covering land use types do not further change their distribution. The second peak in the temporal dynamics of the smaller land use types can be explained by assuming that those land use types have greater difficulties to occupy favourable locations. The manner in which competition is incorporated in CLUE might overrate the competitive power of the large land use types. The spatially explicit addition of economic variables, like price of labour, or location of processing plants, could account for the economic strength of bananas, coffee, and to a lesser extent of sugar cane. This conclusion is confirmed by the analysis of differences between the statistical analysis (Table 6.6) and validation results (Table 6.4), that shows that correlation coefficients of at least 0.50 for permanent crops in multiple regression equations often do not result in a significant models during validation.

CLUE was validated for three additional cases at various scales: the island Java (basic grid: 20 × 20 km; Verburg *et al.*, 1999b), the country Ecuador (10 ×10 km; De Koning *et al.*, 1998) and the Atlantic Zone of Costa Rica (2 × 2 km; Kok and Veldkamp, 2000). However, those studies did not separate calibration and validation, nor did they include a systematic evaluation of the multi-scale validation results. Moreover, except for the Java case none were based on two equally detailed independent data sets. Nevertheless, findings serve to confirm the results of this paper. De Koning *et al.* (1998) presented *r*'s between 0.66 and 0.92 for changes in the area of annuals, pasture and permanent crops for the canton (n=162) and province (n=19) aggregation levels, with a significant increase from canton to province level. The high values for the lumped class of permanent crops (> 0.65) indicate that grouping of bananas, coffee, and sugar cane can improve the results of this study. Verburg *et al.* (1999b) aggregated their validation for Java to three levels, obtaining stable figures from the basic grid level (n=329, *r* between 0.20 and 0.60) to a coarser scale (n=97, *r* between 0.22 and 0.66) and a dramatic increase going to agroecological zones (n=4, $r = 0.93$). Model validation for the Atlantic Zone of Costa Rica (Kok and Veldkamp, 2000) yielded similar successes for pasture and forest ($r = 0.90$), but faced similar problems for bananas ($r = 0.74$; but $\beta_b = 0.38$). This growing body of evidence demonstrates the value of the CLUE modelling framework in the field of spatial explicit land use change modelling.

6.5 Conclusions

- Calibration of the CLUE allocation module reveals a strong influence of the parameter that controls the influence of autonomous development at the finest resolution, with improving results when the influence of autonomous development is large.
- The CLUE allocation module is successfully validated over a time period of at least a decade for Costa Rica and Honduras. Validation of omnipresent land uses like natural vegetation and pasture is more successful than the validation of spatially more clustered land uses like bananas and coffee.
- The multi-resolution validation indicates that the increase of predictive power with a lessening spatial resolution is strongly exponential.
- The various studies on the validity of the CLUE modelling framework in Latin America and Asia demonstrate the ability of the model to handle very distinct land use change processes.

CHAPTER 7[#]

The spatial scale effect in land use modelling: problems and solutions

Abstract

Land use research is becoming increasingly important, because of the increased influence of humans on the earth's system. Recently, focus has shifted towards spatially explicit modelling, catalysed by an interest in the effects of land use (change). Issues like biodiversity and particularly carbon sequestration in vegetation and soil call for spatial explicitness. These types of land use models entail new problems, of which the so-called 'scale effect' is the most intriguing. Despite the theoretical and often documented awareness on the possible influence of spatial scale on model assumptions and results, few structural quantifications exist. An exception is the CLUE (Conversion of Land Use and its Effects) modelling framework, which is used to demonstrate how a multi-scale model can function. On the basis of four modelling phases as recognised in the modelling framework, the influence of the spatial extent and resolution is analysed. During the establishment of relationships between land use and their spatial determinants, choice of both resolution and extent strongly and sometimes counterintuitively influences results. Relationships should therefore be determined empirically. During the model building phase, again both aspects of spatial scale are influential. CLUE incorporates multiple scales, whose influences are dynamically altered during the modelling process. Model validation incorporates multiple resolutions, to determine the relation between gain of validity and loss of spatial detail. Finally, the spatial extent at which resulting maps are presented influences the conclusions that can be drawn. The CLUE modelling framework attempts to resolve all abovementioned spatial scale dependencies. It can serve as a prototype for a future generation of more evolved multi-scale land use models.

7.1 Introduction

7.1.1 The role of land use research

In recent years, land use (change) research has taken a pivotal position within earth sciences (Turner *et al.*, 1995) and beyond. Human alteration of regional and global (eco)systems is substantial through a rapidly growing human population and technological progress (Vitousek *et al.*, 1997). This growing influence of the human factor has boosted research of human-influenced systems, and above all, of the land use system. The initialisation of the Land Use and Cover Change (LUCC) program of

[#] Based on: Kok, K. *et al.*, in prep. The spatial scale effect in land use modelling: problems and solutions. To be submitted to Global Environmental Change.

IGBP and HDP (Turner *et al.*, 1995) further stimulated land use research. Within the community, a marked shift towards spatially explicit modelling has occurred (Gustafson, 1998), driven by the widespread belief in the necessity of a spatial component in land use models (Nunes and Augé, 1999). A large body of evidence has emerged that demonstrates the additional value of spatial models of land use (see *e.g.* Bockstael, 1996; Lambin *et al.*, in press).

In spite of the growing importance of the land use system as such, it were particularly the manifold *effects* of land use change that intensified the interest for spatially explicit models. Besides traditional issues like (loss of) biodiversity (see Chapin *et al.*, 2000; Sala *et al.*, 2000; Qian and Ricklefs, 2000 for recent contributions), or land degradation (*e.g.* De Koning *et al.*, 1997) an important role was earmarked for the issue of global change, particularly since the Kyoto protocol in 1997 (see Parry *et al.*, 1998; Tangen, 1999). Questions concerning the carbon sink and the possibilities of carbon sequestration can only be fully understood with the use of spatially explicit land use models. Some have emphasised the importance of location-specific land use history when modelling nutrient cycles (Veldkamp, 1993; Keller *et al.*, 1994). Others have stressed the high dynamics of forest patterns (*e.g.*, Brown *et al.*, 1999) and forest regeneration (Hughes *et al.*, 2000), which need to be understood and modelled to analyse standing biomass. Moreover, recent literature indicates strong links between vegetation and soil in the Brazilian Amazon (Fearnside and Imbrozio, 1998; Laurance *et al.*, 1999), which accentuates the need for spatial explicitness.

7.1.2 Theoretical background

Spatially explicit models engender a new set of problems that need to be solved. The land use system, however, has emerged relatively recently as a scientific research topic (Loucks, 1977). Azzi (1956) and Tischler (1965) first introduced the concept of the agro-ecosystem, but not before the 1980s (Conway, 1987) system's theory was it applied systematically. Because of this lack of history, ecosystem theory is often used to describe the land use system. Although different in some essential aspects (Conway, 1987), both the ecosystem and land use system are highly complex (Allen and Hoekstra, 1990; Jørgensen, 1994; Turner *et al.*, 1995; Gibson *et al.*, 2000). The notion of complexity has consequences for the manner in which the system should be described (Kolasa, 1989). Of those, the focus here is on the so-called 'scale effect', which relates to the observation that relationships and apparent processes change with the temporal and spatial scale of analysis.

The existence of the scale effect has been exhaustively elaborated upon, especially by landscape ecologists. In the early 1980s (Allen and Starr, 1982) the hierarchy theory, stating that within an ecosystem multiple hierarchical level of organisation exist, was first conceptualised. Processes at coarse levels are too large and too slow to be seen at the level of observation, while processes at more detailed levels are too small and too fast to appear as anything but background noise (Reynolds *et al.*, 1993). Since, the theory has been paraphrased (*e.g.* O'Neill, 1986; Allen and Hoekstra, 1992) and applied (Dutilleul, 1998; Saunders *et al.*, 1998; Gibson *et al.*, 2000), and scale has rapidly become "a new ecological buzzword" (Wiens, 1989). Finding ways to translate information among scales is one of the fundamental challenges faced by researchers in land use analysis (Levin, 1993). An important related aspect is that of emergent properties (Miller, 1975), where effects of lower level processes have a proximate effect at the level of observation. In order to account for the existence of multiple levels of organisation, it is essential to model land use at multiple scales, *i.e.* at multiple levels of observation (Veldkamp and Fresco, 1997, De Koning *et al.*, 1999).

7.1.3 Multi-scale models

Despite the unabated flow of literature on scaling theories and concepts (see Gibson *et al.*, 2000), there is a remarkable lack of models that attempt to incorporate multiple scales in order to systematically deal with the scale effect, either in ecology or in land use research. Particularly in landscape ecology the call for multi-scale applications is noticeable (Peterson and Parker, 1998; Stafford Smith, 2000). Cellular automata (Baltzer *et al.*, 1998) and agent-based modelling are good examples of attempts to account for the scale effect. Both methodologies appear to be appealing solutions to the problem, but so far both have failed to dynamically deal with cross-scale interactions and offer little possibilities to regulate the effects of one scale on another. The CLUE modelling framework (Veldkamp and Fresco, 1996b, De Koning *et al.*, 1999; Verburg *et al.*, 1999a) is in many ways the only land use model that offers a framework that can be used over a range of scales and that dynamically accounts for scale dependencies and cross-scale interactions. Within the framework, the focus is on two aspects of spatial scale, *extent* (total area coverage) and *resolution* (size of smallest analysis unit). Although spatial extent and resolution are not completely independent for practical reasons, the effect on conclusions of an analysis can be different. A coarser resolution will reduce heterogeneity, while a larger extent will include more processes related to land use and land use change, and previously important processes may lose significance (King, 1991).

7.1.4 Objectives

The objective of this chapter is to demonstrate the strong influence of spatial scale dependencies and the necessity of using a multi-scale model when analysing the land use system in a spatially explicit way, using the CLUE modelling framework as an example. The paper is structured around the various modelling steps in the CLUE framework.

7.1.5 Modelling phases in CLUE

In the application of the CLUE modelling framework to Central America, four modelling phases can be discerned that will be used to categorise the influence of spatial scale on land use analysis:

1. Data handling and system description
2. Modelling structure and modelling procedure
3. Model validation
4. Presentation

In the subsequent sections, spatial scale issues in the various phases are elaborated. Most of what is concluded is valid only for the range of spatial scales for which the CLUE model has been executed. CLUE applications using spatial scales of the same order of magnitude but for other geographical regions, however, arrived at similar findings (see De Koning *et al.*, 1999; Verburg *et al.*, 1999b; Verburg and Chen, 2001). Table 7.1 lists the scale-related characteristics of four hierarchically nested case studies in Central America, of which all examples given in this paper are drawn. The data set is the result of the efforts of a variety of institutes and universities (see Stoorvogel and Eppink, 1995; CIAT, 1998; CIAT, 2000) and took almost a decade to complete. It is the best data set available and most likely to date the only consistent multi-scale data set in existence for Central America as a whole. The range of scales in Table 7.1 indicates that the focus of the model is between the landscape or village level and the supra-national level.

Table 7.1. Temporal and spatial scale characteristics of CLUE case studies in Central America.

spatial extent	spatial resolution (km)			temporal extent		temporal
	min.	optimal	max.	start	end	resolution (year)
Atlantic Zone	2	7.5	7.5	1984	2005	1
Costa Rica	7.5	30	45	1984	2005	1
Honduras	7.5	37.5	45	1993	2005	1
Central America	15	75	75	1996	2010	1

7.2 Scale and system description

With a decreasing resolution and increasing extent, the structure of the land use system becomes more complex, while the degree of randomness increases. Following Easterling (2000), it is argued that the system becomes too complex for analytical solution at those coarser scales, which necessarily calls for an empirical solution. All too often, before the analysis, a hypothetical model is established, in which certain groups of factors are said to influence land use (patterns) at a certain scale (*e.g.*, Turner *et al.*, 1995, p. 32, 33; Innes, 1998, p. 434). Those *a priori* assumptions are mostly based either on local case studies or on intuition and are applied at a coarser scale without the required analysis of scale sensitivity (see Rastetter *et al.*, 1992; Easterling, 1997). The following predetermination is often used: Soil factors are said to be important at the local level, demographic factors at some intermediate level, and climatic factors at more regional levels. This hypothesis is challenged by the results established within the CLUE framework. Table 7.2 lists the three main determinants of the spatial distribution of cultivated grasslands and annuals over a range of extents

Table 7.2. Three most important variables and their sign in multiple regression equations at various spatial extents and resolutions for the distribution of pasture and annuals in Central America. Boxes indicate the hypothetical relationship between factor importance and scale as often assumed in literature.

Pasture

Spatial extent	Atlantic zone of Costa Rica			Costa Rica			Central America	
Spatial resolution (km)	2	3.7	7.5	7.5	15	75	15	75
favourable soil conditions		1–	3–	2+	1+	3–	2+	1+
well drained					3+		3–	3–
slope steepness								
rural population density								
urban population density	1+	3–						
access to market/port	3–				2–	1–	1–	
altitude			1–	3–				
precipitation/number of wet months	2–	2–	2–	1+		2+		2+

Annuals

Spatial extent	Atlantic zone of Costa Rica			Costa Rica			Central America	
Spatial resolution (km)	2	3.7	7.5	7.5	15	75	15	75
favourable soil conditions	3+		3–		2–	2–	3+	3+
well drained	2+	1+			3+			
slope steepness	1–	2–	2–					
rural population density				3+			2+	
urban population density				2–				
access to market/port						3–		
altitude			1–	1+				2+
precipitation/number of wet months		3–			1+	1+	1+	1+

and resolutions, based on multiple regression techniques. For details on the followed methodology, and discussion of individual cases, we refer to Kok and Veldkamp (2000) for the Atlantic Zone of Costa Rica, Veldkamp and Fresco (1997) for Costa Rica, and Kok and Veldkamp (2001) for the whole of Central America. The distribution of annuals is indeed determined by soil factors at the most detailed spatial scales and by climatic factors at the scale of Central America. The distribution of pasture, on the other hand, cannot be explained by soil variability at the local scale, while soil factors are among the most important determinants at the supra-national extent. The influence of human factors is weak, despite the importance that population pressure is normally given at coarser scales, when explaining the forest to pasture conversion in Latin America (Cuffaro, 1997; Tilman, 1999). Besides, factor loadings and sometimes even their sign change with resolution and extent, for both land use types. The results presented here are partly counterintuitive and make it dangerous if not impossible, to determine beforehand which of the large group of potential factors influence land use and in which way. The intuitive perception of the scale at which variable groups surface does not always tally with the empirical results, and should therefore not guide the decision to exclude or include factors from the variable selection procedure. Before in-depth knowledge is gathered from a variety of disciplines, an empirical determination of relationships between land use and their spatial determinants, however unsatisfactory, should be preferred.

7.3 Scale and model structure

Quantification of scale dependencies in the description of the land use system has to be followed by the dynamic incorporation of the findings in a land use model. Nevertheless, many studies have employed methodologies similar to multiple regression techniques to empirically demonstrate the influence of spatial resolution (*e.g.* Malingreau and Belward, 1992; Walsh *et al.*, 1997; Walsh *et al.*, 1999) but besides the CLUE modelling framework, few have used those results to model land use change. Other applications of multiple regression techniques are mostly based on logistic regression and use satellite images as data source (*e.g.*, Schneider and Pontius, 2001; Serneels and Lambin, 2001). As explained in Chapter 1, CLUE uses temporally detailed data without a spatial component that offer the possibility to incorporate short-term fluctuations *e.g.* in macro-economic developments. These data are then combined with spatially detailed data on a multitude of socio-economic and biogeophysical factors that determine the spatial pattern of land use change. Thus, the model dynamically combines information from various scales, with a focus on economic development at national scale and environmental and demographic variables on the spatially explicit scales. An illustrative example is the cultivation of bananas in Costa Rica. Total demand for Latin American bananas in the 1990s was influenced heavily by a dispute, ultimately settled by the WTO, between several Latin American countries and the EU that tried to stimulate banana production in former colonies (McQueen, 1998; Raynolds and Murray, 1998). Within Costa Rica, banana production is concentrated in the Atlantic Zone, as the distance to both the US and the European market is shorter than on the Pacific side. Location of banana plantations within the Atlantic Zone is related to the presence of highly fertile soils, flat areas, and a low flooding risk (Kok and Veldkamp, 2000). Similar shifts in dominant processes with scale of observation can be established for all other types of land use in Central America (Kok and Veldkamp 2001; Kok and Winograd, subm.). Restriction to either a single discipline or a single scale eliminates the possibility to dynamically account for scale dependencies and is therefore likely to impoverish model results.

7.3.1 Model results

Figure 7.1 exemplifies the added value of the CLUE modelling framework. The bottom part shows modelled hot-spots of deforestation and reforestation between 1996 and 2010 under two scenarios, protection of parks (bottom left) and the strike of a major hurricane (bottom right), which resembles hurricane Mitch that struck Central America in 1998. Total protection of national parks prevents deforestation within them, which would normally have taken place. Land squatters are forced to cultivate crops and pasture elsewhere. New hot-spots of deforestation therefore emerge in forested areas outside the parks, predominantly in Costa Rica and Nicaragua. Deforestation has shifted but not lessened. The scenario demonstrates how the CLUE modelling framework deals with interconnectivity between cells and scales, and how actions taken at one location (protection of parks) trigger reactions at other locations. In the second scenario, spatially explicit changes are coupled with changes at

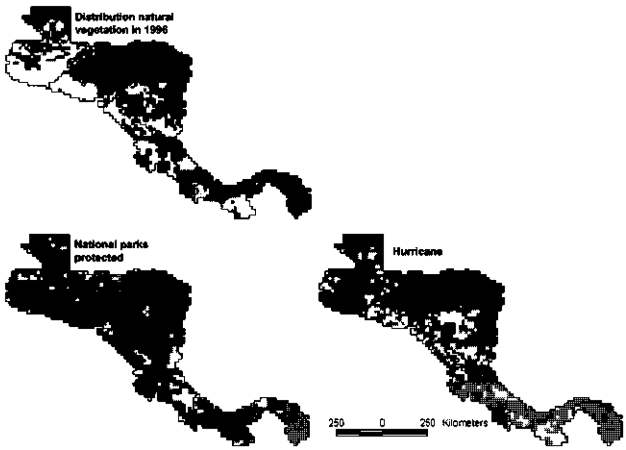

Figure 7.1. Example of spatially explicit hot-spots of deforestation and reforestation in Central America under different scenarios, between 1996 and 2010, using a resolution of 15 × 15 km. Top left: darker grey tones indicate a higher cover percentage. Bottom: (very) Dark grey tones indicate a (strong) decrease in forest cover, light tones an increase; changes in medium grey areas are small.

(inter)national level. The impact of a hurricane temporarily excludes areas from production, but at the same time causes an economic depression. A detailed description of the assumptions of this scenario is given in Chapter 5. Overall, the assumed lower income results in a lower demand for beef and thus agricultural area, which results in clear hot-spots of forest regrowth in Nicaragua and Panama. Note that for some countries the patterns of deforestation are very similar in both scenarios. The scenario shows that CLUE can combine strong local preferences as they apparently exist in Guatemala and to a lesser extent in Costa Rica with a strong influence of coarser levels, as is apparently the case in Panama and Nicaragua. Both examples demonstrate the distinct influence of various spatial scales on patterns of land use change. The national level stands out as indispensable organisational level to incorporate in the model, besides at least one spatially explicit scale.

7.4 Scale and validation

Most modellers do not claim that their models are valid at the scale of analysis (Jansen, 1998) and the results of a multi-scale model can therefore potentially be mis-used if not coupled with a multi-scale validation. Yet, examples of such validations are few (Costanza, 1989; Pontius *et al.*, 2001). A multi-scale validation, using a fairly straightforward method that systematically aggregates data from the basic grid level to various coarser resolutions was performed for various Central American applications of CLUE. The validity at the basic grid and the –strongly increasing– model performance at coarser scales are elaborated upon in Chapter 6 (see Kok *et al.*, 2001). Aggregation to agro-ecological zones resulted in a close to perfect model

Figure 7.2. Multi-resolution and multi-extent distribution of natural vegetation in 1996 (top) and hot-spots of change between 1996 and 2010 in the distribution of pasture (bottom). Grid sizes are 15 km for Central America, 7.5 km for Costa Rica, and 2 km for the Atlantic Zone. Top: light shades indicate a low cover percentage; dark shades a high cover percentage. Bottom: White indicates a decreasing cover, (very) dark shades a (strong) increase; medium shades indicate areas without significant changes.

performance. The relationship between loss of spatial explicitness and gain of explanatory power proved to be highly non-linear. More similar validations are needed to test the robustness of this statement. The method applied within the CLUE modelling framework quantifies the scale-dependency of model validity. The multi-scale validation simultaneously provides a tool to serve both the scientific community by quantifying the relationship between model performance and spatial resolution and the model users by addressing model validity at any desirable level, like watersheds or planning regions as present in Costa Rica.

7.5 Scale and presentation

An underrated phase in the modelling sequence is the influence of how results are presented. Even when a multi-scale methodology is employed, the focus when presenting results is often on the most detailed resolution (here: Atlantic Zone of Costa Rica) and at the largest extent, as this provides most detailed results for the largest area. Particularly the information from coarser scales that was used in the modelling process is not provided. Figure 7.2 demonstrates how results from a multi-scale model should ideally be generated and subsequently presented. It displays the spatially explicit input data for natural vegetation, and output in the form of hot-spots of change for pasture. Maps were obtained from separate model runs for the Atlantic Zone of Costa Rica, Costa Rica, and Central America, using a similar base scenario. In the top part the effect of input resolution and extent on *input data* can be clearly observed. At the Central American level, areas of forest are present in the south of Panama and Honduras and Nicaragua share a large continuous area of tropical rainforest. Costa Rica has relatively little forested areas. When zooming in to Costa Rica, relatively small areas of forest become apparent, among others in the most northern part of the Atlantic Zone. When scaling down to that region, the existence of a previously invisible small strip of natural vegetation along the coast is revealed. These scale-dependent differences in input data, combined with the multi-scale model structure, have great impact on model outputs, as visualised in the bottom part of Figure 7.2. Hot-spots of increase of pasture, mainly as a result of deforestation, differ with resolution and extent. A more challenging conclusion is that 'cool-spots', *i.e.* areas without apparent changes, at a coarse scale can contain hot-spots at a more detailed scale. That is, one can assume that changes in hot-spot areas are generally stronger, but the reverse conclusion that no changes take place in the cool-spots cannot be drawn, as there might be 'hidden' hot-spots that are only revealed at more detailed scales. Combining spatially explicit information from various scales in one analysis can provide powerful insights in the functioning of the land use system and the spatial scale at which land use dynamics are revealed.

Table 7.3. Importance of spatial scale aspects in various phases of the modelling process.

Step in modelling process	Importance of spatial scale	
	resolution	extent
System description	++	+
Model structure	++	++
Model validation	+	0
Presentation	+	++

7.6 Discussion and conclusions

During all model phases as present in the CLUE modelling framework, spatial resolution and spatial extent influence the outcome. The effect of both aspects of spatial scale, however, varies as indicated in Table 7.3. Spatial resolution is particularly influential during the system description and model building phases. The CLUE methodology has provided strong indications that when complex systems are studied at coarser scales (*i.e.*, an area larger than a village), a multi-scale analysis to check for non-linearities and scale dependencies should be included. During model building and execution, the spatial extent also strongly influences the results. In Chapter 4, it is argued that the effect of spatial extent is underestimated and should receive more attention. Particularly global modellers should be aware that using regions larger than a country produces questionable results. Model validation is especially sensitive to changes in resolution. The improvement of results with lessening spatial resolution is a well-recognised fact, but more multi-scale validations as executed within the CLUE modelling framework are needed. Finally, the presentation of the results is more sensitive to the spatial extent. Given the complex nature of the land use system, linking up of a series of nested case studies at different spatial scales, but all executed with the same modelling framework, seems the best way to counteract scale sensitivities during the presentation phase.

The CLUE modelling framework provides a land use model that:

- systematically analyses the effects of spatial scale on input relationships
- dynamically incorporates multiple spatial scales during model execution
- systematically analyses the effect of spatial scale on model results
- is constructed such that it can be applied at a range of spatial scales.

Wilbanks (2000) noted that a full-fledged multi-scale methodology would be difficult to capture in formal modelling logic and difficult to replicate precisely, but that it is both intuitively and intellectually attractive. The CLUE modelling framework can be considered a first attempt to establish such a methodology. It could act as a prototype for a future generation of multi-scale land use models.

CHAPTER 8
General discussion and conclusions

The case studies in Central America were chosen such that the range of scales included was maximised, given the restrictions of data availability and data resolution. Spatial resolution ranged from 2 × 2 km for the Atlantic Zone of Costa Rica to 75 × 75 km for Central America, a range of almost 1500 ($75^2/2^2$) in terms of surface area. Spatial extent varied a factor 1000, between 5,000 km^2 and 500,000 km^2. Potential driving factors, spatial resolutions, scenarios, and model settings were all chosen as similar as possible. A comparison over the range of (spatial) scales considered is thus enabled and justified.

8.1 The failure of an 'a priori' hypothetical model

In Chapter 7, it is argued that if a system becomes too complex to describe analytically, an empirical solution has to be sought necessarily (Easterling, 2000). It is concluded that especially in the case of pasture, spatial determinants of land use change can be counterintuitive and can contradict prevailing hypotheses on causes of land use change (see Table 7.2). This chapter evaluates examples from previous chapters dealing with empirical land use analysis (Chapter 2- 4) where resulting spatial determinants of land use did not tally with intuitive ideas. In this way the plea for empirical methodologies is substantiated:

- Atlantic Zone of Costa Rica, 2 × 2 km: Rainfall explains the distribution of natural vegetation (Table 2.5). Rainfall ranges from 3000 - 8000 mm per year (Stoorvogel and Eppink, 1995), which gives rise to the hypothesis from an agricultural viewpoint that rainfall is not an important factor, as water availability is never limited. However, the grains of annuals (beans, rice, and maize) need at least one dry month to ripen, a period that does not occur at very high levels of precipitation. Parts of the Atlantic Zone are therefore not suitable for cultivation of many crops and are still covered by forest.
- Honduras 7.5 × 7.5 km: Number of dry months and rural population density are present in the equations of most land use types (Table 3.3). The land use system in the wetter parts of the country is different from the system in the drier parts to such a degree, that any additional local variation is overruled by climatic and demographic factors, at any of the included spatial resolutions. An additional analysis in which the country was divided into three agroecological zones (unpublished data), resulted in a similar dominance of population and climate in all three zones.
- Central America 75 × 75 km: Highly fertile soils correlate with the distribution of banana plantations (Table 4.5). Within the CLUE methodology, every grid cell contains sub-grid information, which means that 'high fertility' should be read as 'a high percentage of highly fertile soils'. Thus, the significance of soil fertility at

coarser resolutions indicates that banana plantations are found in areas that generally have fertile soils, whereas the actual location might be on or *in the vicinity of* fertile soils. Apparently, banana corporations select locations that have more areas with fertile soils than those currently occupied, probably in view of (likely) future area expansion.

These examples plus other evidence gathered in Chapter 2-4 strongly suggest that the use of hypothetical models, where the possible influence of certain groups of variables is omitted beforehand, will impoverish results. When singled out and discussed, the above examples seem obvious, almost self-explanatory, and it is hard to believe that those factors would be overlooked when defining the hypothetical model. Yet, those three examples are but a very small portion of all analyses that were conducted. It would simply be too complicated to consider the response that all different factors might have on the distribution of all land use types considered, thus justifying the statement made by Easterling. At the range of spatial scales considered here, the land use system is too complex to model analytically. Empirical methodologies are always needed to generate hypotheses that can subsequently be tested with process-based models.

8.2 Organisational levels in the Central American land use system

The Hierarchy Theory assumes multiple hierarchically nested organisational levels in ecological systems (see Chapter 1). From the theory it follows directly that when sufficient scales are included in the analysis, 'natural breaks' will become apparent that indicate where distinct levels of organisation exist (see *e.g.* Goodwin and Fahrig, 1998, p. 198). Although not undisputed, even by those who proposed the theory (O'Neill and King, 1998), there is some evidence for the existence of hierarchical levels (Fresco, 1995; Wilbanks and Kates, 1999; Gibson *et al.*, 2000) in various types of systems. The results of the multi-scale statistical analyses performed for the various cases (see Chapter 2-4) need to be separated in effects from a changing spatial resolution and spatial extent. When considering a range of spatial resolutions, without changing the extent, a clear natural break occurs in none of the cases that were analysed. Coefficients of determination of multiple regression equations invariably increase gradually with decreasing resolution, and factor composition over the resolutions is mostly very stable. Yet, when comparing the whole range of resolutions over a range of extents, statistical models are far from stable, and factor composition does change abruptly. Unfortunately, it is difficult to draw the generalising conclusion that the 'resolution effect' is less important than the 'extent effect' in land use systems, although results point in that direction. Any extra enlargement of the extent, *e.g.* to Latin America at large, could include other processes that dominate at other distinct levels, thus increasing the influence of a changing resolution.

The existence of levels of organisation is neither rejected nor accepted, with one exception. In Chapter 4 it is hypothesised that the country is an important organisational level. The statistical models strongly confirm this hypothesis. The influence of national borders suggests that the search for scale dependencies should focus on administrative or political levels (planning regions, provinces) rather than on biophysically defined levels, *e.g.* agroecological zones. Although a more crop-specific selection of agroecological zones might prove otherwise, analysing as many spatial resolutions as possible to reveal natural breaks might be unnecessary. It could perhaps be replaced by an in depth analysis of existing organisations in the political and the social systems.

8.3 Scale-consistency of land use changes

An important question is whether the location of hot-spots of change, being the main output of a model run, is meaningful at other scales. Some years ago, the idea of a modelling tool-box was first proposed (see the following section), where a coarse scale model like CLUE could be used to indicate major hot-spots, which could subsequently be studied in more detail using other (types of) models. In order to be potentially possible, hot-spots derived at one particular scale have to be scale independent, at least partly. The various case studies resulted in spatially explicit maps of hot-spots of change over a range of resolutions. Figure 7.3, depicting hot-spots of change for pasture derived for the various case studies, offers some information. It shows that areas without major hot-spots of change in pasture area, like Costa Rica at the Central American level, are not necessarily without changes when zooming in. On the contrary, new, previously invisible, hot-spots emerge. To check whether hot-spots at one scale are also present at another, one has to construct a case study that zooms in on areas with specific hot-spots. Comparison of *e.g.* the hot-spots of deforestation in the southeast of Cost Rica (see Figure 5.6) coincided with hot-spots derived at the more detailed scale (unpublished results). In general, when a hot-spot was indicated at the coarser scale, it was also present at the more detailed scale. Hot-spots of change normally do not change position, but new locations emerge when modelling a detailed area. Summarising, a coarse-scale model can be used to identify the *presence* of hot-spots, but not their *absence*.

8.4 Stakeholders

So far, the scientific value of the input and output of the CLUE model has been exhaustively enlarged upon. The value of the model outside the scientific realm remains to be discussed, which has little to do with theoretical soundness, but rather deals with model applicability.

8.4.1 Other land-use modellers: Development of a tool-box

The development of the CLUE modelling framework was initiated by a demand from the global modelling community. Modellers that were developing IMAGE, a global integrated assessment model, were interested in comparing the results of their land use module with models that operated at the regional level (see Veldkamp *et al.*, 1996). The first version of CLUE was also developed to fulfil this need. The CLUE model operates at a range of intermediate scales, providing a link between global and more local models. While comparison with results of Integrated Assessment Models could help test key assumptions of those models, comparison with more detailed models could in turn improve the CLUE methodology. Eventually, a number of models could be used together in a sequence, where results of a coarse scale model can help focus other more detailed models, which can then be employed to model local processes. Construction of such a modelling tool-box will result in a highly flexible framework that can address a large range of questions over a large range of scales. The research conducted over the past 10 years in the Atlantic Zone of Costa Rica is an example of how a tool-box could be set up (see Bouman *et al.*, 2000). Although the various modelling tools were largely developed independently, modellers closely collaborated. Additionally, model types were chosen such that both a range of scales was addressed and various model scopes as listed in Chapter 1 were represented. Another example of how a modelling tool-box could function is the Strategic Cyclical Scaling method, where scale-down and scale-up approaches are cyclically applied in a strategic design (Root and Schneider, 1995; Schneider and Root, 1996). Stronger collaborations between various groups of modellers will strengthen the application possibilities inside and outside the scientific community.

8.4.2 Farmers

In its present form, the CLUE model has little use at the farm level. In view of the development of a modelling tool-box, it seems pointless to further extend a single model. However, the integration of various methodologies within one framework offers the possibility to dynamically link several scales and scopes in a much more flexible way. Probably the most valuable addition to the present CLUE version would be the farm level. It would provide the opportunity to test the robustness of the CLUE framework at a level where other spatial determinants (economic and social) are more important. Furthermore, effects of spatial resolution might become far larger when scales range from farm (a few hectares) to village (a few km^2), thus starting a search for organisational levels other than the ones mentioned in Section 8.2.

Given the present farm sizes in Central America between 1 and 10,000 ha, the most detailed resolution of the present model applications (2×2 km = 40,000 ha) will contain too many farms. CLUE, however, is constructed such that neither the application at a more detailed level, nor the replacement of statistical equations by any other kind of (process based) rules is problematic. Currently, CLUE is being applied to a small island in the Philippines at a basic resolution of 250×250 m, which approaches the farm size (Verburg *et al.*, 2000). This version uses grid cells with one dominant land use instead of percentage information and applies logistic regression techniques instead of multiple regression equations.

8.4.3 Policy makers

Policy makers at various organisational levels are a group of potential stakeholders that can be addressed with the model in its present form. In the various discussion sections in this thesis, particularly in Chapter 5 and Chapter 7, the application of the model in the political arena has been touched upon. The Natural Hazard scenario for Honduras is a clear example of which types of scenarios could be used by policy makers. As shown in Chapter 5, CLUE could be used to mimic the effects of hurricane Mitch that struck Central America in 1998. Spatially explicit data that became available shortly after the event took place enabled the evaluation of the potential short-term and long-term effects of the hurricane on Honduran land use. As it is to be expected that data availability will only increase through the use of Internet, scenarios of this type will become more and more realistic. In the same chapter, the potential effects of a natural hazard like Mitch are evaluated for the whole of Central America. CLUE incorporates actual data in order to project plausible near-future changes, which makes it an attractive tool to analyse the impact of extreme events. Economic disasters, like an international oil crisis or an economic recession, are equally possible to implement. Especially scenarios that are sensitive for changes in macroeconomic parameters enable policy makers to participate interactively. The Central America case study presented in Chapter 5 is an example of how this could function in practice. The model application was developed in the framework of a

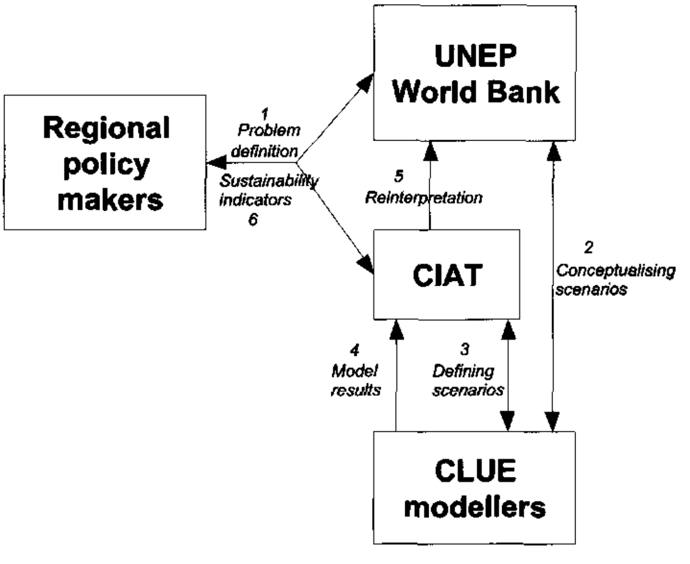

Figure 8.1. Interactions between modellers, organisations, and regional policy makers during modelling process.

project conducted by members of the GIS department of the Centro Internacional de Agricultura Tropical (CIAT, Colombia) together with members of the World Bank and United Nations Environment Programme (UNEP). This project was entitled 'Indicators of rural sustainability: An outlook for Central America', and its goal was to develop a set of rural sustainability indicators, largely based on the view of policy makers from Central American countries (Farrow and Winograd, 2001). Figure 8.1 visualises the main steps that were taken to effectuate the input of CLUE. The project started with a launch workshop at which an extensive list of indicators was put together (Step 1 in Figure 8.1). The participants included the project partners, delegates from regional organisations, as well as representatives of relevant ministries and departments from each of the six countries. The list of indicators included spatially explicit land use changes, and for several reasons (see Farrow and Winograd, 2001), the CLUE model was selected.

Scenarios were developed during a second, three-day, workshop. Participants included the partners of the project (CIAT, UNEP and the World Bank) and a CLUE representative. Thus, initially rather vague wishes ('sustainable future', 'disaster', 'most likely future') could dynamically be transformed into plausible scenarios that could be implemented in the CLUE model. Eventually a number of scenarios as described in Chapter 5 were broadly defined (Step 2). Details were discussed with the partners from CIAT in the subsequent weeks (Step 3). Spatially explicit results of various model runs were fed back to CIAT (Step 4). They then reinterpreted the resulting maps in order to fit the expectations of the World Bank and UNEP (Step 5). Instead of one map for every land use type, separate results were reclassified to create one map per scenario with production systems, like 'mixed system', 'highly altered', and 'natural'. These maps were subsequently combined with other maps. An example is given in Figure 8.2, depicting the combination of the production systems in 2010 under a sustainable scenario and a suitability map (compare *e.g.* with the six maps of

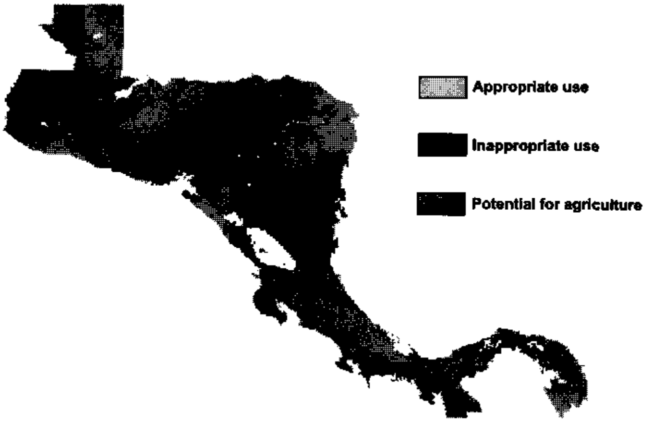

Figure 8.2. Example of use of CLUE results: Land use index map 2010 under the sustainable scenario (adapted from Figure 3, Farrow and Winograd (2001)).

Figure 5.6). During a final workshop with all project partners, the final list of rural sustainability indicators will be presented and discussed (Step 6). The collaboration was mutually beneficial and showed how a model like CLUE, designed primarily from a scientific theoretical basis and developed to fulfil scientific needs, can be used by other stakeholders. The case explained above indicates that the incorporation of a knowledge-broker, an intermediary that links the people who use knowledge and those who create it, can provide the settings for a successful communication. In this case, the intermediary between science and policy (CIAT), who understood both the scientific basics of the model and the wishes of the policy makers involved, was also a scientist. Thus, the intermediary and the modeller communicated smoothly, whereas the interaction between the policy maker and the intermediary was more difficult. Future efforts might consider the employment of a knowledge-broker that is less biased towards science, thus increasing the role of the policy maker. Eventually, this can create a mutually beneficial continuous interaction between the producers and the users of knowledge.

8.5 Conclusions

- Complex system theory, especially as developed for the ecosystem, is a good foundation when defining model architecture as well as when explaining the modelled behaviour of the land use system (Chapter 1). On the other hand, the presence of important differences (Chapter 1) could call for a separate theory for the land use system (Chapter 8).
- The land use system in Central America is functionally complex (Chapter 1), *i.e.* factors from various disciplines influence land use patterns, for each of four hierarchically nested case studies (Chapters 2, 3, and 4). Omission of *e.g.* soil-related or demographic variables from the list of potential drivers would lead to an incomplete system description.
- The land use system is not very structurally complex (Chapter 1), *i.e.* the influence of the scale effect is small. Besides the national level (Chapter 5), no important organisational levels were detected with the applied multi-scale analysis. The effects of changes in spatial resolution on the relation between land use patterns and a set of drivers were relatively small (Chapters 2, 3, and 4).
- As long as our knowledge of the highly complex land use system is incomplete, an *a priori* hypothetical model fails and needs to be replaced or preceded by an empirical methodology (Chapter 8). For the near future, only through the employment of a modelling tool-box processed-based information can be used at coarser scales (Chapter 8).
- The multi-scale analysis was successfully coupled with scenario studies in a multi-scale land use change model, the CLUE modelling framework. The spatially explicit results of various types of scenarios, including market liberalisation (Chapter 2), park protection (Chapter 2), sustainable (Chapter 5), and natural hazard (Chapter 5) were analysed.
- The execution of a natural hazard scenario demonstrated resilience of the land use system and proved model's feasibility to mimic stochastic events (Chapter 5).
- Multi-scale analysis and multi-scale modelling should be accompanied by a multi-scale validation (Chapter 6). Although full-fledged model validation and calibration of spatially explicit land use models is often not feasible (Chapter 6), any attempt should quantify the gain of model performance.
- The collaboration between various international institutes and through these institutes with Central American policy makers demonstrated the feasibility and essential importance of involving stakeholders (Chapter 8). A high rate of success was ensured, mainly because of the well-structured input of the stakeholders and the involvement of CIAT as knowledge broker.

References

AFE-COHDEFOR, 1995. Mapa Forestal. Corporación Hondureña de Desarrollo Forestal (AFE-COHDEFOR), Tegucigalpa.

Alcamo, J. (Ed.), 1994. IMAGE 2.0: Integrated modeling of global climate change. Kluwer Academic Publishers, Dordrecht.

Alcamo, J., Leemans, R., Kreileman, E., 1998. Global change scenarios of the 21st century. Results from the IMAGE 2.1 model. Elsevier Science, London.

Allen, T.F.H., Hoekstra, T.W., 1990. The confusion between scale-defined levels and conventional levels of organization in ecology. Journal of Vegetation Science 1: 5-12.

Allen, T.F.H., Hoekstra, T.W., 1992. Towards a unified ecology. Colombia University Press, New York.

Allen, T.F.H., Starr, T.B., 1982. Hierarchy: perspectives for ecological complexity. University of Chicago Press, Chicago.

Angelsen, A., 1999. Agricultural expansion and deforestation: modelling the impact of population, market forces and property rights. Journal of Development Economics 58: 185-218.

Anselin, L., Griffith, D.A., 1988. Do spatial effects really matter in regression analysis? Papers of the Regional Science Association 65: 11-34.

Ardon, P., Eade, D., 1999. Post-war reconstruction in Central America: lessons from El Salvador, Guatemala and Nicaragua. Oxfam, Oxford.

Azzi, G., 1956. Agricultural Ecology. Constable, London.

Balzter, H., Braun, P.W., Koehler, W., 1998. Cellular automata for vegetation dynamics. Ecological Modelling 107: 113-125.

Bartell, S.M., Cale, W.G., O'Neill, R.V., Gardner, R.H., 1988. Aggregation error: research objectives and relevant model structure. Ecological Modelling 41: 157-168.

Bawa, K.S., Dayanandan, S., 1997. Socioeconomic factors and tropical deforestation. Nature 386: 562-563.

Beck, M.B., 1999. Coping with ever larger problems, models, and databases. Water Science and Technology 39: 1-11.

Becker, A., Bloeschl, G., Hall, A., 1999. Preface to special issue on scale in hydrology. Journal of Hydrology 217: 169-170.

Becker, H.A., Dewulf, G., 1989. Terugkijken op toekomstonderzoek. ISOR, University of Utrecht.

Becker, J., 1998. Examples of sustainable development efforts in Costa Rica. International Journal of Sustainable Development and World Ecology 5: 172-181.

Bessembinder, J.J.E., 1997. Uncertainty and temporal aspects in long-term explorations of sustainable land use – with reference to the Northern Atlantic Zone of Costa Rica. PhD-thesis. Wageningen University and Research Centre, Wageningen.

Blaikie, P., Brookfield, H., 1987. Land degradation and society. Metheun, London.

Blaikie, P., Cannon, T., Davis, I., 1994. At risk: natural hazards, people's vulnerability, and disasters. Routledge, London.

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

Borenstein, D., 1998. Towards a practical method to validate decision support systems. Decision Support Systems 23: 227-239.

Boserup, E., 1965. The conditions of agricultural growth. The economics of agrarian change under population pressure. Unwin University Books, London.

Boserup, E., 1981. Population and technology. Blackwell, Oxford.

Bouma, J., 1997. The role of quantitative approaches in soil science when interacting with stakeholders. Geoderma 78: 1-12.

Bouma, J., 1998. Introduction. In: Stoorvogel, J.J., Bouma, J., Bowen, W.T. (Eds.), Information technology as a tool to assess land use options in space and time. Proceedings of an international workshop, Lima, September 28 - October 4, 1997. Quantitative Approaches in Systems Analysis 16, Wageningen, pp. 1-11.

Bouman, B.A.M., Jansen, H.G.P., Schipper, R.A., Hengsdijk, H., Nieuwenhuyse, A. (Eds.), 2000. Tools for land use analysis on different scales. With case studies for Costa Rica. Kluwer Academic Publishers, Dordrecht.

Brockett, C.D., 1988. Land, power, and poverty: agrarian transformation and political conflict in Central America. Allen & Unwin Inc., Winchester.
Brown, L.R., 1994. Full house: Reassessing the earth's population carrying capacity. W.W. Norton, New York.
Brown, S.L., Schroeder, P., Kern, J.S., 1999. Spatial distribution of biomass in forests of the eastern USA. Forest Ecology and Management 123: 81-90.
Bulmer-Thomas, V., 1998. The Central American Common Market: from closed to open regionalism. World Development 26: 313-322.

CCE, 1990. Desarrollo rural integrado. ¿Concepto o finalidad? Una experiencia en Costa Rica. Comisión de las Comunidades Europeas, Proyecto CEE NA/82-12. Arafototechnica, Firenze.
Chapin, F.S., Zavaleta, E.S., Eviner, V.T., Naylor, R.L., Vitousek, P.M., Reynolds, H.L., Hooper, D.U., Lavorel, S., Sala, O.E., Hobbie, S.E., Mack, M.C., Diaz, S., 2000. Consequences of changing biodiversity. Nature 405: 234-242.
Chomitz, K.M., Gray, D.A., 1996. Roads, land use, and deforestation: a spatial model applied to Belize. World Bank Economic Review 10: 487-512.
Chou, Y.H., 1991. Map resolution and spatial autocorrelation. Geographical Analysis 23: 228-246.
CIAT, 1998. The Honduras database. Collected in the framework of a project entitled 'Methodologies for integrating data across geographical scales in a data rich environment. Examples from Honduras'. Centro Internacional de Agricultura Tropical, Cali.
CIAT, 2000. The Central America database. Collected in the framework of a project entitled 'Indicators of Rural Sustainability'. Centro Internacional de Agricultura Tropical, Cali.
CINDI, 1998. Central American Disaster Atlas. Centre for Integration of Natural Disaster Information, USGS. http://cindi.usgs.gov/events/mitch/atlas/index.html or through CINDI homepage http://cindi.usgs.gov/.
Clayton, A.M.H., Radcliffe, N.J., 1996. Sustainability: a systems approach. Earthscan, London.
Cocklin, C., Blunden, G., Moran, W., 1997. Sustainability, spatial hierarchies, and land-based production. In: Ilbery, L., Chiotti, Q., Rickard, T. (Eds.), Agricultural restructuring and sustainability, a geographical perspective. Cab International, Wallingford, pp. 25-39.
Conway, G.R., 1987. The properties of agroecosystems. Agricultural Systems 24: 95-117.
Costanza, R., 1989. Model goodness of fit: a multiple resolution procedure. Ecological Modelling 47: 199-215.
Cuffaro, N., 1997. Population growth and agriculture in poor countries: a review of theoretical issues and empirical evidence. World Development 25: 1151-1163.

David, M.B.D.A., Dirven, M., Vogelgesang, F., 2000. The impact of the New Economic Model on Latin America's agriculture. World Development 28: 1673-1688.
De Koning, G.H.J., 1999. Spatially explicit analysis of land use change: a case study for Ecuador. PhD-thesis. Wageningen University and Research Centre, Wageningen.
De Koning, G.H.J., Van de Kop, P.J., Fresco, L.O., 1997. Estimates of sub-national nutrient balances as sustainability indicators for agro-ecosystems in Ecuador. Agriculture, Ecosystems and Environment 65: 127-139.
De Koning, G.H.J., Veldkamp, A., Fresco, L.O., 1998a. Land use in Ecuador: a statistical analysis at different aggregation levels. Agriculture, Ecosystems and Environment 70: 231-247.
De Koning, G.H.J., Veldkamp, A., Verburg, P.H., Kok, K., Bergsma, A.R., 1998b. CLUE: a tool for spatially explicit and scale sensitive exploration of land use changes. In: Stoorvogel, J.J., Bouma, J., Bowen, W.T. (Eds.), Information technology as a tool to assess land use options in space and time. Proceedings of an international workshop, Lima, September 28 - October 4, 1997. Quantitative Approaches in Systems Analysis 16, Wageningen, pp. 97-106.
De Koning, G.H.J., Verburg, P.H., Veldkamp, A., Fresco, L.O., 1999. Multi-scale modelling of land use change dynamics in Ecuador. Agricultural Systems 61: 77-93.
Delvaux, B., 1995. Soils. In: Gowen, S. (Ed.), Bananas and plantains. Chapmann & Hall, London, pp. 230-257.
DGEC, 1976. Censo agropecuario 1973. Dirección General de Estadística y Censos, Ministerio de Economía, Industria y Comercio, San José.
DGEC, 1978. Censo agropecuario 1974. Dirección General de Estadística y Censos, Tegucigalpa.
DGEC, 1987. Censo agropecuario 1984. Dirección General de Estadística y Censos, Ministerio de Economía, Industria y Comercio, San José.
DGEC, 1987b. Censo de población 1984. Dirección General de Estadística y Censos, Ministerio de Economía, Industria y Comercio, San José.

Diaz-Bonilla, E., 1990. Structural adjustment programs and economic stabilization in Central America. EDI Policy Seminar Report no. 23, World Bank, Washington.

Dumanski, J., Pettapiece, W.W., McGrgor, R.J., 1998. Relevance of scale dependent approaches for integrating biophysical and socio-economic information and development of agroecological indicators. Nutrient Cycling in Agroecosystems 50: 13-22.

Dutilleul, P., 1998. Incorporating scale in ecological experiments: data analysis. In: Peterson, D.L., Parker, V.T. (Eds.), Ecological Scale. Columbia University Press, New York, pp. 387-425.

Edelman, M., 1992. The logic of the latifundio: The large estates of northwestern Costa Rica since the late nineteenth century. Stanford University Press, Stanford.

Easterling, W.E., 1997. Why regional studies are needed in the development of full-scale integrated assessment modelling of global change processes. Global Environmental Change 7: 337-356.

Easterling, W.E., 2000. Emergent properties of scale in global environmental modeling. Are There Any? Paper presented at the Matrix 2000 workshop 12-19 July 2000, Mechelen. ICIS, Maastricht.

Easterly, W., Loayza, N., Montiel, P., 1997. Has Latin America's post-reform growth been disappointing? Journal of International Economics 43: 287-311.

FAO, 1994. Integrated approach to the planning and management of land resources. Draft report of the UN Secretary-General on the implementation of Chapter 10 of Agenda 21 (UNCED) to the Commission on Sustainable Development. Third Draft of Task Manager's Report. FAO/AGL, 28 November 1994, Rome.

FAO, 1999. The FAOSTAT databases. http://apps.fao.org/lim500/agri_db.pl or through the FAO homepage: http://www.fao.org/. Databases accessed between November 1998 and March 1999 (data used in Chapter 3) and between February and May 1999 (data used in Chapter 5).

Farrow, A., Winograd, M., 2001. Land use modelling at the regional scale: an input to rural sustainability indicators for Central America. Agriculture, Ecosystems and Environment 00: 000-000.

Fearnside, P.M., Imbrozio B., R., 1998. Soil carbon changes from conversion of forest to pasture in Brazilian Amazonia. Forest Ecology and Management 108: 147-166.

Fields, G.S., 1988. Employment and economic growth in Costa Rica. World Development 16: 1493-1509.

Fresco, L.O., 1995. Agro-ecological knowledge at different scales. In: Bouma, J., Kuyvenhoven, A., Bouman, B.A.M., Luyten, J.C., Zandstra, H.G. (Eds.), Eco-regional approaches for sustainable land use and food production. Kluwer Academic Publishers, Dordrecht, pp. 133-141.

Fresco, L.O., Kroonenberg, S.B., 1992. Time and spatial scales in ecological sustainability. Land Use Policy 9: 155-168.

Geske Dijkstra, A., 2000. Trade liberalization and industrial development in Latin America. World Development 28: 1567-1582.

Geurts, J.A.M.M., Jansen, H.G.P., Van Tilburg, A., 1997. Domestic demand for food in Costa Rica: a double hurdle analysis. Serie técnica. Informe técnico, CATIE, Turrialba.

Gibson, C.C., Ostrom, E., Ahn, T.K., 2000. The concept of scale and the human dimensions of global change: a survey. Ecological Economics 32: 217-239.

Godoy, R., O'Neill, K., Groff, S., Kostishack, P., Cubas, A., Demmer, J., Mcsweeney, K., Overman, J., Wilkie, D., Brokaw, N., Martinez, M., 1997. Household determinants of deforestation by Amerindians in Honduras. World Development 25: 977-987.

Goluboay, J.M., Vega, H., 1988. La actividad bananera en Costa Rica. In: FLACSO/CEDAL/FES (Eds.), Cambio y continuidad en la economía bananera. FLACSO/CEDAL/FES, San José, pp. 131-161.

Gomez, L.D., 1986. Vegetación de Costa Rica. First edition, EUNED, San José.

Goodwin, B.J., Fahrig, L., 1998. Spatial scaling and animal population dynamics. In: Peterson, D.L., Parker, V.T. (Eds.), Ecological Scale. Columbia University Press, New York, pp. 193-206.

Gustafson, E.J., 1998. Quantifying Landscape Spatial Pattern: What Is the State of the Art? Ecosystems 1: 143-156.

Hallam, D., 1995. The world banana economy. In: Gowen, S. (Ed.), Bananas and plantains. Chapmann & Hall, London, pp. 509-533.

Hall, C., Tian, H., Qi, Y., Pontius, R.G., Cornell, J.D., Uhlig, J., 1995. Spatially-explicit models of land-use change and their application to the tropics. DOE Research Summary 31, February. Carbon Dioxide Information and Analysis Center: Oak Ridge National Laboratory.

Hansen-Kuhn, K., 1993. Sapping the economy. Structural adjustment policies in Costa Rica. The Ecologist 23: 179-185.

Hardin, G., 1968. The tragedy of the commons. Science 162: 1243-1248.

Harrison, S., 1991. Population growth, land use and deforestation in Costa Rica, 1950-1984. Interciencia 16: 83-93.

Hart, R.D., 1985. An ecological systems conceptual framework for agricultural research and development. In: Shaner, W.W., Philipp, P.F., Schmehl, W.R. (Eds.), Readings in farming systems research and development. Westview Press, Boulder, pp. 44-58.

Hazell, P.B., Norton, R.D., 1986. Mathematical programming for economic analysis in agriculture. Collier MacMillan Publ., London.

Heilig, G., 1996. World population prospects. Analyzing the UN population projections. IIASA, Working paper WP-96-146. IIASA, Laxenburg.

Heuvelink, G.B.M., Pebesma, E.J., 1999. Spatial aggregation and soil process modelling. Geoderma 89: 47-65.

Hijmans, R.J., van Ittersum, M.K., 1996. Aggregation of spatial units in linear programming models to explore land use options. Netherlands Journal of Agricultural Science 44: 145-163.

Hilferink, M., Rietveld, P., 1999. LAND USE SCANNER: An integrated GIS based model for long term projections of land use in urban and rural areas. Journal of Geographical Systems 1: 155-177.

Holling, C.S., 1973. Resilience and stability of ecological systems. Annual Review of Ecology and Systems 4: 1-24.

Holling, C.S., 1992. Cross-scale morphology, geometry, and dynamics of ecosystems. Ecological Monographs 62: 447-502.

Holling, C.S., Schindler, D.W., Walker, B., Roughgarden, J., 1995. Biodiversity in the functioning of ecosystems: an ecological synthesis. In: Perrings, C., Maeler, K-G, Folke, C., Holling, C.S., Jansson, B-O. (Eds.), Biodiversity loss: economic and ecological issues. Cambridge University Press, Cambridge, pp. 44-83.

Hope, C., Anderson, J., Wenman, P., 1993. Policy analysis of the greenhouse effect. Energy Policy 23: 327-338.

Howard-Borjas, P., 1995. Cattle and crisis: the genesis of unsustainable development in Central America. Land Reform 1995: 89-116.

Hughes, R.F., Kauffman, J.B., Cummings, D.L., 2000. Fire in the Brazilian Amazon. 3. Dynamics of biomass, C, and nutrient pools in regenerating forests. Oecologia 124: 574-588.

Humphries, S., 1998. Milk cows, migrants, and land markets: unraveling the complexities of forest-to-pasture conversion in northern Honduras. Economic Development and Cultural Change 47: 95-124.

IGN, 1991. Mapa geológico de Honduras. Second edition. Secretaria de Comunicaciones Obras Publicas y Transporte & Instituto Geográfica Nacional, Tegucigalpa.

INETER, 1999. Las lluvias del siglo. Instituto Nicaragüense de Estudios Territoriales, Managua.

Innes, J.L., 1998. Measuring environmental change. In: Peterson, D.L., Parker, V.T. (Eds.), Ecological Scale. Columbia University Press, New York, pp. 429-457.

Jansen, H.G.P., Stoorvogel, J.J., 1998. Quantification of aggregation bias in regional agricultural land use models: application to Guácimo county, Costa Rica. Agricultural Systems 58: 417-439.

Jansen, M.J.W., 1998. Prediction error through modelling concepts and uncertainty from basic data. Nutrient Cycling in Agroecosystems 50: 247-253.

Jarvis, P.G., 1993. Prospects for bottom-up models. In: Ehleringer, J.R., Field, C.B. (Eds.), Scaling physiological processes. Leaf to globe. Academic Press, San Diego, pp. 115-126.

Joly, L.G., 1989. The conversion of rain forests in Panama. In: Schumann, D.A., Partridge, W.L. (Eds.), The human ecology of tropical land settlement in Latin America. Westview special studies on Latin America and the Caribbean, Westview Press, Boulder, pp. 86-129.

Jones, J.R., 1988. Colonization in Central America. In: Mansherd, W., Morgan, W. (Eds.), Agricultural expansion and pioneer settlement in the humid tropics. United Nations University, Tokyo, pp. 241-265.

Jones, J.R., 1989. Human settlement of tropical colonization in Central America. In: Schumann, D.A., Partridge, W.L. (Eds.), The human ecology of tropical land settlement in Latin America. Westview special studies on Latin America and the Caribbean, Westview Press, Boulder, pp. 43-85.

Jørgensen, S.E. (Ed.), 1994. Fundamentals of ecological modelling (2^{nd} edition). Developments in Environmental Modelling 19: 1-628.

Kaimowitz, D., Angelsen, A., 1998. Economic models of tropical deforestation. Center for International Forestry Research (CIFOR), Bogor.
Kammerbauer, J., Ardon, C., 1999. Land use dynamics and landscape pattern in a typical watershed in the hillside of central Honduras. Agriculture, Ecosystems and Environment 75: 93-100.
Keller, M., Veldkamp, E., Weitz, A.M., Reiners, W.A., 1993. Effect of pasture age on soil trace-gas emissions from a deforested area of Costa Rica. Nature 365: 244-246.
King, A.W., 1991. Translating models across scales in the landscape. In: Turner, M.G., Gardner, R.H. (Eds.), Quantitative methods in landscape ecology. Ecological Studies 82, Springer Verlag, Berlin, pp. 239-288.
Kok, K., Veldkamp, A., 2000. Using the CLUE framework to model changes in land use on multiple scales. *In:* Bouman, B.A.M., Jansen, H.G.P., Schipper, R.A., Hengsdijk, H., Nieuwenhuyse, A. (Eds.), Tools for land use analysis on different scales. With case studies for Costa Rica. Kluwer Academic Publishers, Dordrecht, pp. 35-63.
Kok, K., Veldkamp, A., 2001. Evaluating impact of spatial scales on land use pattern analysis in Central America. Agriculture, Ecosystems and Environment 00: 000-000.
Kok, K., Bouma, J., submitted. Spatial determinants of Honduran land use: Empirical evidence for Malthus' theory. Submitted to Annals of the Association of American Geographers.
Kok, K., Winograd, M., submitted. Spatially explicit modelling of the Central American land-use system. Submitted to Ecological Modelling.
Kok, K., Farrow, A., Veldkamp, A., Verburg, P.H., 2001. A method and application of multi-scale validation in spatial land use models. Agriculture, Ecosystems and Environment 00: 000-000.
Kok, K. *et al.*, in prep. The spatial scale effect in land use modelling: problems and solutions. To be submitted to Global Environmental Change.
Kolasa, J., 1989. Ecological systems in hierarchical perspective: breaks in community structure and other consequences. Ecology 70: 36-47.
Kolasa, J., Pickett, S.T.A., 1992. Ecosystem stress and health: an expansion of the conceptual basis. Journal of Aquatic Ecosystem Health 1: 7-13.

Lambin, E.F., 1994. Modelling deforestation processes: a review. TREES Series B, research report 1. European Commission, EUR 15744 EN, Brussels.
Lambin, E.F., Rounsevell, M.D.A., Geist, H.J., in press. Are agricultural land use models able to predict changes in land use intensity? Agriculture, Ecosystems and Environment 00: 000-000.
Laurance, W.F., Fearnside, P.M., Laurance, S.G., Delamonica, P., Loveloy, T.E., Rankin-de Merona, J.M., Chambers, J.Q., Gascon, C., 1999. Relationship between soils and Amazon forest biomass: a landscape-scale study. Forest Ecology and Management 118: 127-138.
Leemans, R., 1999. Modelling for species and habitats: new opportunities for problem solving. The Science of the Total Environment 240: 51-73.
Leemans, R., van den Born, G.J., 1994. Determining the potential distribution of vegetation, crops and agricultural productivity. Water, Air and Soil Pollution 76: 133-161.
Lele, U., Stone, S.W., 1989. Population pressure, the environment and agricultural intensification in sub-Saharan Africa: Variations on the Boserup hypothesis. MADIA Discussion Paper No 4., World Bank, Washington DC.
Levin, S.A., 1992. The problem of pattern and scale in ecology. Ecology 73: 1943-1967.
Levin, S.A., 1993. Concepts of scale at the local level. In: Ehleringer, J.R., Field, C.B. (Eds.), Scaling physiological processes. Leaf to globe. Academic Press, San Diego, pp. 7-19.
Loucks, O.L., 1977. Emergence of research on agro-ecosystems. Annual Review of Ecology and Systematics 8: 173-192.
Ludeke, A.K., Maggio, R.C., Reid, L.M., 1990. An analysis of anthropogenic deforestation using logistic regression. Journal of Environmental Management 31: 247-259.
Lutz, E., Daly, H., 1991. Incentives, regulations, and sustainable land use in Costa Rica. Environmental and Resource Economics 1: 179-194.

Malingreau, J.P., Belward, A.S., 1992. Scale considerations in vegetation monitoring using AVHRR data. International Journal of Remote Sensing 13: 2289-2307.
Malthus, T.R., 1967. Essay on the principle of population. 7th edition, Dent, London.
May, P.H., Bonilla, O.S., 1997. The environmental effects of agricultural trade liberalization in Latin America: an interpretation. Ecological Economics 22: 5-18.
McQueen, M., 1998. Lome versus free trade agreements: the dilemma facing the ACP countries. World Economy 21: 421-443.

Meentemeyer, V., 1989. Geographical perspectives of space, time, and scale. Landscape Ecology 3: 163-173.
Miller, J.G., 1975. The nature of living systems. Behavioral Science 20: 343-365.
Mitchell, P.L., 1997. Misuse of regression for empirical validation of models. Agricultural Systems 54: 313-326.
Musters, C.J.M., De Graaf, H.J., Ter Keurs, W.J., 1998. Defining socio-environmental systems for sustainable development. Ecological Economics 26: 243-258.

Nordhaus, W., 1992. An optimal transition path for controlling greenhouse gasses. Science 258: 1315-1319.
Nunes, C., Augé, J.I. (Eds.), 1999. Land-use and land-cover change: implementation strategy. IGBP report no. 48 and IHDP report no. 10, Stockholm.

O'Neill, R.V., 1988. Hierarchy theory and global change. In: Rosswall, T., Woodmansee, R.G., Risser, P.G. (Eds.), Scales and global change. Spatial and temporal variability in biospheric and geospheric processes. SCOPE 35, John Wiley & Sons Ltd., Chichester, pp. 29-45.
O'Neill, R.V., King, A.W., 1998. Homage to St. Michael; or, why are there so many books on scale? In: Peterson, D.L., Parker, V.T. (Eds.), Ecological Scale. Columbia University Press, New York, pp. 3-15.
O'Neill, R.V., DeAngelis, D.L., Waide, J.B., Allen, T.F.H., 1986. A hierarchical concept of ecosystems. Monographs in population biology 23. Princeton University Press, Princeton.
Overmars, K.P., 2000. Analysis of spatial autocorrelation for land use studies. Internal Report, Wageningen University and Research Centre, Wageningen.

Parayil, G., Tong, F., 1998. Pasture-led to logging-led deforestation in the Brazilian Amazon: The dynamics of socio-environmental change. Global Environmental Change 8: 63-79.
Parry, M., Arnell, N., Hulme, M., Nicholls, R., Livermore, M., 1998. Buenos Aires and Kyoto targets do little to reduce climate change impacts. Global Environmental Change 8: 285-289.
Pelupessy, W., Weeks, J., 1993. Economic maladjustment in Central America. Houndmills/MacMillan, Washington.
Pelupessy, W. (Ed.), 1991. Perspectives on the agro-export economy in Central America. Macmillan Press Ltd., Washington.
Pender, J.L., 1998. Population growth, agricultural intensification, induced innovation and natural resource sustainability: An application of neoclassical growth theory. Agricultural Economics 19: 99-112.
Peterson, D.L., Parker, V.T. (Eds.), 1998. Ecological Scale. Columbia University Press, New York.
Pfaff, A.S.P., 1999. What drives deforestation in the Brazilian Amazon? Journal of Environmental Economics and Management 37: 26-43.
Pickett, S.T.A., Kolasa, J., Armesto, J.J., Collins, S.L., 1989. The ecological concept of disturbance and its expression at various hierarchical levels. Oikos 54: 129-136.
Pontius Jr., R.G., Cornell, J.D., Hall, A.S., 2001. Modeling the spatial pattern of land-use change with GEOMOD2: application and validation with Costa Rica. Agriculture, Ecosystems and Environment 00: 000-000.

Qian, H., Ricklefs, R.E., 2000. Large-scale processes and the Asian bias in species diversity of temperate plants. Nature 407: 180-182.
Quiros, J.G., Di Mare, A., Vargas, T., Cespedes, V.H., Corrales, J., Baldares, M., 1987. La política de precios en Costa Rica. Consultores Económicos y legales, San José.

Ramírez, A., Madonado, T., 1988. Desarrollo socioeconómico y el ambiente natural de Costa Rica: situación actual y perspectivas. Editorial Heliconia, San José.
Rastetter, E.B., King, A.W., Cosby, B.J., Hornberger, G.M., O'Neill, R.V., Hobbie, J.E., 1992. Aggregating fine-scale ecological knowledge to model coarser-scale attributes of ecosystems. Ecological Applications 21: 55-70.
Raynolds, L.T., Murray, D.L., 1998. Yes, we have no bananas: re-regulating global and regional trade. International Journal of Sociology of Agriculture and Food 7: 7-44.
Reynolds, J.F., Hilbert, D.W., Kemp, P.R., 1993. Scaling ecophysiology from the plant to the ecosystem: a conceptual framework. In: Ehleringer, J.R., Field, C.B. (Eds.), Scaling physiological processes. Leaf to globe. Academic Press, San Diego, pp. 127-140.

Rodgers, E.B., Baik, J.J., Pierce H.F., 1994. The environmental influence on tropical cyclone precipitation. Journal of Applied Meteorology 33: 573-593.
Roebeling, P.C., Jansen, H.G.P., Van Tilburg, A., Schipper, R.A., 1999. Spatial equilibrium modelling for inter-regional trade flow estimation and agricultural policy analysis in Costa Rica. Report No 142, REPOSA, CATIE/MAG/WAU, Turrialba.
Root, T. L., Schneider, S.H., 1995. Ecology and climate: research strategies and implications. Science 269: 334-341.
Rosswall, T., Woodmansee, R.G., Risser, P.G. (Eds.), 1998. Scales and global change. Spatial and temporal variability in biospheric and geospheric processes. SCOPE 35, John Wiley & Sons Ltd., Chichester.
Rudel, T., Roper, J., 1997. The paths of rain forest destruction: crossnational patterns of tropical deforestation. World Development 25: 53-65.
Rueda-Juquera, F., 1998. Regional integration and agricultural trade in Central America. World Development 26: 345-362.

Sader, S.A., Joyce, A.T., 1988. Deforestation rates and trends in Costa Rica, 1940 to 1983. Biotropica 20: 11-19.
Sala, O.E., Chapin, F.S., Armesto, J.J., Berlow, E., Bloomfield, J., Dirzo, R., Huber-Sanwald, E., Huenneke, L.F., Jackson, R.B., Kinzig, A., Leemans, R., Lodge, D.M., Mooney, H.A., Oesterheld, M., Poff, N.L., Sykes, M.T., Walker, B.H., Walker, M., Wall, D.H., 2000. Global biodiversity scenarios for the year 2100. Science 287: 1770-1774.
Saunders, S.C., Chen, J., Crow, T.R., Brosofske, K.D., 1998. Hierarchical relationships between landscape structure and temperature in a managed forest landscape. Landscape Ecology 13: 381-395.
Schelhas, J., 1996. Land use choice and change: intensification and diversification in the lowland tropics of Costa Rica. Human Organization 55: 298-306.
Schipper, R.A., 1996. Farming in a fragile future. Economics of land use with applications in the Atlantic Zone of Costa Rica. PhD-thesis. Wageningen University and Research Centre, Wageningen.
Schipper, R.A., Bouman, B.A.M., Jansen, H.G.P., Hengsdijk, H., Nieuwenhuyse, A., 2000. Integrated biophysical and socio-economic analysis of regional land use. In: Bouman, B.A.M., Jansen, H.G.P., Schipper, R.A., Hengsdijk, H., Nieuwenhuyse, A. (Eds.), Tools for land use analysis on different scales. With case studies for Costa Rica. Kluwer Academic Publishers, Dordrecht, pp. 115-144.
Schipper, R.A., Jansen, H.G.P., Bouman, B.A.M., Hengsdijk, H., Nieuwenhuyse, A., Sáenz, F., 1998. Evaluation of development policies using integrated bio-economic land use models: applications to Costa Rica. Paper presented at the AAEA pre-conference 'Agricultural intensification, economic development, and the environment', July 31 – August 1, 1998, Salt Lake City, Utah.
Schneider, L.C., Pontius Jr., R.G., 2001. Modelling land-use change in the Ipswich watershed, Massachusetts, USA. Agriculture, Ecosystems and Environment 00: 000-000.
Schneider, S.H., Root, T.L., 1996. Ecological implications of climate-change will include surprises. Biodiversity and Conservation 5: 1109-1119.
Schoorl, J.M., Veldkamp, A., Fresco, L.O., 1997. The Conversion of Land Use and its Effects (CLUE-CR), a regression based model applied to Costa Rica (Pascal version 1.2). Quantitative Approaches in Systems Analysis 8: 1-53.
Schumann, D.A., Partridge, W.L. (Eds.), 1989. The human ecology of tropical land settlement in Latin America. Westview special studies on Latin America and the Caribbean, Westview Press, Boulder.
SECPLAN, 1994. Censo agropecuario 1993. Secretaria de planificación, Tegucigalpa.
Sellers, P.J., Heiser, M.D., Hall, F.G., Verma, S.B., Desjardins, R.L., Schuepp, P.M., MacPherson, J.I., 1997. The impact of using area-averaged land surface proportions – topography, vegetation condition, soil wetness – in calculations of intermediate scale (approximately 10 km^2) surface-atmosphere heat and moisture fluxes. Journal of Hydrology 190: 269-301.
Serneels, S., Lambin, E.F., 2001. Proximate causes of land-use change in Narok District, Kenya: a spatial statistical model. Agriculture, Ecosystems and Environment 00: 000-000.
Simons, C.S., 1977. Informe al Gobierno de Honduras sobre los suelos de Honduras. Secretaria de recursos naturales, Tegucigalpa.
Sklar, F.H., Costanza, R., 1991. The development of dynamic spatial models for landscape ecology: a review and prognosis. In: Turner, M.G., Gardner, R.H. (Eds.), Quantitative methods in landscape ecology. Ecological Studies 82, Springer Verlag, Berlin, pp. 239-288.
Skole, D.L., Chomentowski, W.H., Salas, W.A., Nobre, A.D., 1994. Physical and human dimensions of deforestation in Amazonia. Bioscience 44: 314-322.

Southgate, D., Sierra, R., Brown, L., 1991. The causes of tropical deforestation in Ecuador: A statistical analysis. World Development 19: 1145-1151.
Stafford Smith, M., 2000. Lessons from applications: what problems do we encounter and what do we learn from it. Keynote at the 2000 World Conference on Natural Resource Modelling: The Ecology of Scale.
Stonich, S.C., 1993. The political ecology of poverty and environmental destruction in Honduras. Westview Press Inc., Oxford.
Stoorvogel, J.J., 1995. Geographical information systems as a tool to explore land characteristics and land use with reference to Costa Rica. PhD-thesis. Wageningen University and Research Centre, Wageningen.
Stoorvogel, J.J., Eppink, G.P., 1995. Atlas de la Zona Atlántica Norte de Costa Rica. Programa Zona Atlántica (CATIE-UAW-MAG), Guápiles.
Sunderlin, W.D., 1997. Deforestation, livelihoods, and the preconditions for sustainable management in Olancho, Honduras. Agriculture and Human Values 14: 373-386.

Tangen, K., 1999. The climate change negotiations: Buenos Aires and beyond. Global Environmental Change 9: 175-178.
Thorpe, A., 1997a. Structural adjustment and the agrarian sector in Latin America. In: Spoor, M. (Ed.), Agrarian transformation in developing countries and former socialist economies. Intermediate Technology Publications, London, pp. 15-28.
Thorpe, A., 1997b. Adjustment, agricultural modernization and land markets: the case of Honduras. In: Spoor, M. (Ed.), Agrarian transformation in developing countries and former socialist economies. Intermediate Technology Publications, London, pp. 43-56.
Tischler, W., 1965. Agrarökologie. Gustaw Fischer, Jena.
Tilman, D., 1999. Global environmental impacts of agricultural expansion: the need for sustainable and efficient practices. Proceedings of the National Academy of Sciences of the USA 96: 5995-6000.
TSC/WRI, 1991. Accounts overdue: natural resource depreciation in Costa Rica. World Resource Institute and Tropical Science Center, San José.
Turner II, B.L., Ali, A.M.S., 1996. Induced intensification: agricultural change in Bangladesh with implications for Malthus and Boserup. Proceedings of the National Academy of Sciences of the USA 93: 14984-14991.
Turner II, B.L., Skole, D.L., Sanderson, S., Fischer, G., Fresco, L.O., Leemans, R., 1995. Land-use and land-cover change. Science/Research Plan. IGBP report no. 35 and HDP report no. 7, Stockholm and Geneva.
Turner, M.G., O'Neill, R.V., 1994. Exploring aggregation in space and time. In: Jones, C.G., Lawton, J.H. (Eds.), Linking species and ecosystems. Chapmann & Hall, New York, pp. 194-208.

UN, 1997. World population prospects 1950 – 2050. The 1996 revision. United Nations Population Division, New York.
US Census Bureau, 1998. International Data Base. Accessed between July and December 1998. http://www.census.gov/ftp/pub/ipc/www/idbnew.html.
US Census Bureau, 2000. International Data Base. Accessed between January 1999 and January 2000. http://www.census.gov/ftp/pub/ipc/www/world.html.
USDA, 1998. USDA Agricultural Baseline Projections to 2007. World Agricultural Outlook Board, Office of the Chief Economist, U.S. Department of Agriculture. Staff Report No. WAOB-98-1.
USDA, 1999. USDA Agricultural Baseline Projections to 2008. World Agricultural Outlook Board, Office of the Chief Economist, U.S. Department of Agriculture. Staff Report No. WAOB-99-1.

Van Ittersum, M.K., Rabbinge, R., Van Latesteijn, H.C., 1998. Exploratory land use studies and their role in strategic policy making. Agricultural Systems 58: 309-330.
Van Latesteijn, H.C., 1999. Land use in Europe: a methodology for policy-oriented future studies. PhD-thesis, Sdu Uitgevers, The Hague.
Veldkamp, A., Fresco, L.O., 1996a. CLUE: a conceptual model to study the Conversion of Land Use and its Effects. Ecological Modelling 85: 253-270.
Veldkamp, A., Fresco, L.O., 1996b. CLUE-CR: an integrated multi-scale model to simulate land use change scenarios in Costa Rica. Ecological Modelling 91: 231-248.
Veldkamp, A., Fresco, L.O., 1997. Reconstructing land use drivers and their spatial scale dependence for Costa Rica (1973 and 1984). Agricultural Systems 55: 19-43.
Veldkamp, A., Zuidema, G., Fresco, L.O., 1996. A model analysis of the terrestrial vegetation model of IMAGE 2.0 for Costa Rica. Ecological Modelling 93: 263-273

Veldkamp, E., 1994. Organic carbon turnover in 3 tropical soils under pasture after deforestation. Soil Science Society of America Journal 58: 175-180.

Verburg, P.H., 2000. Exploring the spatial and temporal dynamics of land use. With special reference to China. PhD-thesis. Wageningen University and Research Centre, Wageningen.

Verburg, P.H., Veldkamp A., 1997. Modelling the spatial pattern of land use change in China. Proceedings of a Workshop Wageningen-China May 1997. Report 84 AB-DLO, Wageningen.

Verburg, P.H., Chen, Y.Q., 2001. Multi-scale characterisation of land-use patterns in China. Ecosystems 00: 000-000.

Verburg, P.H., Veldkamp, A., Bouma, J., 1999b. Land-use change under conditions of high population pressure. The case of Java. Global Environmental Change 9: 303-312.

Verburg, P.H., Veldkamp, A., Fresco, L.O., 1999c. Simulation of changes in the spatial pattern of land use in China. Applied Geography 19: 211-233.

Verburg, P.H., De Koning, G.H.J., Kok, K., Veldkamp, A., Bouma, J., 1999a. A spatial explicit allocation procedure for modelling the pattern of land use change based upon actual land use. Ecological Modelling 116: 45-61.

Verburg, P.H., Chen, Y.Q., Soepboer, W., Veldkamp, A., 2000. GIS-based modeling of human-environment interactions for natural resource management - applications in Asia. In: Parks, B.O., Clarke K.M., Crane M.P. (Eds.), Proceedings of the 4th international conference on integrating geographic information systems and environmental modeling: problems, prospects, and needs for research, September 2-8; University of Colorado, Cooperative Institute for Research in Environmental Science, Boulder (www and CD).

Vitousek, P.M., Mooney, H.A., Lubchenco, J., Melillo, J.M., 1997. Human domination of earth's ecosystems. Science 277: 494-499.

Wagenet, R.J., 1998. *Scale issues in agroecological research chains.* Nutrient Cycling in Agroecosystems 50: 23-34.

Walsh, A.J., Moody, A., Allen, T.R., Brown, D.G., 1997. Scale dependency of NDVI and its relationship to mountainous terrain. In: Quattrochi, D.A., Goodchild, M.F. (Eds.), Scale in remote sensing and GIS. Lewis Publishers Inc., Boca Raton, pp. 27-55.

Walsh, S.J., Evans, T.P., Welsh, W.F., Entwisle, B., Rindfuss, R.R., 1999. Scale-dependent relationships between population and environment in Northeastern Thailand. Photogrammetric Engineering and Remote Sensing 65: 97-105.

Weaver, F.S., 1994. Inside the volcano: the history and political economy of Central America Westview, Boulder.

Weinberg, B., 1991. War on the land: ecology and politics in Central America. Zed Books, London.

White, J.D., Running, S.W., 1994. Testing scale dependent assumptions in regional ecosystem simulations. Journal of Vegetation Science 5: 687-702.

Wilbanks, T.J., Kates, R.W., 1999. *Global change in local places: how scale matters.* Climatic Change 43: 601-628.

Wilbanks, T.J., 2000. Scaling issues in integrated assessments of climate change. Paper presented at the Matrix 2000 workshop 12-19 July 2000, Mechelen. ICIS, Maastricht.

Wielemaker, W.G., Vogel, A.W., 1993. Un sistema de información de suelos y tierras para la Zona Atlántica de Costa Rica. AZP, phase 2, report no. 22. CATIE/MAG/AUW, Guápiles.

Wiens, J.A., 1989. Spatial scaling in ecology. Functional Ecology 3: 385-397.

World Bank, 1998. World Development Indicators, 1997. World Bank CD-ROM. World Bank, Washington.

World Bank, 2000. Country briefs. Accessed April 2000. Accessible through http://www.worldbank.org/html/extdr/regions.htm.

Zuidema, G., van den Born, G.J., Alcamo, J., Kreileman, G.J.J., 1994. Simulating changes in global land cover as affected by economic and climatic factors. Water, Air, and Soil Pollution 76: 163-198.

Summary

Introduction

There is a growing demand for quantitative information on actual land use/land cover and their future changes in space and time. Particularly during the last decade, land use and land cover change have become important issues. Besides local and direct effects like loss of biodiversity through deforestation or soil degradation through unsustainable land use, increasing importance is given to the global impact of more indirect (future) effects like greenhouse gas emissions and carbon fixation.

The land use system is highly complex and this notion of complexity has consequences for the way the system should be described. Theories applied in this thesis draw from ecology, a field of science that has acquired ample experience in describing the complexity of the ecosystem. The land use system was considered to be functionally complex, *i.e.* land use patterns are governed by a broad variety of potential spatial determinants. International agreements initiated by *e.g.* the United Nations, World Bank or GATT influence regional and national policies that trickle down to local decision-makers and that will ultimately affect farmers' decision to change land use. A second property of the land use system was its structural complexity, that is, which variables will emerge as important spatial determinants of land use depends largely on the adopted (spatial) scale of analysis. Finding ways to translate information among scales is one of the fundamental challenges faced by researchers in land use analysis. Models are crucial tools to help understand the dynamics and complexity of a land use system. The CLUE (Conversion of Land Use and its Effects) modelling framework was selected as the appropriate means to model land use change. It was one of the few examples of land use models that take into account both structural and functional complexity.

Objectives

The main objectives of this study were to analyse the present land use patterns and to project possible future pathways of the dynamics of those patterns for a number of hierarchically nested cases. Following the structure of the CLUE modelling framework, three sub-objectives were formulated:

1. To identify biogeophysical and socioeconomic determinants of land use patterns at different spatial extents and resolutions, by means of an empirical analysis of actual land use systems.
2. To analyse demand for the major agricultural commodities at the national or regional level and to develop a limited number of scenarios that explore plausible future pathways of land use change.
3. To spatially explicit allocate national changes as projected in those scenarios, using the information of the spatial analysis of the land use system.

Study area
All case studies concerned (parts of) Central America. The region has specific characteristics that made it very suitable for the research described in this thesis. Firstly, biophysical, climatic, and socioeconomic gradients are steep over small distances, which induces a strong variation in land use over relatively small areas. High mountain ranges with steep slopes, shallow soils, low temperatures, and low population densities could be near to flat, fertile, and hot lowlands that were densely populated. Secondly, the area included six countries that display large economic and political differences. Honduras and Nicaragua rank among the poorest in the Western Hemisphere, while Costa Rica is one of the more stable and robust democracies of Latin America based on a strong, export-led, development. Finally, most countries collected extensive data sets. Detailed agricultural censuses exist for Honduras and Costa Rica, and because of the presence of a research centre of Wageningen University, an outstanding data set exists for the Atlantic Zone of Costa Rica. As a result, Central America offered the unique possibility to construct a hierarchically nested range of case studies to systematically analyse land use dynamics that are influenced by a variety of factors over a range of spatial scales. A total of four case studies were modelled: the Atlantic Zone of Costa Rica ('Atlantic Zone'), Costa Rica, Honduras, and Central America.

Statistical analysis
Within this thesis, the quantification of the relationships between land use and their spatial determinants for the Atlantic Zone (Chapter 2), Honduras (Chapter 3), and all countries of Central America (Chapter 4) were discussed. Except for the Atlantic Zone, agricultural censuses were always the main source of spatially explicit land use data. Despite the huge amount of information, little use has been made of this potentially valuable data source. All data were transformed to a raster. Instead of using uniform grid cells with one dominant land use and *e.g.* one type of soil, sub-grid information (using percentages) was present for most of the spatial determinants and each land use. Spatial resolution ranged from 2 × 2 km for the Atlantic Zone to 75 × 75 km for Central America. Spatial extent varied between 5,000 km^2 and 500,000 km^2. For all cases, the influence of spatial scale was quantified by executing the statistical analysis at a range of spatial resolutions or spatial extents. Specific results varied from case to case, but the following general conclusions applied:

- The patterns of land uses that produce basic foodstuffs (maize, beans, rice, pasture) were very well explained, whereas distributions of crops that are export-oriented (bananas, coffee, sugar cane) were less well captured.
- Socioeconomic, soil-related, climatic and sometimes (Atlantic Zone) political factors were necessary to describe land use patterns. Omission of whichever of those groups of variables from the analysis would impoverish results, which proved that the land use system is functionally complex.

- Relationships were relatively stable over time. Although total quantities as well as patterns changed considerably in all cases, composition of explaining variables remained relatively constant.
- Relationships were not very sensitive for changes in spatial resolution. In none of the cases, large changes in composition of explaining variables were observed with changing spatial resolution.
- Description of land use patterns proved very sensitive to changes in spatial extent as demonstrated by varying extent between national and regional (Chapter 4). The importance of national borders suggested that the search for scale dependencies should focus on administrative or political levels rather than on biophysically defined levels, as is proposed by ecosystem theory. This would call for a separate land use system theory.
- Spatial determinants of land use change were sometimes counterintuitive and contradicted prevailing hypotheses on causes of land use change. A variety of examples substantiated the plea to start an analysis at coarser scales with empirical methodologies.

Scenario development

The near future area changes of land use at the national or regional (Atlantic Zone) level were studied by developing a limited number of plausible scenarios. The time period for which scenarios were developed varied from case to case, but usually started in the early 1990s and finished in 2005 or 2010. Scenarios were developed for a number of commodities that translated into a smaller number of land uses. Scenarios were divided into two types. In the demand-controlled scenarios, only the total area to be allocated was variable. Changes in land use depended on (macro-)economic, demographic, and crop specific factors at national level. Most important factors included population growth, income growth, export/import development, and yield. All variants of the developed base scenario (market liberalisation; market protection; 1%, 3%, and 5% GDP growth) and the sustainable scenario belonged to this type. In the allocation-controlled scenarios, land use changes also depended on spatially specific allocation conditions. The developed park protection scenario, where deforestation within national parks was inhibited, was an example of this type. The natural hazard scenario described in Chapter 5 was an example of a realistic scenario that combined changes in demand with location-specific alterations.

Spatially explicit modelling

Resulting maps from the allocation module of the CLUE modelling framework were discussed for the Atlantic Zone (Chapter 2), and Honduras and Central America (Chapter 5). The allocation module combined the spatially explicit information obtained from the multi-scale empirical analyses and the non-spatial area development from the scenario studies. Results from the various cases, mostly maps of hot-spots of change, demonstrated the feasibility of the application of the CLUE model at different spatial scales. Satisfactory results were obtained for the Atlantic

Zone as well as for Central America as a whole. Results of the natural hazard scenario for Honduras separately and for Central America indicated the likeliness of the effects of a hurricane on land use patterns, though initially strong, to largely disappear within a period of 10 year. Concepts from ecology were used to illustrate the modelled behaviour of the land use system. CLUE thus proved to be able to mimic spatially explicit land use changes for a number of diverging scenarios. The effects of protecting national parks, macroeconomic changes, as well as an extreme weather event could be evaluated.

Validation

In spite of the large number of models and in spite of a general agreement that validation should be an essential part of any model, the majority lacked a validity check, often because of data problems. All case studies in this thesis were validated, also because for all cases independent data from two different points in time was available. Statistical relationships between land use and their spatial determinants were established for the older of the two data sets. Subsequently, the CLUE allocation module was run, starting at the oldest year until the most recent year. Validation was quantified by statistically comparing the modelled and actual land use changes. For the Atlantic Zone, Honduras and Costa Rica, the allocation module of the CLUE model was successfully validated, yielding satisfactory coefficients of determination for the relationships between actual and modelled land use patterns. Besides, for Honduras and Costa Rica a multi-scale validation was executed, as it should accompany multi-scale analysis and multi-scale modelling. Results improved strongly, and exponentially, with a coarsening of spatial resolution. Validations demonstrated that the CLUE modelling framework could reproduce changes as they took place in Central America between the 1970s and 1990s.

Stakeholders

Three possible groups of users of the CLUE model were identified, namely other modellers, farmers, and national or regional policy makers. The development of the CLUE modelling framework was initiated by a demand from the global modelling community. Eventually, a number of land use models could be used together in a sequence, forming a so-called modelling tool-box. Results of a coarse scale model could help focus other more detailed models, which could then be employed to model local processes. In its present form, the CLUE model would have little value at the farm level. The model, however, was constructed such that neither the application at a more detailed level, nor the replacement of statistical equations by any other kind of (process-based) rules would be problematic. Policy makers at various organisational levels are a group of potential stakeholders that could be addressed with the model in its present form. The Central America case study presented in Chapter 5 was an example of how this could function in practice. The mutually beneficial collaboration between various international institutes showed how a model like CLUE, designed primarily to fulfil scientific needs, was used by other stakeholders. The incorporation of a knowledge-broker, an intermediary that links the people who use knowledge (policy makers) and those who create it (scientists), provided the setting for the successful communication.

Resumen

Introducción

Hay una demanda creciente de información cuantitativa sobre uso y cobertura actual de la tierra y sobre sus futuros cambios espaciales y temporales. Particularmente durante la década pasada, los cambios de uso y cobertura de la tierra fueron cuestiones importantes. Además de efectos locales y directos como la pérdida de biodiversidad por deforestación o degradación del suelo por uso insostenible de la tierra, se ha dado más y más importancia al impacto global de (futuros) efectos más indirectos como las emisiones de gases invernadero y la fijación del carbón. El sistema de uso de la tierra es sumamente complejo y esta noción de la complejidad tiene consecuencias en la manera en que el sistema debe ser descrito. Las teorías que se aplicaron en esta tesis aprovecharon de la ecología, una rama de la ciencia que ha adquirido experiencia suficiente en describir la complejidad del ecosistema. El sistema de uso de la tierra se consideró funcionalmente complejo, es decir los patrones de uso de la tierra son controlados por una amplia variedad de determinantes espaciales potenciales. Acuerdos internacionales iniciados por ejemplo por las Naciones Unidas, el Banco Mundial, o el GATT (Acuerdo General sobre Aranceles y Comercio) influyen sobre las políticas regionales y nacionales. Estos acuerdos tienen su influencia en las correspondientes entidades responsables locales y eventualmente afectarán la decisión de los campesinos para cambiar el uso de la tierra. Una segunda característica del sistema de uso de la tierra fue su complejidad estructural, es decir, cuáles variables emergen como determinantes espaciales importantes de uso de la tierra las cuales dependen en gran parte de la escala (espacial) del análisis. Encontrar maneras de pasar información entre escalas es uno de los desafíos fundamentales para los investigadores en el campo del análisis de uso de la tierra. Los modelos son instrumentos cruciales para ayudar a entender la dinámica y la complejidad de los sistemas de uso de la tierra. El modelo CLUE ("Conversion of Land Use and its Effects", en otras palabras, Conversión del Uso de la Tierra y sus Efectos) fue seleccionado como la forma apropiada de modelar el cambio de uso de la tierra. Es uno de los pocos ejemplos de modelos de cambio de uso de la tierra que consideran ambas la complejidad estructural y funcional.

Objetivos

Los objetivos principales de este estudio fueron analizar los patrones de uso actual de la tierra y proyectar las dinámicas futuras posibles de esos patrones para un número de casos jerarquizados. De acuerdo con la estructura del marco para modelar CLUE, tres objetivos secundarios fueron formulados:

1. Identificar los determinantes biogeofísicos y socioeconómicos de los patrones de uso de la tierra en varias extensiones y resoluciones, por medio de un análisis empírico de los sistemas de uso actual de la tierra.

2. Analizar la demanda de los productos agrícolas principales al nivel nacional o regional y desarrollar un número limitado de escenarios que exploren las dinámicas futuras plausibles de cambio de uso de la tierra.
3. Asignar de manera espacialmente explícita los cambios al nivel nacional según lo proyectado en esos escenarios, usando la información del análisis espacial del sistema de uso de la tierra.

Área del estudio

Todos los estudios de caso se refirieron a (regiones de) América Central. La región tiene características específicas, que la hicieron muy apropiada para la investigación descrita en esta tesis. En primer lugar, los gradientes biofísicos, climáticos, y socioeconómicos son abruptos en distancias pequeñas, lo que causa una variación fuerte en uso de la tierra en extensiones relativamente pequeñas. Cordilleras con cumbres altas y pendientes escarpadas, suelos pocos profundos, bajas temperaturas, y densidades demográficas bajas podrían estar cerca de tierras bajas planas, fértiles, calientes, y densamente pobladas. En segundo lugar, el área incluyó seis países que mostraron grandes diferencias económicas y políticas. Honduras y Nicaragua son de los países más pobres del hemisferio occidental, mientras que Costa Rica es una de las democracias más estables y más robustas de América Latina, basado en un desarrollo fuerte fundado en la exportación. Finalmente, la mayoría de los países recogieron bases de datos extensas. Censos agropecuarios detallados existen para Honduras y Costa Rica, y debido a la presencia de un centro de investigación de la Universidad de Wageningen, una base de datos excepcional existe para la Zona Atlántica de Costa Rica. Consecuentemente, América Central ofreció la posibilidad única para construir una serie jerarquizada de estudios de caso para analizar sistemáticamente las dinámicas en el uso de la tierra que son influenciadas por una variedad de determinantes por una serie de escalas espaciales. Un total de cuatro estudios de caso fueron modelados: la Zona Atlántica de Costa Rica ('Zona Atlántica'), Costa Rica, Honduras, y América Central.

Análisis estadístico

Dentro de esta tesis, las cuantificaciones de las relaciones entre el uso de la tierra y sus determinantes espaciales para la Zona Atlántica (Capítulo 2), Honduras (Capítulo 3), y todos los países de América Central (Capítulo 4) fueron discutidas. Con excepción de la Zona Atlántica, censos agropecuarios siempre fueron la fuente principal de los datos espacial explícitos de uso de la tierra. A pesar de la cantidad de información enorme, se ha hecho poco uso de esta fuente de datos potencialmente valiosa. Todos los datos fueron transformados al formato raster. En vez de usar celdas uniformes con un uso de la tierra dominante y por ejemplo un tipo de suelo, la información era presente al nivel de sub-celdas (utilizando porcentajes) para la mayoría de los determinantes espaciales y para cada uso de la tierra. La resolución espacial varió de 2 × 2 kilómetros para la Zona Atlántica a 75 × 75 kilómetros para América Central. La extensión espacial varió entre 5.000 km^2 y 500.000 km^2. Para todos los casos, la influencia de la escala espacial fue cuantificada ejecutando el análisis estadístico para una serie de resoluciones o extensiones espaciales. Resultados específicos variaron de caso a caso, pero las siguientes conclusiones generales se aplican:

- Los patrones de usos de la tierra que producen comestibles básicos (maíz, frijoles, arroz, pasto) se explicaron muy bien, mientras que explicar las distribuciones de cultivos para la exportación (banano, café, caña de azúcar) fue más difícil.
- Factores socioeconómicos, climáticos, políticos (Zona Atlántica), y factores relacionado con el suelo fueron necesarios a veces para describir patrones de uso de la tierra. Omisión de cualquiera de esos grupos de variables del análisis empobrecería los resultados. Esto probó que el sistema de uso de la tierra es funcionalmente complejo.
- Las relaciones fueron relativamente estables en el tiempo. Aunque las cantidades totales así como los patrones cambiaron considerablemente en todos los casos, la composición de variables necesarias para explicar los patrones siguió siendo relativamente constante.
- Las relaciones no fueron muy sensibles a los cambios en la resolución espacial. En ninguno de los casos, se observaron cambios grandes en la composición de variables explicadas con cambios en resolución espacial.
- La descripción de patrones de uso de la tierra probó ser muy sensible a cambios en la extensión espacial tal como fue demostrado al variar la extensión de nacional a regional (Capítulo 4). La importancia de fronteras nacionales sugirió que la búsqueda de dependencia de la escala tiene que centrarse en niveles administrativos o políticos más que en niveles definidos por factores biofísicos, tal y como es propuesto por la teoría del ecosistema. Esto haría necesario una teoría separada para el sistema de uso de la tierra.
- Los determinantes espaciales de cambio de uso de la tierra a veces fueron contrarios a los esperados según la intuición y además contradijeron hipótesis sobre las causas de cambio de uso de la tierra que prevalecían. Una variedad de ejemplos verificó la súplica de comenzar análisis en escalas menos detalladas con metodologías empíricas.

Desarrollo de escenarios

Cambios en el área total de uso de la tierra en el futuro cercano a nivel nacional o regional fueron estudiados desarrollando un número limitado de escenarios plausibles. El período para el cual los escenarios fueron desarrollados dependió del caso de estudio, pero generalmente comenzó temprano en los años 90 y acabó en el año 2005 o 2010. Los escenarios fueron desarrollados para un número de productos agrícolas principales que tradujeron a un número más pequeño de usos de la tierra. Los escenarios fueron divididos en dos tipos. En los escenarios controlados por la demanda, solamente el área total que tenia que ser asignado era variable. Cambios de uso de la tierra dependieron de factores (macro-)económicos, demográficos, y factores específicos para cada cultivo a nivel nacional. Los factores más importantes incluyeron crecimiento de la población, crecimiento de los ingresos, desarrollo de exportación e importación, y rendimiento de productos agrícolas. Todas las variantes del escenario básico que fue desarrollado (liberalización del mercado; protección del mercado; crecimiento del PIB de 1%, 3%, y 5%) y el escenario sostenible, fueron de este tipo. Cambios de uso de la tierra en los escenarios controlados por la asignación también dependieron de condiciones espacialmente explícitas de la asignación. El escenario en el que Parques Naturales fueron protegidos y deforestación dentro de los Parques Nacionales fue inhibida fue un ejemplo de este tipo. El escenario de un desastre natural tal y como se especificó en Capítulo 5, es un ejemplo de un escenario realista que combinó cambios en demanda con cambios espacialmente específicos.

Modelación espacialmente explícita
Los mapas que resultaron del módulo de asignación del marco para modelar CLUE fueron discutidos para la Zona Atlántica (capítulo 2), Honduras y América Central (Capítulo 5). El módulo de asignación combinó la información espacialmente explícita obtenida de los análisis empíricos a escala múltiple con el desarrollo del área al nivel nacional proyectado en los escenarios. Resultados de los varios casos, sobre todos los mapas con 'áreas claves' de cambio de uso de la tierra, demostraron la viabilidad de la aplicación del modelo CLUE a varias escalas espaciales. Se obtuvieron resultados satisfactorios para la Zona Atlántica así como para América Central en su totalidad. Los resultados del escenario de un desastre natural para Honduras separadamente y para América Central indicaron que los efectos de un huracán, a patrones de uso de la tierra, aunque inicialmente fuertes, probablemente desaparecerán dentro de un período de 10 años. Se utilizaron conceptos de la ecología para ilustrar la conducta modelada del sistema de uso de la tierra. CLUE así demostró ser capaz de reproducir cambios espacialmente explícitos de uso de la tierra para un número de escenarios diferentes. Se evaluaron los efectos de proteger Parques Nacionales, de cambios macroeconómicos, tanto como de un evento extremo del tiempo.

Validación
A pesar de la multitud de modelos y a pesar de un acuerdo general de que la validación debe ser parte esencial de cualquier modelo, faltó una investigación de la validez, normalmente debido a problemas con los datos. Todos los estudios de caso en esta tesis fueron validados, ya que una base de datos independiente (dos puntos diferentes en el tiempo) estaba disponible para todos los casos. Se establecieron las relaciones estadísticas entre el uso de la tierra y sus determinantes espaciales para la menos reciente de las dos bases de datos. Después, el módulo de asignación de CLUE fue ejecutado, comenzando en el año más anterior hasta el año más reciente. La validación fue cuantificada comparando de una manera estadística los cambios modelados y reales de uso de la tierra. Para la Zona Atlántica, Honduras y Costa Rica, el módulo de asignación de CLUE fue validado con éxito, rindiendo coeficientes de determinación satisfactorios para las relaciones entre patrones actuales y modelados

de uso de la tierra. Además, se ejecutó una validación de escala múltiple para Honduras y Costa Rica, porque es lo que debe acompañar al análisis de escala múltiple y modelación de escala múltiple. Los resultados mejoraron fuertemente y exponencialmente con la disminución de la resolución espacial. Las validaciones demostraron que el marco para modelar CLUE podía reproducir cambios como ocurrieron en América Central entre los años 70 y los años 90.

Grupos de interés

Se identificaron tres grupos posibles de usuarios del modelo CLUE, a saber, otros modeladores, campesinos y legisladores al nivel nacional o regional. El desarrollo del marco para modelar CLUE fue iniciado por una demanda de la comunidad de modeladores globales. Finalmente, se podrían utilizar un número de modelos de uso de la tierra juntos en una secuencia, formando así una 'caja de herramientas' para modelación. Los resultados de un modelo a una escala poco detallada podrían ayudar a enfocar otros modelos más detallados, que después se podrían emplear para modelar procesos locales. En su forma actual, el modelo CLUE tendría poco valor al nivel de la finca. Sin embargo, el modelo fue construido de tal manera que ni la aplicación a un nivel más detallado, ni el reemplazo de las ecuaciones estadísticas por cualquier otro tipo de reglas (por ejemplo, basado en procesos) sería problemático. Legisladores a varios niveles de organización son grupos de interés potenciales que podrían ser dirigidos con el modelo en su forma actual. El estudio de caso de América Central en su totalidad como fue presentado en Capítulo 5 fue un ejemplo de cómo éste podría funcionar en la practica. La colaboración mutuamente beneficiosa entre varios institutos internacionales mostró cómo un modelo como CLUE, diseñado en primer lugar para satisfacer necesidades científicas, fue utilizado por otros grupos de interés. La incorporación de un 'mediador de conocimiento', un intermediario que conecta la gente que utiliza el conocimiento (los que toman decisiones políticas) con las que lo creen (los científicos), suministró la configuración para la comunicación acertada.

Samenvatting

Inleiding

Er is een groeiende vraag naar kwantitatieve informatie over de huidige situatie van landbedekking/landgebruik en hun toekomstige veranderingen in ruimte en tijd. Met name de laatste tien jaar zijn de veranderingen in landbedekking en landgebruik belangrijke kwesties geworden. Naast lokale en directe gevolgen, zoals verlies van biodiversiteit of bodemdegradatie door niet duurzaam landgebruik, wordt er in toenemende mate belang gehecht aan de mondiale impact van meer indirecte gevolgen, zoals emissie van broeikasgassen en koolstofvastlegging. Het landgebruiksysteem is uiterst complex en dit besef van complexiteit heeft gevolgen voor de manier waarop het systeem beschreven zou moeten worden. De theorieën die toegepast werden in dit proefschrift, maakten gebruik van ideeën uit de ecologie, een wetenschapsgebied dat ruime ervaring heeft opgedaan met de beschrijving van de complexiteit van met ecosysteem. Het landgebruiksysteem werd beschouwd functioneel complex te zijn, dat wil zeggen dat patronen van landgebruik gestuurd worden door een breed scala aan mogelijke ruimtelijke bepalende factoren. Internationale overeenkomsten, geïnitieerd door bijvoorbeeld de Verenigde Naties, de Wereld Bank, of GATT (algemene overeenkomst inzake tarieven en handel), beïnvloeden regionaal en nationaal beleid, dat op zijn beurt weer zijn weerslag heeft op lokale besluitvormers. Dit zal uiteindelijk van invloed zijn op beslissingen van de boeren om hun landgebruik te veranderen. Als tweede eigenschap van het landgebruiksysteem werd beschouwd dat het structureel complex was, met andere woorden dat de vraag welke variabelen naar voren komen als belangrijke ruimtelijke bepalende factoren in grote mate afhangt van de (ruimtelijke) schaal waarop de analyses worden uitgevoerd. Het vinden van manieren om informatie over te brengen van de ene naar de andere schaal is één de van fundamentele uitdagingen voor onderzoekers van landgebruik. Modellen zijn cruciale hulpmiddelen om de dynamiek en complexiteit van een landgebruiksysteem te helpen begrijpen. Het CLUE ("Conversion of Land Use and its Effects", oftewel verandering van landgebruik en zijn gevolgen) modelleer-raamwerk werd gekozen als de passende methode om landgebruikveranderingen te modelleren. Het was één van de weinige voorbeelden van landgebruikmodellen die rekening houden met zowel functionele als structurele complexiteit.

Doelstellingen

De hoofddoelstellingen van dit onderzoek waren om huidige patronen van landgebruik te analyseren en om mogelijke toekomstige veranderingen in de dynamiek van die patronen weer te geven voor een aantal hiërarchisch geneste deelstudies. Op grond van de structuur van het CLUE modelleer-raamwerk werden er drie secondaire doelstellingen geformuleerd:

1. Om de biofysische, geografische en socioeconomische bepalende factoren van patronen van landgebruik te identificeren voor meerdere ruimtelijke extensies en resoluties, door middel van een empirische analyse van huidige landgebruik-systemen.
2. Om de vraag naar de belangrijkste agrarische producten op nationaal dan wel regionaal niveau te analyseren en om een klein aantal scenario's te construeren die de plausibele toekomstige ontwikkeling van landgebruikveranderingen verkennen.
3. Om de in die scenario's uitgestippelde veranderingen op nationaal niveau ruimtelijk expliciet toe te delen, daarbij gebruikmakend van de informatie van de ruimtelijke analyse van het landgebruiksysteem.

Studiegebied

Alle deelstudies betroffen (delen van) Midden-Amerika. De regio heeft specifieke kenmerken waardoor het een zeer geschikt gebied was voor het onderzoek dat is beschreven in dit proefschrift. Ten eerste zijn biofysische, klimatologische, en socioeconomische gradiënten zeer groot over korte afstanden, wat een sterke variatie in landgebruik over relatief kleine afstanden tot gevolg kan hebben. Hoge bergruggen met steile hellingen, ondiepe bodems, lage temperaturen en lage bevolkings-dichtheden kunnen naast vlakke, vruchtbare, warme, dichtbevolkte laaglandgebieden voorkomen. In de tweede plaats omvatte het gebied zes landen die grote economische en politieke verschillen vertonen. Honduras en Nicaragua horen bij de armste landen van het Westelijk Halfrond, terwijl Costa Rica één van de meest stabiele en robuuste democratieën van Latijns Amerika is, gebaseerd op een sterke, op de export georiënteerde, ontwikkeling. Tenslotte hebben de meeste landen uitgebreide datasets verzameld. Er zijn gedetailleerde agrarische censussen voor Honduras en Costa Rica en omdat Wageningen Universiteit er een steunpunt heeft gehad, bestaat er een voortreffelijke dataset voor de Atlantische Zone van Costa Rica. Derhalve bood Midden-Amerika de unieke mogelijkheid om een hiërarchisch geneste reeks van deelstudies op te zetten. Zo kon er een systematische analyse van de dynamiek van landgebruik dat beïnvloed werd door een verscheidenheid aan factoren over een reeks van schalen uitgevoerd worden. In totaal werden vier deelstudies gemodelleerd: de Atlantische Zone van Costa Rica ('Atlantische Zone'), Costa Rica, Honduras en heel Midden-Amerika.

Statistische analyse

In dit proefschrift werd de kwantificatie van de relaties tussen landgebruik en hun ruimtelijke bepalende factoren behandeld voor de Atlantische Zone (Hoofdstuk 2), Honduras (Hoofdstuk 3) en alle landen van Midden-Amerika (Hoofdstuk 4). Behalve voor de Atlantische Zone, waren agrarische censussen steeds de voornaamste bron van ruimtelijk expliciete data over landgebruik. Ondanks de veelheid van informatie, is er in het algemeen te weinig gebruik gemaakt van deze potentieel waardevolle bron van data. Alle gegevens werden omgezet naar rasterformaat. In plaats van uniforme rastercellen met één dominant landgebruik en bijvoorbeeld één bodemtype, bevatte iedere cel deelcel-informatie over de meeste ruimtelijke bepalende factoren en alle landgebruiktypen in de vorm van percentages. De ruimtelijke resoluties liepen uiteen van 2 × 2 km voor de Atlantische Zone tot 75 × 75 km voor Midden-Amerika. De ruimtelijke extensies varieerden van 5.000 km^2 tot 500.000 km^2. In alle studies werd de invloed van de ruimtelijke schaal gekwantificeerd door de statistische analyse uit te voeren voor een reeks van ruimtelijke resoluties of extensies. Specifieke resultaten verschilden van deelstudie tot deelstudie, maar de volgende algemene conclusies konden getrokken worden:

- De patronen van landgebruiken die eerste levenbehoeften (maïs, bonen, rijst, gras) produceren konden heel goed verklaard worden, terwijl de verspreiding van gewassen die vooral voor de export verbouwd worden (bananen, koffie, suikerriet) moeilijker te verklaren was.
- Socioeconomische, bodemgerelateerde, klimatologische en soms (Atlantische Zone) politieke variabelen waren nodig om landgebruikpatronen te beschrijven. Het weglaten van welke groep van variabelen ook van de analyse zou de resultaten verslechteren, wat bewees dat het landgebruiksysteem functioneel complex was.
- Relaties waren betrekkelijk stabiel in de tijd. Hoewel zowel totale hoeveelheden alsook ruimtelijke patronen behoorlijk veranderden in alle studies, bleef de samenstelling van de verklarende variabelen relatief constant.
- Relaties waren niet erg gevoelig voor veranderingen in ruimtelijke resolutie. Grote veranderingen in de samenstelling van de verklarende variabelen bij een veranderende ruimtelijke resolutie werden in geen van de studies gesignaleerd.
- De beschrijving van landgebruikpatronen bleek uitermate gevoelig voor veranderingen in de ruimtelijke extensie, zoals aangetoond werd door de extensie te variëren tussen nationaal en regionaal (Hoofdstuk 4). Het belang van nationale grenzen suggereert dat de zoektocht naar schaalafhankelijkheden zich zou moeten concentreren op administratieve dan wel politieke niveaus, meer dan op biofysisch afgebakende niveaus zoals wordt voorgesteld door ecologische theorieën. Dit laatste zou een aparte theorie voor landgebruiksystemen nodig maken.
- Ruimtelijke bepalende factoren van landgebruikveranderingen waren soms anders dan wat intuïtief juist leek en konden heersende theorieën over de oorzaken van landgebruikveranderingen tegenspreken. Een reeks voorbeelden staafde dit pleidooi om op grovere schalen de analyse te beginnen met een empirische benadering.

Ontwikkeling van scenario's

De gebiedsveranderingen van landgebruik op nationaal of regionaal (Atlantische Zone) niveau in de nabije toekomst werden onderzocht door een beperkt aantal plausibele scenario's te ontwikkelen. De tijdsspanne waarvoor scenario's werden ontwikkeld hing af van de deelstudie, maar het beginjaar was normaal gesproken ergens in de vroege jaren 90 en het eindjaar was 2005 of 2010. Scenario's werden ontwikkeld voor een aantal belangrijke agrarische producten, wat zich vertaalde in een kleiner aantal landgebruiktypen. Scenario's werden verdeeld in twee soorten. In de vraaggestuurde scenario's varieerde alleen het totale gebied dat moest worden toegedeeld. Landgebruikveranderingen hingen af van veranderingen in demografische, (macro-)economische, en gewasspecifieke factoren op nationaal niveau. De meest invloedrijke factoren waren bevolkingsgroei, ontwikkeling van export en import, en gewasopbrengst. Alle varianten van het ontwikkelde basisscenario (marktliberalisatie, marktbescherming; 1%, 3% en 5% groei van het BNP) en het duurzaamheidscenario hoorden bij dit type. Bij de allocatiegestuurde scenario's hingen landgebruikveranderingen ook af van ruimtelijk specifieke toedelingsvoorwaarden. Het ontwikkelde scenario waarin parken beschermd worden, waardoor ontbossing binnen nationale parken niet meer plaats kon vinden, was een voorbeeld van dit type scenario. Het scenario van een natuurramp, zoals beschreven in Hoofdstuk 5, was een voorbeeld van een realistisch scenario waar veranderingen in de vraag werden gecombineerd met locatiespecifieke wijzigingen.

Ruimtelijk expliciete modellering

De resulterende kaarten uit de allocatiemodule van het CLUE modelleer-raamwerk werden besproken voor de Atlantische Zone (Hoofdstuk 2), en Honduras en Midden-Amerika (Hoofdstuk 5). De allocatiemodule combineerde de ruimtelijk expliciete informatie, zoals die verkregen werd uit de empirische analyses op meerdere schalen, met de niet-ruimtelijke gebiedsontwikkeling resulterende uit de scenariostudies. Resultaten van de verschillende deelstudies, meest in de vorm van kaarten die de plekken met de hevigste veranderingen ("hot-spots") aangaven, toonden de haalbaarheid van de toepassing van het CLUE model op verschillende ruimtelijke schalen. Bevredigende resultaten werden geboekt voor zowel de Atlantische Zone als voor heel Midden-Amerika. Resultaten van het natuurrampscenario voor Honduras afzonderlijk en voor heel Midden-Amerika gaven aan dat de gevolgen van een orkaan op landgebruikpatronen, hoewel in eerste instantie groot, waarschijnlijk zouden verdwijnen binnen een periode van 10 jaar. Concepten uit de ecologie werden gebruikt om het gemodelleerde gedrag van het landgebruiksysteem te illustreren. Op die manier werd aangetoond dat CLUE in staat was om ruimtelijk expliciete veranderingen in landgebruik voor een aantal uiteenlopende scenario's na te bootsen. De gevolgen van het beschermen van nationale parken, macroeconomische veranderingen, alsmede een extreme weersituatie konden geëvalueerd worden.

Validatie

Ondanks de veelheid aan modellen en ondanks de algemene consensus dat validatie een essentieel onderdeel zou moeten zijn van elk model, ontbeerde de meerderheid een validiteitscontrole, veelal vanwege problemen met data. Alle deelstudies in dit proefschrift werden gevalideerd, mede omdat voor alle studies onafhankelijke datasets beschikbaar waren voor twee verschillende punten in de tijd. Statistische relaties tussen landgebruik en de ruimtelijke bepalende factoren werden vastgesteld voor de oudste van de twee datasets. Daarna werd de CLUE allocatiemodule gedraaid, van het oudste jaar tot aan het meer recente jaar waarvoor data beschikbaar waren. De validatie werd gekwantificeerd door de gemodelleerde en de feitelijke landgebruikveranderingen statistisch te vergelijken. Voor de Atlantische Zone, Honduras en Costa Rica, werd de allocatiemodule van CLUE met succes gevalideerd. Bevredigende statistische determinatiecoëfficiënten voor de relaties tussen feitelijke en gemodelleerde landgebruikpatronen werden verkregen. Daarnaast werd voor Honduras en Costa Rica een validatie uitgevoerd op meerdere schalen, een logisch voortvloeisel van het analyseren en modelleren op meerdere schalen. Resultaten verbeterden snel en exponentieel met de verslechtering van ruimtelijke resolutie. De validaties toonden aan dat het CLUE modelleer-raamwerk veranderingen zoals ze plaatsvonden in Midden-Amerika tussen de jaren 70 en jaren 90 kon reproduceren.

Belanghebbenden

Er werden drie groepen van mogelijke gebruikers van het CLUE model geïdentificeerd, namelijk andere modelleurs, boeren en nationale of regionale beleidmakers. De ontwikkeling van het CLUE modelleer-raamwerk werd geïnitieerd door een vraag vanuit de gemeenschap van mondiale modelleurs. Uiteindelijk zou een aantal landgebruikmodellen samen in een serie gebruikt kunnen worden, om zo een zogenaamde 'gereedschapskist' van modellen te vormen. Resultaten van een model dat op een grove schaal werkt zouden ruimtelijk meer gedetailleerde modellen kunnen helpen focussen. Die modellen kunnen dan gebruikt worden om plaatselijke processen te modelleren. In zijn huidige vorm zou het CLUE model weinig waarde hebben op boerderijniveau. Het model is echter zo gemaakt, dat noch de toepassing op een ruimtelijk meer gedetailleerd niveau, noch de vervanging van statistische relaties door enig ander soort van (op processen gebaseerde) regels problematisch zou zijn. Beleidmakers op verschillende organisatorische niveaus zijn een groep van mogelijke belanghebbenden, die aangesproken kunnen worden met het model in zijn huidige vorm. De Midden-Amerika deelstudie die gepresenteerd werd in Hoofdstuk 5, was een voorbeeld van hoe dit in de praktijk zou kunnen functioneren. De wederzijds profijtelijke samenwerking tussen verschillende internationale instituten toonde aan hoe een model zoals CLUE, in de eerste plaats ontwikkeld om in een wetenschappelijke behoefte te voorzien, gebruikt werd door andere belanghebbenden. Het gebruik van een kennisbemiddelaar, een tussenpersoon die de mensen die de kennis gebruiken (beleidmakers) verbindt met diegenen die de kennis creëren (wetenschappers), was het decor voor deze succesvolle communicatie.

Curriculum vitae

Kasper Kok was born in Oss on March 22nd, 1968. He completed secondary school (VWO) in 1986 at the Rijksscholen Gemeenschap (RSG) in Lochem and started his study biology at the Universiteit van Amsterdam. In 1992 he graduated 'cum laude' as tropical ecologist, with specialisations in vegetation analysis and modelling, population dynamics, and the effects of burning and grazing on the páramo ecosystem in Colombia. In 1992 he took a course on rural land evaluation at the International Institute for Aerospace Survey and Earth Sciences (ITC) in Enschede, which skilled him in various remote sensing techniques and the use of Geographical Information Systems. After this shift of interest, he was stationed at ITC from 1993 until 1996. During this period he was involved in a multitude of research and educational activities. A key research topic was a multi-scale analysis of actual water erosion in Spain as part of the ASMODE (ASsessment and MOnitoring of DEsertification in the Mediterranean region) project. Further research activities concerned an agroecological characterisation of Burkina Faso using satellite imagery. Teaching activities included lecturing (remote sensing and GIS principles), fieldwork assistance, and practical assistance (aerial photo interpretation and GIS). In March 1996 he started the PhD-research that is described in this thesis at the Agronomy Department of Wageningen University. The research was financed by the Dutch National Programme on Global Air Pollution and Climate Change. Since March 1999, he was stationed at the Laboratory of Soil Science and Geology. He carried out extensive parts of his work at and in close collaboration with the GIS department of the Centro Internacional de Agricultura Tropical (CIAT) in Colombia. He also spent stretches of time at the Research Centre of Wageningen University in Guápiles, Costa Rica. As from January 2001, he will be employed as post-doc at the International Centre for Integrative Studies (ICIS) in Maastricht.