Exploring the spatial and temporal dynamics of land use with special reference to China

Peter Verburg

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Proefschrift
ter verkrijging van de graad van doctor
op gezag van de rector magnificus
van Wageningen Universiteit
Dr. C.M. Karssen,
in het openbaar te verdedigen
op maandag 19 juni 2000
des namiddags te half twee in de Aula.

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

CIP-gegevens Koninklijke Bibliotheek, Den Haag

Verburg, P.H., 2000

Exploring the spatial and temporal dynamics of land use - with special reference to China.
Thesis Wageningen University. - With summaries in English and Dutch.

ISBN 90-5808-200-8

Keywords: land use change, agro-ecosystems, spatial scales, modelling, natural resources, China, Ecuador, Indonesia

Stellingen

1. Er bestaat niet één optimale schaal waarop we agro-ecosystemen kunnen bestuderen. Daarom moet het gedrag van deze systemen geanalyseerd worden als een functie van de schaal van analyse.
   Dit proefschrift
   S.A. Levin, 1992. The problem of pattern and scale in ecology. Ecology 73: 1943-1967.

2. Het bestuderen van het huidige landgebruikpatroon in relatie tot de natuurlijke en sociaal-economische omgeving is onmisbaar om inzicht te verkrijgen in de factoren en processen die landgebruikveranderingen veroorzaken.
   Dit proefschrift

3. Het identificeren van potentiële toekomstige 'hot-spots' van landgebruikveranderingen door middel van ruimtelijk expliciete modellen maakt het mogelijk interventie in het landgebruiksysteem te richten op de juiste geografische locaties.
   Dit proefschrift

4. Kennis van het sociaal-economisch gedrag van individuele actoren van landgebruikveranderingen is niet afdoende voor het voorspellen van landgebruikveranderingen op regionale schaal.
   B.L. Turner II, D.L. Skole, S. Sanderson, G. Fischer, L.O. Fresco, R. Leemans, 1995. Land-Use and Land-Cover Change, Science/Research Plan. IGBP Report 35, HDP Report 7.

5. De ruimtelijke variabiliteit in inkomen en gewaskeuze illustreren dat van de enorme economische groei die China de afgelopen decennia kende weinigen veel en velen weinig hebben geprofiteerd.
   Dit proefschrift

6. Ondanks het vele praten over interdisciplinariteit is er nog steeds een groot gebrek aan wetenschapplijke methoden voor interdisciplinair onderzoek.

7. Optimistische schattingen van de capaciteit van de aarde om voedsel te produceren die gebaseerd zijn op berekeningen van de potentiële gewasproductie doen onrecht aan de ernst van het wereldvoedselprobleem.
   F.W.T. Penning de Vries, H. van Keulen, R. Rabbinge, 1995. Natural resources and limits of food production in 2040. In: J. Bouma et al. (eds.), Eco-regional approaches for sustainable land use and food production, Kluwer Academic Publishers, 65-87.

8. Onderzoek naar landgebruikveranderingen is teveel gericht op (tropische) ontbossing terwijl conversies als gevolg van urbanisatie en intensivering van het landgebruik minstens even verstrekkende gevolgen kunnen hebben voor duurzame ontwikkeling en het functioneren van ecosystemen en biogeochemische kringlopen.
   E.F. Lambin, X. Baulies, N. Bockstael, G. Fischer, T. Krug, R. Leemans, E.F. Moran, R.R. Rindfuss, Y. Sato, D. Skole, B.L. Turner II, C. Vogel, 1999. Land-Use and Land-Cover Change (LUCC) Implementation Strategy. IGBP Report 48, IHDP Report 10.

9. Betrouwbare afspraken over reducties van de emissie van broeikasgassen en handel in emissierechten zijn onmogelijk zolang de wetenschap niet in staat is emissies op regionale schaal op betrouwbare wijze te kwantificeren.
   Kyoto-protocol of the United Nations Framework Convention on Climate Change, Kyoto, December 1997.

10. Variabiliteit en diversiteit moeten meer gewaardeerd worden als bron van informatie en inspiratie voor wetenschap en samenleving.

11. Je kunt onmogelijk het denken als zodanig verwerpen maar de toepassing toejuichen.
    Herman Hesse, Narziss und Goldmund, 1930.

12. Het falen van het communisme als staatsvorm wordt ten onrechte gezien als het succes van het kapitalistische staatsbestel.

13. Teveel bureaucratie is een gevolg van de angst voor machteloosheid.

14. Het leven is te belangrijk om het serieus te nemen.
    Rita Mae Brown, Bingo, 1988.

Stellingen bij het proefschrift:
Exploring the spatial and temporal dynamics of land use - with special reference to China

Peter Verburg, Wageningen, 19 juni 2000

C'est n'est pas le géographe qui va faire le compte des villes, des fleuves, des montagnes, des mers, des océans et des déserts. Le géographe est trop important pour flâner. Il ne quitte pas son bureau.

(Antoine de Saint-Exupéry, Le Petit Prince)

Acknowledgements

The work presented in this dissertation is fortunately not a piece of work that I could have done all by myself. Apart from it being impossible and boring, it would not have respected the interdisciplinary approach which I enjoyed such a lot.

First of all, I thank my (co-)promotors Louise Fresco, Johan Bouma and Tom Veldkamp. Louise, thanks for your enthusiasm which motivated me to work on the subject of land use change and for introducing me into the scientific jungle. Unfortunately, after the first year of the work on this dissertation, you left for Rome. I am happy that even from there, you still showed interest in my work. After Louise Fresco's departure Johan Bouma and Tom Veldkamp joined the team as promotor and co-promotor. Johan, I really enjoyed your interest in our work, your real fast comments on the manuscripts and the discussions on the broader perspectives of the work. Tom, as a daily supervisor you were very much involved, which I really appreciate. Thanks also for your sharp insights, clever comments and nice brainstorming sessions.

The case-studies in this thesis are part of the work on land use change modelling of our research team: 'The CLUE group', consisting of Kasper Kok, Free de Koning, Aldo Bergsma and Jörg Priess. Free, thanks for the nice collaboration during the programming of the model, the use of your data-set of Ecuador and all the discussions. Kasper, you were always there for endless discussions on methodologies and very different issues. For everything that had to do with data-handling and GIS Aldo was there to help me. But, above all, you were there to listen to my enthusiasm and complaints. Thank you very much.

As a member of the project 'Upscaling and downscaling of regional methane sources - Rice agriculture as a case study' I would like to thank our project leader Nico van Breemen as well as the other project members, Hugo Denier van der Gon, Peter van Bodegom and Sander Houweling. Hugo and Peter, I will keep good memories of the travels to Asia we made together. Hugo: thanks for all your support.

Many other colleagues within Wageningen University and Research Center made important contributions in discussions, especially Herman van Keulen and Geert Thijssen, and the participants of the PhD-discussion group guided by Alfred Stein.

An important part of this research was done in China, Indonesia and the Philippines. During my short stays in these countries I learned to know a lot of people that have made an important contribution through introducing the characteristics of land use in their country and through giving me a good time. Many governmental institutes, universities and obscure offices were visited abroad and in the Netherlands to collect the numerous databases and documents to make the analysis for the different case-studies. I don't remember names of all the people that provided the data, either because of their duty, interest in our work or just because of their friendliness; you all have been important.
Special thanks go to my counterparts at the Institute of Natural Resources and Regional Planning at the Chinese Academy of Agricultural Sciences in Beijing: Dr. Huajun Tang and Youqi Chen. This research has been very much dependent on you both, not only because of our collaboration during the editing of the database for China, but also because of the joined modelling efforts. Youqi, thanks a lot, and I hope to work with you again in the near future!

I would like to thank my colleagues at the former Department of Agronomy of Wageningen University, as well as at the Laboratory of Soil Science and Geology, where I moved after the organisational changes at the university. Thank you all for providing a pleasant place to work.

Without naming anybody specifically, I would like to thank all my friends who were special to me during these four years!

Mijn ouders verdienen de meeste dank. Jullie continue steun en hulp zijn zo vanzelfsprekend dat mijn dankbaarheid meestal tekort schiet. Daarom: heel erg bedankt.

Wageningen, March 2000

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Chapter 1

Introduction

1.1 The importance of land-use change research

Land cover is defined as the layer of soils and biomass, including natural vegetation, crops and human structures, that cover the land surface. Land use refers to the purposes for which humans exploit the land cover (Fresco, 1994). Land-cover change refers to the complete replacement of one cover type by another, while land-use changes also include the modification of land-cover types, e.g., intensification of agricultural use, without changing its overall classification (Turner II et al., 1993). Changes in land use/cover are the major determinants of changes in our natural environment through numerous interactions between land use/cover and the atmosphere, aquatic systems and surrounding land. Changes in our natural environment directly influence our living conditions through the possibilities that we have to obtain a safe food production in a healthy environment, but also in aesthetic ways through our perception of landscapes and diversity. On the longer term, these changes are not always beneficial for the quality of human existence. Burning of biomass and oxidation of soil organic matter after deforestation or pasture reclamation can increase emissions of greenhouse gases, leading to fast, and therefore unfavorable, changes in global climatic conditions (Riebsame et al., 1994). Intensive cultivation on steep slopes leads to soil degradation, decreasing the possibilities to use this land for food production while uncontrolled pollution of the environment can threaten human health as well as the functioning of ecosystems as a whole.

To avoid unfavorable consequences of land-use changes, systematic approaches of intervention with land use are developed. Land-use planning concerns the whole process in which humans plan to alter land use based upon goals and objectives in combination with information on the functioning of the land-use system (FAO, 1989).

Intervention in the dynamics of land-use systems is impossible without a proper understanding of the driving factors in these systems and their behavior. This introduction gives an overview of different approaches of land-use change research that can inform land-use planning. Special emphasis is given to the role each type of research can play within a research sequence that leads to appropriate land-use negotiations and planning. Based on this overview it is indicated how the methodologies and case-studies presented in this thesis can contribute to this research sequence.

1.2 Research sequences in land-use change studies

The field of land-use change studies is strongly divided by scientific discipline, tradition and scale of analysis. Researchers in the social sciences have a long tradition of studying individual behavior in human-environment interactions at the micro-scale, mostly by narrative approaches. At higher levels of aggregation, geographers and ecologists have studied land-use change either by direct observation, using remote sensing and GIS, or have applied the systems/structures perspective to better understand the organization of society and landscapes (Lambin et al., 1999).

Apart from these differences caused by scientific tradition and scale of analysis there are inevitable also large variations in research approach because of differences in research objectives and stakeholders addressed. Some studies aim at understanding (parts of) the land-use system dynamics by itself, while others aim at intervention in land-use dynamics by means of land-use planning or the design of alternative land-use systems.

A complete analysis of systems, as complex as land-use systems, is impossible with a single research methodology (Bouma, 1997, 1998). Therefore, different research approaches, originating from different disciplinary backgrounds and different scales of analysis should not be considered in isolation but should, rather, be linked and inter-related following a logical sequence (Levin, 1992; Fresco, 1995; Rindfuss and Stern, 1998). This sequence of interconnected methodologies for studying land-use change research problems can be called a 'research sequence' in which the different research methodologies ('tools') are ordered according to their spatial scale of analysis and phase of research.

This section gives an example of a research sequence which aims to achieve changes in the land-use system by steering specific characteristics of the system to avoid or decrease negative impacts of land-use changes (Figure 1.1).

Problem identification phase

Before any in-depth analysis of the land-use dynamics can start, a need exists for a detailed identification and exploration of the problems that may be associated with future land-use changes. Most often, problems are identified by means of rough extrapolations of current trends or monitoring of changes in the environment. A good example of this type of studies are studies by the World Watch Institute (e.g., Brown, 1995a; Brown and Kane, 1994), which contain warnings for global food shortages as a result of growing food demands and deteriorating environmental conditions. In 1995, Lester Brown, president of the World Watch Institute, published a book called 'Who Will Feed China?'. In this rather provoking book he predicts, based on trends and comparisons with other Asian countries, large shortfalls in grain production in China in the near future. This would be induced by conversion of arable land

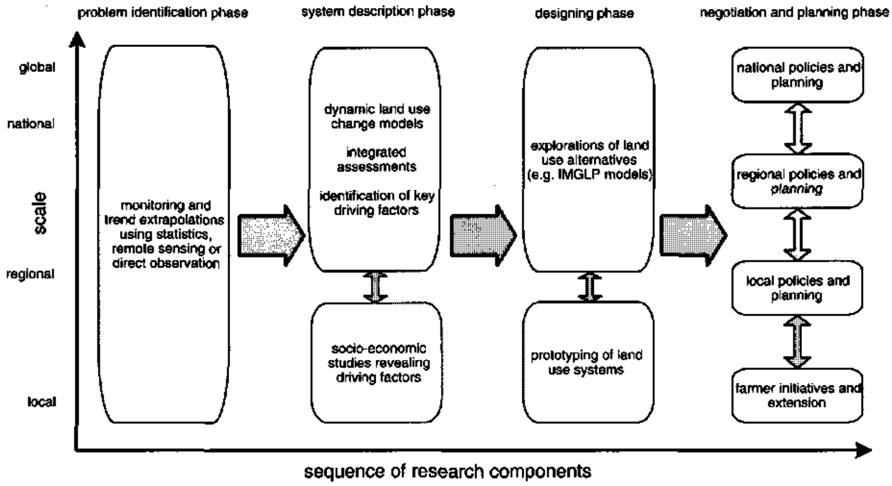

Figure 1.1 *Research sequence for land-use change research*

into urban, industrial and horticultural use, in combination with increasing demands for grain, driven by population growth and changes in consumption pattern. In another book, published in the same period, Smil warns for the large extent of environmental pollution and degradation in China (Smil, 1993). These books have made the world aware of the potential problems China might face in the near future with respect to its food security and the impact that these shortfalls in grain production might have for international trade of grain. Therefore much research was initiated dealing with China's ability to produce it's own grain and how this is influenced by land-use changes (e.g., Heilig, 1997; Lin, 1998; Alexandratos, 1997; Fan and Agcaoili-Sombilla, 1997). Although most of this research proved that China's food problem is not as large as Brown expected, his publication was important for putting these issues on the agenda of politicians and scientists. This is exactly the objective of studies in this research phase.

System description phase

As soon as a potential land-use change problem is identified and research funds have become available, a need for better insight in the land-use system arises. During this 'system description phase' more detailed statements can be made about the land-use situation by adding a spatial dimension to the research. A typical example of such studies is the identification of regions and locations with high rates of land cover change, so-called 'hot-spots', based on remote sensing images (e.g., Achard et al., 1998; Imbernon, 1999). Apart from these 'hot-spots' of land-use change it is also important to obtain more insight into factors that cause land-use changes. At the local level this is mostly done by narrative studies revealing causes and incentives of actors of land-use change (e.g., Rudel and Horowitz, 1993; Jones, 1999). Other approaches include the agent-based and system approach. The former seeks to define the general nature and rules of individual agents' behaviour in their daily decision making. Central to this perspective is the significance given to human agents in determining land-use decisions and the search for generalisations about this behaviour. The systems approach in contrast, finds its basis in the organisation of society and the character of nature that establish opportunities and constraints on decision making (Ostrom, 1990). At coarser scales this approach is more feasible because it is more difficult to distinguish individual actors and relations between actors and the diverse environment. At these scales land-use patterns are related to macro-variables representing proximate drivers of land-use change. Based on these understandings, models can be used to explore scenarios of near-future land-use change (e.g., Hall et al., 1995; Veldkamp et al., 1996). Such spatially explicit models can provide information on what might happen if certain policies or other land-use determinants change. Models are needed because land use is the result of complex processes requiring reflection of non-linearity and spatial and temporal lags in the analysis. Therefore, these models are useful and reproducible tools, supplementing our existing mental modelling capabilities to make more informed decisions (Costanza and Ruth, 1998). Based on information and insights obtained in this phase of the research sequence, scientists, policy makers and other stakeholders can decide if foreseen land-use dynamics are desirable. Agri-environmental indicators (Moxey et al., 1998) are a suitable means to summarise and communicate results and facilitate decision making on the desirability of the foreseen developments. Based upon the understandings obtained in this research phase it is possible to efficiently design alternative land-use plans, focussed on the appropriate issues and geographical locations.

Designing phase

Many methodologies for the design of interventions in present land-use systems are available ranging from the design of appropriate policies and subsidies to landscape design by architects. At the farm level, prototyping (e.g., Vereijken, 1997) is a way to develop farming systems to meet a set of environmental and socio-economic objectives. Based on these objectives, established on the basis of the shortcomings of current farming systems in a region, a theoretical prototype is designed by linking indicators for these objectives to farming methods and designing these methods until they are ready for testing and implementation. At coarser scales studies are made of optimal land-use configurations under a number of constraints. One series of models aimed at designing alternatives for present land use are models using linear programming in order to optimise the land-use configuration and management under a number of agro-technical, food security, socio-economic and environmental objectives (e.g., Bouman and Nieuwenhuyzen, 1999; Zander and Kächele, 1999; Barbier, 1998; Van Ittersum et al., 1998). Results of a run by a linear programming model are characterised by optimised objective values and the associated optimal set of decision variables (agricultural land-use activities: where, what type of agriculture to which extent). Such results can be presented in a table or a bar diagram showing the objective values, and in a map showing the optimum land-use allocation.

Negotiation and planning phase

Based upon the system description phase, which identified the driving factors and sensitivities of the land-use system, and the designed land-use alternatives and prototypes, a plan can be made to implement the research results. During this phase the proper incentives and conditions are created, in close collaboration with the stakeholders involved, that will make the designed land-use plans become reality.

1.3 Objectives of the CLUE modelling framework

The studies presented in this thesis focus on the development and application of methodologies in the 'system description phase' of the research sequence described above. These methodologies are developed to fit within the research sequence, making the methodologies complementary to other methodologies operating at different scales and/or in different phases of research.

Existing methodologies in the 'system description phase' either focus on detailed scales (actor-oriented studies) or are based on the inventory of land-use change by remote sensing. Spatially explicit land-use change models are sparse. Spatially explicit assessments are needed because environmental change does not affect all places similarly, differential impacts and abilities to respond creates winners and losers in this change (Lambin et al., 1999). The identification of the dynamics giving rise to vulnerability of people and places in the face of global change is therefore essential. All methodologies presented in this thesis are therefore designed for spatially explicit analysis at the regional scale. Research that is regional is important because several of the effects accompanying global change will be most significant at the regional level. In addition, the regional level is usually the level at which policy interventions are both possible and effective.

The CLUE (Conversion of Land Use and its Effects) modelling framework has been designed to explore near-future changes in the spatial pattern of land use in Costa-Rica (Veldkamp and Fresco, 1996). The study for Costa-Rica describes where 'hot-spots' of land-use dynamics are probable for a series of different scenarios including variations in urbanisation rate, protection of national parks and biophysical feedback (Veldkamp and Fresco, 1997a).

This thesis describes the development of this framework for the analysis of various aspects of land-use change including changes in land cover, livestock distribution and changes in agricultural management at the regional scale. The tools that make up the CLUE modelling framework are developed with the objective to:

- Provide insight into the spatial variability of land use and its determinants
- Indicate which (proximate) factors determine the spatial distribution of land use
- Account for the scale-dependency of these relations
- Indicate potential near-future 'hot-spots' of land-use change for realistic scenarios

The CLUE modelling framework provides tools to obtain insights into the complexity of the land-use situation as well as tools to explore and quantify near-future pathways of land-use development. This information is meant to serve the effective design of land-use plans in the designing phase. As the CLUE modelling framework primarily is used at relatively coarse scales, additional information at more detailed scales is needed to fully understand the processes involved. Socio-economic, actor-oriented, studies provide a useful tool to investigate these fine scale dynamics. This type of studies could be targeted at 'hot-spots' identified at coarser scales.

1.4 Outline of the thesis

This thesis is essentially a collection of interconnected papers that have been or will be published in international peer-reviewed journals. As a consequence the chapters contain some inevitable overlaps, especially with respect to the description of study area and data-set. It is worthwhile to notice that the studies for China described in Chapter 2 and 7 use a slightly more recent and improved data set as compared to the studies in Chapter 4 and 5. This causes slight differences in simulation results.

Chapter 2 presents the basic principles for studying the pattern of land use in relation to its explanatory variables. Special attention is given to the scale dependency of these relations. Land-use patterns in China are used as a case study.

Chapter 3 consists of a technical description of the tools used for exploring near future changes in the pattern of land use. This chapter outlines the basic characteristics of the approach and underlying theoretical considerations. The procedures used for modelling near-future land-use patterns are described and illustrated with a data set of land use in Ecuador. This chapter also contains a discussion about the behaviour of the model.

Chapter 4, 5 and 6 consist of three applications of the model in densely populated regions where agricultural land is under pressure as a consequence of urban and industrial development. Whereas a larger part of land-use change research has focussed on regions that are characterised by expansion of the agricultural area at the cost of natural vegetation, predominantly rainforest, it is currently recognised that rural-urban dynamics in densely populated areas should be central to land-use change research. Rural-urban dynamics caused by an increasing spread of large, sprawling urban areas competing for peri-urban lands, in combination with changing production-consumption relationships in the hinterlands of these cities, give rise to land-use changes that threaten human and environmental sustainability. *Chapter 4* describes the land-use situation in China and illustrates how the CLUE methodology, as described in Chapter 3, can be used to explore near future changes in land cover. *Chapter 5* elaborates the methodology with a simulation of the dynamic livestock sector in China. Land-use dynamics under population pressures that are even higher than in China are described and modelled in *Chapter 6* for the island of Java in Indonesia. This case-study also allows a proper validation of the model.

Chapter 7 deals with the exploration of changes in the land-use systems of China by combining the results of the land cover dynamics described in Chapter 4 with an analysis of shifts in cropping patterns, grain production intensity and production efficiency. This leads to a more complete assessment of the spatial variability of the different land-use change components that influence food production. *Chapter 8* concludes this thesis with some remarks on the implications of the results for land-use in China and indicates directions for future research.

Chapter

2

Multi-scale characterisation of land-use patterns in China

Peter Verburg and Youqi Chen

Ecosystems (in press)

Abstract

This paper explores the pattern of land use in China to understand the relations between land use and its explanatory variables. Such an understanding is of importance for the development of comprehensive models of land-use dynamics. Correlation and regression analysis are used to identify the most important explanatory variables from a large set of factors that are generally considered to be of importance for the distribution of land use. We found that the spatial distribution of all land-use types in China is best described by an integrated set of biophysical and socio-economic factors. Specific attention is given to the influence of the scale of analysis on the results of the study. Both the resolution of the data and the extent of the study area influence the revealed relations. Relations obtained at a certain scale of analysis may therefore not be directly applied at other scales or in other areas. The possible uses of the systematic and quantitative characterisation of the land-use patterns in China for the use in spatially explicit land-use models is discussed.

2.1 Introduction

The land cover of the earth is heterogeneous at all levels of observation (Allen and Hoekstra, 1991). The distribution of natural land cover types is related to the heterogeneity of environmental conditions such as temperature and moisture (Woodward, 1987). The actual distribution is, however, only occasionally a result of physical limitations. More usually the ecologically allowable is a subset inside what is physically possible (Allen and Hoekstra, 1992). This is mainly due to competition between individual plants or between ecosystems as a whole (Meisel and Turner, 1998).

Human use of land has altered the structure and functioning of ecosystems (Vitousek et al., 1997). Human activities override natural changes of ecosystems caused by climate variations of the past few thousand years. Agriculture, forestry, and other land-management practices have modified entire landscapes and altered plant and animal communities of many ecosystems throughout the world (Ojima et al., 1994). The most spatially and economically important human uses of land globally include cultivation in various forms, livestock grazing, settlement and construction, reserves and protected lands, and timber extraction (Turner II et al., 1994). The pattern of land use can give us insight in the factors that have caused the land cover to change. A better understanding of the determining factors of land-use change is of crucial importance to the study of global environmental change (Ojima et al., 1991; Turner II et al., 1994).

This paper studies the land-use pattern of China to reveal the determining factors of land use at the regional level. The study of land use in China is relevant because China has a long history of human induced modification of land under ever increasing population pressure in a very diverse natural environment. In recent years the high population pressure, in combination with economic developments, has caused the conversion of arable land area into non-agricultural uses. Coupled with the loss of arable land through degradation this is undermining China's food production capacity (Alexandratos, 1997; Smil, 1993; Huang and Rozelle, 1995).

The different processes determining the land-use pattern each have their own optimal scale at which the process can be studied (Fresco, 1995). For the system as a whole there is not an optimal scale (Levin, 1993). Therefore, explicit attention is given in this study to the scale of analysis. A multi-scale approach, comprising the study of the system at different levels of integration, is followed to analyse the system and variety of processes in a more complete way (Holling, 1992).

The objectives of this paper are to provide a spatially explicit characterisation of land use in China by the identification of the major explanatory factors and to determine the spatial scale dependency of the relations found. Furthermore, the paper aims to compare the results of this study with other studies of land-use patterns, especially the classical land allocation theory of Von Thünen (1966). Finally an evaluation is made of the possibilities to use the results of this study for the modelling of land-use change.

2.2 Issues of spatial scale

Land-use patterns are the result of the many processes within the landscape that act over a large number of scales and are linked together in hierarchies. Phenomena occurring at any level are affected by mechanisms occurring at levels below and above (Gibson et al., 1998; Dumanski et al., 1998). Ecologists have stated that the issues of scaling are a fundamental problem in ecology, if not in all of science (Levin, 1992).

Scale refers to the spatial or temporal dimension used to measure and study a phenomenon. All scales have extent and resolution: extent refers to the size of a dimension, e.g., the size of the study area or the duration of time under consideration, while resolution refers to the precision used in measurement, i.e., grain size (Turner et al., 1989). The grain of an observation is the finest distinction made between isolated datum values. It determines the smallest entities that can be seen in the study. Any two entities so small as to fit inside one period in time or space within the measuring system cannot be distinguished and are, therefore, not detected as separate entities in the analysis. In contrast to the grain, the extent determines the largest entities that can be detected in the data. The scale of the study is an interaction of grain and extent. If the extent is large, the sampling protocol will be expensive unless the grain is relatively coarse (Allen and Hoekstra, 1991).

Each analysis of spatial pattern incorporates scale explicitly or implicitly into the process of identifying research objects: the very act of identifying a particular pattern means that scale, extent, and resolution have been employed. These choices over scale, extent, and resolution critically affect the type of pattern that will be observed: patterns that appear at one level of resolution may be lost at lower or higher levels; patterns that occur over one extent of a dimension may disappear if the extent is increased or decreased (Allen and Hoekstra, 1991; O'Neill et al., 1991b; Bergkamp, 1995). Consequently, changes in scale often imply a change in correlation structure (Allen and Hoekstra, 1991; Reed et al., 1993; Curran et al., 1997). Occurrences that are positively correlated in a large-scale universe can become negatively correlated in a smaller universe. Figure 2.1 illustrates the effect of grain size for the analysis of a classical Von Thünen land-use pattern. According to this theory land is devoted to the use with the highest potential rent. Because of transportation costs, the landscape is organised around the urban market in rings of land use of decreasing intensity with increasing distance from the market. When this type of land-use pattern is studied at a detailed resolution (resolution 1 in Figure 2.1) urban land use and horticulture are negatively correlated. However, when analysed at a coarser resolution (resolution 2 in Figure 2.1) urban land use and horticulture fall within the same unit of observation and are therefore positively correlated. Thus, observations and theories derived at one scale may not apply at another. This figure also illustrates that the scales of organisation of natural and human systems are different from the scales of observation, which are often determined by the measurement technique (Allen and Hoekstra, 1990; O'Neill et al., 1991a; Turner II et al., 1995).

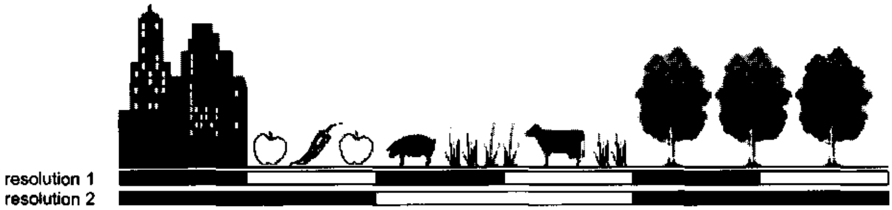

Figure 2.1 *Land-use pattern according to the Von Thünen theory and schematic representation of grain size at two different resolutions*

Previous studies in which the scale dependencies within landscapes have been studied include the work of Bian and Walsh (1993) who explored the scale dependence between terrain and vegetation within the alpine environment of Glacier National Park, Montana. They sought to examine the effective range of spatial scales within which plant biomass and terrain variables were spatially dependent, explore the degree of spatial dependence of these relationships, and assess the optimum spatial scales for representing biomass and terrain relationships. A similar study was made by Walsh et al. (1999) in Northeastern Thailand. In this study they found that the relationships between biophysical and social variables change with the scale of observation. Levin (1992) gives an overview of ecological studies identifying changes in vegetation pattern across scales. Reed et al. (1993); O'Neill et al. (1991b) and Cullinan et al. (1997) illustrate scale effects by changes in the correlation structure of vegetation at different grain sizes and extent.

Although most often applied to natural vegetation at scales ranging from a couple of centimetres to a few kilometres, the concepts of scale dependence are also very relevant to the study of agro-ecosystems (Fresco and Kroonenberg, 1992). Studies by Veldkamp and Fresco (1997b) and De Koning et al. (1998) have shown that the analysis of land-use patterns is subject to scale dependency also at grain sizes ranging from a few kilometres to the national level. Therefore, the scale-dependency of land-use patterns in China is studied in a systematic way by varying the resolution and extent of analysis.

2.3 Data and Methods

Data

Land cover and land use are constrained by environmental factors such as soil characteristics, climate and topography (Turner II et al., 1993), while human factors determine where and to what extent land cover is modified at a certain location. Based on a review of literature dealing with the explanatory factors of land-use patterns (Turner II et al., 1993; Turner II et al., 1995; Kaimowitz and Angelsen, 1998), we selected a large set of factors that are possible predictors of the land-use pattern in China. For these factors spatially explicit information was collected. Because finding detailed information for all factors was not always possible, variables were included that can be regarded as proxies for the explanatory factors. Illiteracy can, for example, be considered an indicator of 'access to information and means', while 'distance to urban centres' determines the access to markets, both for selling and access to means of production. A list of all variables contained in the database is presented in the appendix of this chapter. Most data were derived from agricultural and demographic statistics or surveys, linked to administrative boundaries in a Geographical Information System. Biophysical data were derived from digitised maps, digital elevation models and spatial interpolations of long-term climatic records of a large number of climatic stations. The data based on statistics are valid for 1991.

All data were converted to a regular grid to match the representation of the different data sources and ease the analysis. The basic grid size, to which all data were converted, is 32x32 km (~1000 km^2), which equals the average county size (the basic administrative units for all countrywide statistical data) in the eastern part of China. The average county size in the western part of China is much larger, due to the presence of large uninhabited areas (i.e., deserts and mountains). All statistics were recalculated excluding the deserts as designated in

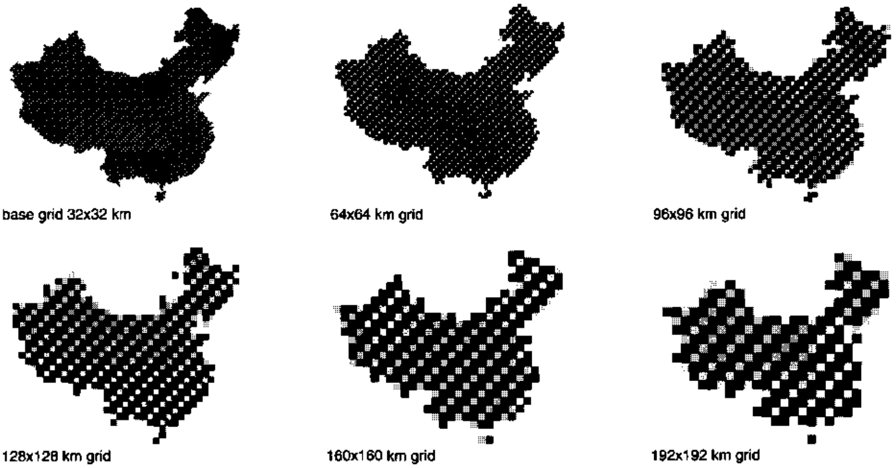
base grid 32x32 km
64x64 km grid
96x96 km grid
128x128 km grid
160x160 km grid
192x192 km grid

Figure 2.3 *Schematic representation of aggregation levels used in analysis*

a vegetation map (CAS, 1979/1996). All other land-use types in the statistics are assumed to be located in the area outside the deserts while population density in the deserts is assumed to be zero.

The dependent variables in our analysis, the distributions of the different land-use types, are represented by designating the relative cover of the land-use types in each grid cell. This data representation differs from the traditional way of representing data, where for each (fine-mazed) grid the dominant land-use type is identified. The data representation is a direct result of the data contained in the census and other statistical surveys that mention for each administrative unit the area occupied by the different land-use types. Figure 2.2 presents the spatial distribution of the analysed land-use types.

There has been considerable discussion on the reliability of Chinese land-use statistics, especially with respect to the amount of cultivated land (Crook, 1993a; Heilig, 1997). The cultivated area in the agricultural survey we have used, equals 133 million hectares, which corresponds with the area generally assumed reliable (Fischer et al., 1998).

Aggregation levels and regional stratification

To test the hypothesis that relationships between determining factors and the land-use distribution will change with the scale of analysis we have used artificial, grid-based data-sets that differ in grain size (i.e., grid cell size). These artificial aggregation levels were created through aggregation of the dependent and independent variables by averaging the data of 2 by 2 cells (64x64 km), 3 by 3 cells (96x96 km), 4 by 4 cells (128x128 km), 5 by 5 cells (160x160 km) and 6 by 6 cells (192x192 km). The six aggregation levels that were created are schematically presented in Figure 2.3. Aggregation of data by a grid-based plurality procedure, where the most frequently occurring sub-grid cover type is used to code each grid cell at each degraded resolution, introduces bias, as some class proportions will diminish and others will increase with scale depending on the spatial and probability distributions of the cover types (Moody and Woodcock, 1994; Milne and Johnson, 1993; Elston and Buckland, 1993). However, all information is retained during our aggregation procedure because of the sub-pixel information data structure as applied in this study.

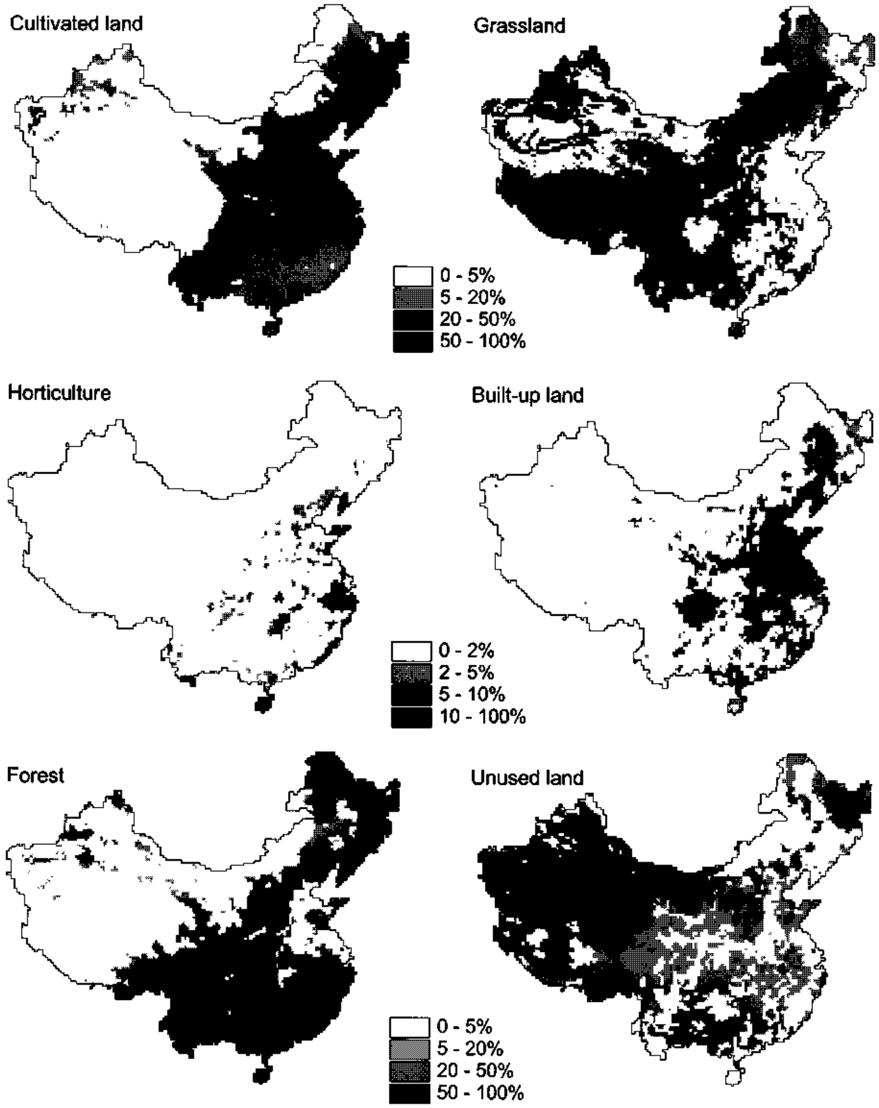

Figure 2.2 *Spatial distribution of the studied land-use types in China; gray shadings indicate the relative proportion of each land-use type within the grid-cell*

Figure 2.4 *Regional sub-division of China*

The influence of the spatial extent of analysis on the results is tested by performing the analysis for the country as a whole as well as for eight individual regions separately. The subdivision in regions decreases the extent of the analysis as compared to the analysis for the country as a whole while the grain size is preserved. The eight regions have been defined based on geographical/natural conditions, demographic and economic features, and province-level administrative subdivisions (Figure 2.4). This stratification differs slightly from the often used regionalisation of the United States Department of Agriculture (Crook, 1993b) which includes the densely populated Sichuan province in the same region as the sparsely populated, remote Tibetan plateau. In our subdivision two separate regions have been created.

Statistical methods

Statistical techniques are well suited to achieve the investigative aims of this study. Simple correlation analysis was used to quantify the relation between individual candidate explanatory factors (independent variables) and the land-use distribution (dependent variables). If no common pattern exists for a candidate explanatory factor, the correlation will likely reflect this in insignificant results. It is essential to emphasise that an explanatory variable found to be significantly related to the land-use distribution, does not necessarily imply that it is a direct cause of the land-use pattern; correlation does not necessarily imply causality.

Multiple regressions are used to derive comprehensive models that describe the pattern of land use as a function of a combination of explanatory factors. Multicollinearity is very common in studies of complex systems, as many candidate explanatory factors are closely related (e.g., geomorphology and soil). A step-wise regression procedure was used to select only the factors that yield a significant ($P<0.01$) contribution to the regression model. For each regression equation the adjusted coefficient of determination (adj-R^2) is a measure for variation in the relative cover of the specific land-use type that can be explained by the model variables. The standardised betas indicate the number of standard deviation changes in the dependent variable associated with a standard deviation change in the independent variable if all other variables are held constant. They are therefore indicative for the relative importance of a variable for land-use change in a given regression equation.

For reasons of simplicity we have only evaluated linear regression. This approach might decrease the explaining power of the regression models, as some explanatory factors will be related to land use in a non-linear way. However, relationships that are non-linear at fine scales tend to be flatter (i.e., more linear) at coarser scales (for details see the discussion by Rastetter et al., 1992). An exploration of the data set indicated that at all scales considered in this study the relations are well represented by linear models.

Geographical patterns nearly always exhibit positive spatial autocorrelation. Stronger spatial autocorrelation indicates a stronger tendency for like values to cluster. So, there is generally a lack of independence present among observations in spatial data sets (Anselin, 1988). In general, autocorrelation results in inefficient parameter estimates and inaccurate measures of statistical significance (Walsh et al., 1997). Correcting the statistical procedures for autocorrelation is not feasible as no satisfactory methods are yet available to deal with spatial autocorrelation in spatial methods (Bockstael, 1996, Fox et al., 1994). The influence of autocorrelation on the results presented in this paper was assessed by estimating the regression models for a large number of replicates of the data-set each consisting of 200 observations randomly selected from the entire set of observations. The average values for the parameter estimates of these replicates did not differ from the parameter estimates for the regression models based on all observations at the same time. This indicates that in this study autocorrelation does not seriously affect the regression results.

Space limitations allow us to present only representative results. All regressions and correlations presented are statistically significant ($P < 0.001$) unless otherwise indicated. R^2 values given are adjusted R^2. However, due to the large sample size, reported and adjusted R^2 were nearly identical.

2.4 Results and interpretations

Land-use patterns

The results of a correlation analysis of the distribution of the main land-use types of China is presented in Table 2.1. The analysis was made for the country as a whole at the finest data resolution (32x32 km). For the different land-use types the 10 variables that have the highest correlation with the distribution of land use are shown.

The distribution of *cultivated land* is strongly correlated with the distribution of population, especially with the distribution of agricultural population. This relation shows the rural character of China, where population and agriculture are strongly clustered. Other important factors explaining the distribution of cultivated land are the suitability of the soil for irrigated rice cultivation, elevation, temperature and some hydrological conditions. This means that cultivated land is also strongly related to the suitability of the soil for agriculture. The distribution of *horticulture* is determined by a similar set of variables. However, here we find that temperature, especially the minimum temperature and the number of months with temperatures above 10 degrees Celsius are important determinants. Horticultural crops often need specific environmental conditions. Especially frost limits the distribution of most horticultural crops. The distributions of *grassland*, *forest* and *unused land* are very much determined by environmental conditions. From the correlations it is clear that these land-use types are mainly found at places unsuitable for agriculture far away from concentrations of population. As the largest areas of grassland in China are found in the highly elevated Plateau region and in Inner Mongolia, *grasslands* are correlated with low temperatures and high elevations. The high and positive correlation with the percentage of the population that is illiterate can be explained by the remoteness of this area. Most *forest* is found in the South of China and in the South Western mountain fringes. This area is also characterised by the highest amount of precipitation in China and relatively high temperatures. The positive correlation with mountainous geomorphology and negative correlation with plain land shows the location of forest on sloping land, unsuitable for agriculture. The category of *unused land* is dominated by the large desert areas, leading to high correlations with low precipitation and many sunshine hours. Finally, the distribution of *built-up land* is correlated with the same factors as the distribution of cultivated land. Obviously, the strongest correlation is found with the total population density followed by biophysical variables indicating the suitability of the land. These correlations show that expansion of built-up land leads to a loss of mainly high-quality, primary farmland.

Many variables indicated in Table 2.1 are highly correlated, hence, some variables yield non-significant contributions in regression models. Multiple regression models, as derived for the different land-use types indicate that the most comprehensive description of the distribution of land use is obtained when at least one variable is included concerning the population distribution, one variable indicating the soil quality, one geomorphological variable and one climatic variable. Explanations range between 0.3 for horticulture and 0.8 for cultivated land. As an example, the derived multiple regression equation for cultivated land is shown in Table 2.2. A large part of the distribution of cultivated land is explained by this equation. Interpretation of multiple regression equations is difficult because, although multicollinearity is reduced by stepwise regression, the remaining correlation between parameters influences the relative importance of the parameters in the equation. In the equation, correlation between the total precipitation and the range in precipitation causes both variables to be included in the model with opposite signs.

Table 2.2 *Variables and standardised beta coefficients (stb) for a multiple regression model*[*] *explaining the distribution of cultivated land (adj-r^2 = 0.81)*

Variable	stb
PRC_TOT	-0.42
PRC_RNG	0.41
PAGLF91	0.37
PTOT91	0.23
MEANELEV	-0.19
GEOMOR2	0.16
PAGPER91	0.12
S1IRRPAD	0.09
MODDRAIN	-0.09
S1MAIZER	0.08
FERT3	0.06
GEOMOR4	0.06

[*] significant at P<0.0001

Table 2.1 *Pearson correlation coefficients[a] for the explanatory factors most related to the distribution of different land use types (n=9204)*

Cultivated land		Horticulture		Grassland		Forest		Unused land		Built-up land	
PAG91	0.81	PTOT91	0.45	TMP_10C	-0.52	PRC_50M	0.67	PRC_RNG	-0.64	PTOT91	0.82
PAGLF91	0.79	PAG91	0.44	TMP_AVG	-0.51	PRC_TOT	0.66	PRC_50M	-0.58	PAG91	0.80
PTOT91	0.79	PRURLF91	0.44	TMP_MAX	-0.51	PRC_RNG	0.66	PRC_TOT	-0.52	PRURLF91	0.77
PRURLF91	0.77	PRC_TOT	0.42	MEANELEV	0.47	SUN_TOT	-0.56	RIVERDIST	0.48	PAGLF91	0.75
S1IRRPAD	0.60	PAGLF91	0.42	ILLIT	0.44	GEOMOR1	0.53	SUN_TOT	0.42	PURB91	0.58
NSIRRPAD	-0.59	TMP_MIN	0.41	TMP_MIN	-0.40	GEOMOR5	-0.46	GEOMOR3	0.39	S1IRRPAD	0.58
MEANELEV	-0.54	PRC_RNG	0.41	PAG91	-0.39	TEXT1	-0.42	PAG91	-0.36	NSIRRPAD	-0.55
SMAXHIGH	0.50	TMP_AVG	0.40	PAGLF91	-0.38	GOODDRAI	0.41	PTOT91	-0.36	BADDRAIN	0.50
TMP_MAX	0.49	TMP_10C	0.38	PRURLF91	-0.38	TMP_10C	0.40	PAGLF91	-0.36	MEANELEV	-0.49
BADDRAIN	0.49	PRC_50M	0.37	PTOT91	-0.38	TMP_MIN	0.39	PRLPER91	-0.35	PRC_RNG	0.47

[a] all significant at P<0.0001

Table 2.3 *Results of stepwise regressions[a] with standardised betas (stb) at different grain sizes for horticulture*

32 km (n=9204) adj-r^2 = 0.30		64 km (n=2307) adj-r^2 = 0.37		96 km (n=1027) adj-r^2 = 0.40		128 km (n=581) adj-r^2 = 0.44		160 km (n=370) adj-r^2 = 0.47		192 km (n=258) adj-r^2 = 0.48	
Variable	Stb	Variable	Stb	Variable	Stb	Variable	Stb	Variable	Stb	Variable	Stb
PRC_TOT	0.43	PRC_TOT	0.66	PRC_TOT	0.94	PRC_TOT	0.79	PRC_TOT	1.21	PRC_TOT	1.03
SUN_TOT	0.34	PTOT91	0.38	PTOT91	0.67	PTOT91	0.41	PRC_50M	-0.60	SUN_TOT	0.46
PTOT91	0.29	SUN_TOT	0.34	PRC_50M	-0.32	SUN_TOT	0.34	SUN_TOT	0.44	PRC_50M	-0.41
TMP_MIN	0.19	PRC_50M	-0.21	SUN_TOT	0.32	PRC_50M	-0.28	PURB91	0.26	PURB91	0.38
PAGRUR91	-0.07	TMP_MIN	0.14	PAGLF91	-0.25	NSIRRPAD	0.22	NSIRRPAD	0.24	NSIRRPAD	0.26
SMAXHIGH	-0.07	NSIRRPAD	0.11	PRC_RNG	-0.18	PURB91	0.18	PRURLF91	0.23	PTOT91	0.23
		GEOMOR4	0.07	TMP_MIN	0.13	GEOMOR4	0.08	GEOMOR4	0.14		
		PAGRUR91	-0.06	SMAXLOW	0.13			TEXT3	0.09		
				GEOMOR4	0.09						

[a] all significant at P<0.0001

Effects of spatial scale

The influence of spatial scale on the relations found above is studied by comparing the effects of both the grain size and the spatial extent of the study.

The effect of *grain size* was studied by comparing the results of a correlation and regression analysis at six different artificial aggregation levels. Figure 2.5 displays the correlation coefficient of a selection of variables for cultivated land at the six aggregation levels. For all variables the correlation coefficient increases with grain size. This increase in correlation coefficient may have been caused by areal aggregation, which reduces the variability. However, the correlation coefficients were not inflated consistently with successive aggregation and for the different variables. Whereas the correlation coefficients of maximum temperature (TMP_MAX) and mean elevation (MEANELEV) stay approximately constant over the range of grain sizes, the coefficients for soil suitability (S1IRRPAD) and urban population density (PURB91) increase strongly with grain size. The change in correlation structure is very much related to the spatial variability of the variable and the distance over which the parameter affects land use. The strong increase in correlation between urban population and cultivated land can be explained by the influence a city has on land use in the surrounding area. With the increase in grain size, an increasing part of the cultivated land around a city falls within the same grid-cell as the urban population, yielding high correlations.

Changes in correlation structure also result in different multiple regression models at different aggregation levels. Table 2.3 presents the multiple regression models as derived for the distribution of horticultural land at different aggregation levels. The overall explanation of horticultural land remains low at all aggregation levels. This is probably due to the different environmental requirements of all crops lumped under horticultural crops (e.g., tea, mulberry plantations and orchards). Although the main variables that explain the pattern of horticultural lands are similar over the range of scales, there are differences in the relative importance of the different variables and different additional variables are added that mediate the relations. Similar to the results for cultivated land the urban population becomes a more important variable at higher aggregation levels.

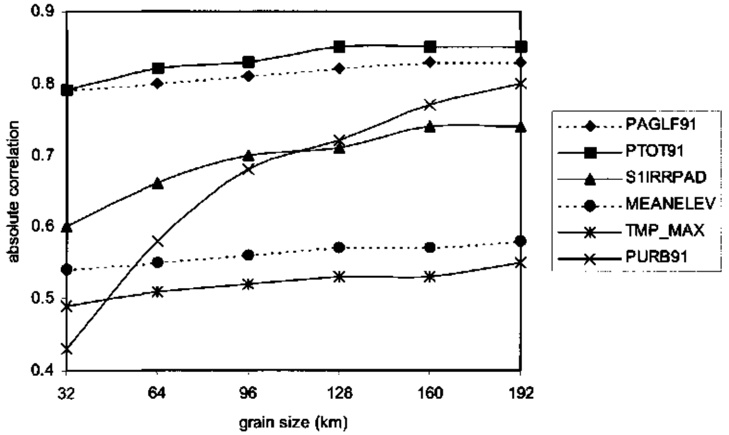

Figure 2.5 *Absolute correlation between the relative cover with cultivated land and a number of explanatory factors (for description see Appendix) at different aggregation levels; all correlations significant at P<0.0001*

Table 2.4 *Most important explanatory factors for the distribution of cultivated land based on Pearson correlation coefficients[a] (n=9204)*

Whole country (n=9204)	Northeast (n=764)	North (n=674)	Northwest (n=3361)	East (n=336)
PAG91	TMP_MAX	GEOMOR1	PAG91	PRC_TOT
PAGLF91	GEOMOR1	PAG91	PAGLF91	GEOMOR1
PTOT91	DEEP	SLOPE	PRURLF91	RANGEELE
PRURLF91	PHYSL	PAGLF91	PTOT91	GOODDRAI
S1IRRPAD	PAG91	GEOMOR5	GEOMOR2	BADDRAIN
Central (n=554)	**South (n=547)**	**Southwest (n=1098)**	**Plateau (n=1870)**	
GEOMOR1	GEOMOR1	PAGLF91	PRURLF91	
PAG91	SLOPE	PAG91	PAGLF91	
PTOT91	TMP_MAX	PRURLF91	PAG91	
GEOMOR5	TMP_AVG	PTOT91	PTOT91	
GOODDRAI	MEANELEV	MEANELEV	PURB91	

[a] all significant at P<0.0001

The influence of the *extent* of analysis was tested by correlation and regression analysis before and after stratification of the base grid data (32x32 km) according to regions (Figure 2.4). The five explanatory factors having the highest correlation with the distribution of cultivated land are presented in Table 2.4. For the country as a whole the pattern of cultivated land corresponds best with the pattern of agricultural population. When the extent of analysis is decreased by analysing the pattern of cultivated land for the individual regions, it is found that not in all of the regions population is the most important explanatory variable. Especially in the regions northeast, east and south the pattern of cultivated land is most related to the geomorphology of the area. Larger differences between the analysis for the country as a whole and the individual regions were found for the less important factors. The most important results for a number of regions are given below. Numbers between brackets indicate the correlation coefficients.

- In the Northeast the land-use distribution is very much dependent on geomorphology and temperature. Cultivated land and orchards are all situated in the plain areas (Northeastern plain and Sanjiang plain), which have comparatively favourable temperatures and deep (DEEP: 0.67), fertile soils (FERT3: 0.34), suitable for agriculture (Qiguo and Qingkui, 1988). The mountainous areas surrounding the plain have a harsh climate only suitable for forest and grassland. Forest and grassland are mainly distributed according to precipitation. Areas with higher precipitation are afforested (PRC_TOT: 0.41) while the dryer areas are mainly covered by grassland (PRC_TOT: -0.47).
- In the Northwest climatic parameters limit the distribution of land-use types. In this dry region cultivated land is only found in the wet and relatively warm areas while forest and grassland are found in the relatively wet, but cooler areas. All other parts of the region are too dry for plant growth (PRC_TOT: -0.71) and are therefore classified as unused land, i.e., desert. Typical for the region is the positive correlation between cultivated land and the area with loess deposits (GEOMOR2: 0.61). The correlation with the loess deposits also explains the lack of clearly negative correlations with slope and other variables representing mountainous land forms, as they are found in other regions. The intensive cultivation of the large loess-covered region explains these observations. The Loess

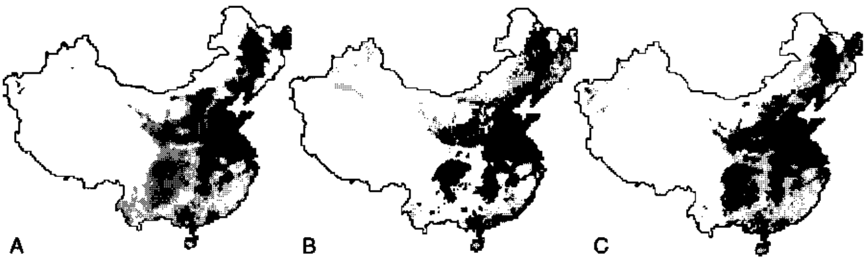

Figure 2.6 *(A) Actual distribution of cultivated land (dark colours indicate high cover percentages); (B) Distribution of cultivated land as modelled with the country-wide regression equations; (C) Distribution of cultivated land as modelled with the region-specific regression equations*

Plateau, a very extensive area (530,000 km^2 - larger than Spain), has been used for agriculture since ancient times (Fang and Xie, 1994; Bojie, 1989). In those times conditions were very favourable for agriculture: the land had a suitable humidity and forest-steppe or grassy vegetation, it possessed fertile and loose soil developed from loess, it was a flat land, which was easily reclaimed as farmland and was convenient for travel. However, the climatic conditions, which cause very variable rainfall which falls in high-intensity rainstorms, together with the soil characteristics make the area very susceptible to soil erosion. Nowadays, the loess plateau is one of the most seriously eroded landscapes in the world and is steeply dissected by deep gullies and valleys (Hardiman et al., 1990). So, the once prosperous agricultural region has turned into one of the most backward regions, which has lost most of its favorable characteristics for agriculture. With respect to the correlation results for cultivated land this means that in earlier times the distribution was more correlated with flat and fertile land, similar to the other regions. Nowadays the distribution can only be explained by the occurrence of high population densities and loess deposits.

- In the Southwestern region, which contains the foot-slopes of the Himalaya mountains, differences in altitude are large. This explains the importance of the elevation for the distribution of population and land-use types. While agriculture is found at low elevations (MEANELEV: -0.72) grassland is found on high elevations (MEANELEV: 0.75). Forest is not strongly correlated to the mean altitude in this region (MEANELEV: 0.07) but mainly found on steep slopes (SLOPE: 0.50). Typical for this region is the negative correlation between cultivated land and high soil fertility (FERT3: -0.48) and the positive relation between soil fertility and grasslands (FERT3: 0.64). These relations do not follow the national pattern but can be explained by the occurrence of fertile soils in the higher mountain ranges and plateaux, which are too high and too cold for agricultural use. So, in spite of the lower soil fertility, agricultural activities must be concentrated on the lower situated soils.
- In the Plateau region agricultural land use is concentrated around the sparsely distributed centres of population (PTOT91: 0.79, PAG91: 0.97, Ryavec and Veregin, 1998). Due to its extremely high elevation, the relation between forest and temperature is opposite to the relation found in other regions: here forest is positively correlated with temperature (TMP_MIN: 0.75). Grasslands and unused land (bare rock etc.) occupy the remaining area.

The results show similarities but also clear differences between individual regions and the results for the entire country. When the country is analysed as a whole, the general relation between land use and its determining factors is found. After stratification, region-specific conditions pop-up in the results. Although the explaining power (R^2) of the regression in the individual regions is generally similar or slightly lower than the R^2 of the regressions for the whole country, the overall explanation of the land-use distribution is much higher after stratification. In Figure 2.6 this is visualised for cultivated land by presenting the actual distribution of cultivated land (A), the distribution as modelled by the regression equation valid for the country as a whole (B, Table 2.2) and the distribution when the regressions are made for the eight individual regions (C). The overall explanation of the distribution of cultivated land equals 0.81 for the countrywide regression. When for all regions the region-specific regressions are used an overall correlation of 0.92 is obtained, showing the important contribution of region specific factors. Especially in the North-Eastern region a much better representation of the distribution of cultivated land is found due to the inclusion of climatic and geomorphologic variables into the regression equation for this region.

2.5 Discussion

Discussion of the methodology

The methodology used in this study is able to characterise the pattern of land use in relation to the spatial distribution of its explanatory variables. The methods used in this study are based on ordinary least squares regression analysis. In most studies of landscape pattern more advanced techniques for pattern analysis are used (Turner et al., 1991; Gustafson, 1998). However, these methods are developed for spatial patterns in which individual observations represent the dominant vegetation or land use at that location. In our study each observation (grid-cell) represents the relative cover of the different land-use types. This data representation is more appropriate for large-scale studies and matches the data structure of land-use statistics.

Many relations found are straightforward and in correspondence with our understanding of land use. However, the systematic analysis allows us to define the relative importance of the different explanatory factors and quantifies the regional differences. Although it is well understood that correlations are no substitute for mechanistic understanding of relationships, correlations can play an invaluable role in suggesting mechanisms for further investigation (Levin, 1993).

In general the explanatory power of the correlations and regression models is high, indicating that we are able to capture the key factors explaining the land-use distribution. Although the current analysis does not include important social-cultural factors such as tenure, ethnicity and tradition, this analysis provides a good framework to incorporate additional social-cultural data when they become available.

The validity of the results is also dependent on the temporal stability of the relations found. Temporal stability was analysed by repeating the analysis with data for 1986. The spatial structure found is very similar to the spatial structure of 1991. This can be attributed to the small changes in land use during this short period. Unfortunately land-use data for years further apart are not available for China. Evidence from studies in Costa Rica (Veldkamp and Fresco, 1997b) and Japan (Hoshino, 1996) has indicated that the land-use structure, i.e., the relation between the land-use distribution and its explanatory factors, can be stable over longer time periods (respectively 11 and 20 years), in spite of large changes in land use.

Scale issues

The results of our analysis show that the relations between land use and its predictors are influenced by the grain and extent of analysis. The methodology presented in this paper enables the identification of scale dependencies. However, it is not possible to indicate the factors causing these scaling properties. Possible explanations for the influence of the grain of analysis are:

- The reduction of spatial variability: coarse grain sizes obscure variability while fine grain sizes obscure the general trends. Shifts in grain size may produce more than averages or constants: they may make homogeneity out of heterogeneity and vice versa (Kolasa and Rollo, 1991).
- Emergent properties: changes in grain size are frequently associated with new or emergent properties. In complex, constitutive hierarchies, characteristics of larger units are not simple combinations of attributes of smaller units.
- The influence some factors can have over a considerable distance. At coarse grains these factors fall within the same unit of analysis and cause therefore a change in correlation structure (Figure 2.1).
- Stronger overlap among variables. Aggregation reduces intraclass variance and the size of the sample population, smoothing the distributions and reducing the number of outlier values identified within each class. This can create strong overlap among variables, greatly reducing the potential value of such variables for distinguishing classes.

The influence of the extent of analysis can be explained by the decreasing importance of local situations with an increasing extent of analysis. Our analysis for the different regions has shown that relations found at the national extent are not always valid at the regional extent and vice versa. A smaller extent also allows the introduction of specific variables that are important for the area under analysis. So, a smaller extent offers better insight into the specific situation of the region while a larger extent allows the identification of the general patterns.

This all illustrates that decisions about the grain size and extent of the study area can greatly influence the strength and nature of the relationships observed. Investigators must be aware of the scale-related limitations of any study. The inclusion of multiple scales of observation through involvement of several grain sizes and varying extent can be critical for the understanding of land-use patterns and processes.

Comparison of results with other studies of large scale land-use patterns

The classical analysis of the allocation of land to competing agricultural activities is that of Von Thünen (1966). Von Thünen's model of the isolated state describes the land-use pattern that is found when land-use intensity is directly related to the potential rent (farm-gate value of output minus the cost of inputs) attached to a plot of land. Von Thünen describes the resulting land-use pattern for a large, uniform, fertile plain surrounded by uncultivated wilderness, by which this state is absolutely cut off from the rest of the world. In the centre of this plain a very large town is found. Under the assumption of a uniform region, economic

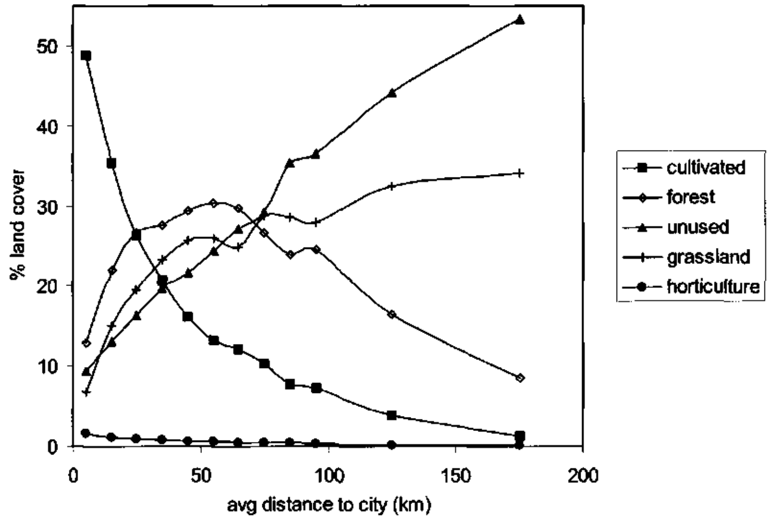

Figure 2.7 *Relation between land cover and the average distance to the nearest city; points represent average land cover for all cells in a 10 km interval (for distance < 100 km) or a 50 km interval (for distance > 100 km)*

rent will decrease as distance from the market increases because of transportation costs. As a result, the landscape is organised around the market in rings of land use of decreasing intensity with increasing distance from the market. In the outermost ring, it is uneconomical to produce for the market due to high transportation costs and, thus, the dominant land use is natural forest. In the classic example, farmers working near a city find that vegetables are more profitable to produce than grain. Because vegetables are perishable, they are more expensive to transport than grain. Thus at some distance from the city grain becomes more profitable to produce than vegetables. The price level and the extent of cultivation of this 'isolated state', is in an equilibrium with the size of the urban population and the quantities demanded of various food stuffs and other agricultural products (Alonso, 1964).

Figure 2.7 presents the average land-use structure for groups of grid cells sharing the same distance class to the city. The area of horticultural and cultivated land decreases strongly with the distance to a city. After an initial increase, forest shows a decrease with distance as the distance to city rises above 70 km. At distances higher than 70 km land use is dominated by grasslands and unused land. At this distance the decrease of forest cannot be attributed to human influence, but mainly to the natural conditions that do not support forests. Although these patterns correspond with the Von Thünen theory, the variation is very large. Factors other than distance to city are often more important determinants of the land-use pattern than the distance to city. In Table 2.1 distance to city is not found with the ten most important factors for any of the land-use types. The distribution of crops in China does not show typical Von Thünen rings around cities at all. This lack of pattern related to city distance can probably be attributed to the inability to capture patterns that occur within a few kilometres distance with our data resolution and to the many interrelating conditions that actually determine the spread of the crops. Furthermore, farms are often highly diversified while the Von Thünen model only focuses on the rentability of individual crops (Walker and Homma, 1996). With the development of infrastructure transportation costs become lower, resulting in less pronounced cultivation patterns as a function of the distance to the city (Peet, 1969).

However, the infrastructure for transportation of agricultural commodities in China is not well developed yet (World Bank, 1997). Several authors have elaborated the theoretical model of Von Thünen to better account for this type of factors (e.g. Alonso, 1964; Beckman, 1968). However, even then, the theory is very simplified compared to real situations, as captured by our analysis, in which the very diverse biophysical conditions and interactions between development, infrastructure and income influence the land-use pattern.

The complexity of the system therefore renders mechanistic models to explain the land allocation not feasible. Empirical and econometric methodologies, like the one proposed in this study, provide, however, valuable tools to estimate the relations that determine the spatial pattern of land use. Studies by Bockstael (1996), Chomitz and Gray (1996), Fox et al. (1994), Walsh et al. (1997), Veldkamp and Fresco (1997b), Hoshino (1996) and De Koning et al. (1998) have all used empirical techniques to quantify the complex relationships between land-use patterns and determining factors. Unfortunately it is difficult to compare the results of these studies as different scales of analysis have been used. Only the most general patterns, which are derived at similar scale levels can be used for comparison. In Ecuador (De Koning et al., 1998) and Costa Rica (Veldkamp and Fresco, 1997b) natural vegetation was found to be associated with less endowed areas with low population densities and natural conditions that are unfavourable for agriculture. Cultivated land and grassland is located in the more populated areas where their surface area is related to the relative preference of one land-use type compared to the others, based on rural and urban demands for specific crop products, suitability of crops to biogeophysical conditions, labour requirements, proximity to markets and infrastructure, and levels of education. Similar patterns were also found in Java under high population pressures which are more similar to the Chinese situation (Verburg et al., 1999c). Hoshino (1996) determined the land-use structure of Kansai District, a densely populated area in Japan. He found that forestry is distinguished from other land-use types by topographical differences between mountain areas and lowland areas and the distance to the cities. Residential land is separated from farm land by the level of economic activity in agriculture.

In spite of the large differences between the studies mentioned, the general structure of land use is very similar. Natural vegetation is always found at the places that are less suitable for agriculture while cities affect land use surrounding the city by the high demands for cash crops. It is also important to notice that in all studies both biophysical and socio-economic factors prove to be important. So, land use is more than the product of human behaviour, for it is intimately tied to the physical environment. Similar social, political, and economic conditions of decision making in dissimilar physical environments usually yields different land uses. Environment mediates and conditions land use (Meyer et al., 1992). Therefore, all analysis of land use should integrate biophysical and socio-economic conditions. Interdisciplinary approaches and theories are needed to analyse land use. Disciplinary theories, like the Von Thünen model, will always be too restrictive for interdisciplinary work (Bockstael, 1996; Myers, 1993; Brush and Turner II, 1987).

Implications for land-use change

A variety of approaches for land-use change modelling have been developed in recent years (reviews are provided by Lambin (1997), Kaimowitz and Angelsen (1998), Dale and Pearson (1999) and Bockstael and Irwin (2000)). All spatially explicit land-use change models need quantitative information about the relation between land use and socio-economic and biophysical factors. In case-studies at relatively detailed scales these relations are often based on mechanistic understanding of the processes underlying the land-use patterns. For higher aggregation levels, comparable to our study, it is extremely difficult to establish deterministic, causal, relations in a straightforward way because most of our understanding of land-use processes is only valid for local situations. The processes and their relative importance at higher aggregation levels are not necessarily the same through scale dependencies and emergent properties. Therefore, even if we would be able to quantify in a process-based way all relations between land use and its explanatory factors, we would still not be able to use these relations straightforwardly at higher aggregation levels. Empirical results, e.g., multiple-regression models, provide a good alternative. These regression models are derived at the scale of analysis and scale dependencies can be quantified. Upon a change in one of explanatory factors of land use (e.g., due to migration, population growth or urbanisation), a new land-use configuration can be calculated. This type of calculation is part of the CLUE modelling framework (Veldkamp and Fresco, 1996), which explores changes in land-use pattern, combining regression models of the spatial structure of land use with the dynamic, multi-scale, simulation of competition between land-use types.

This type of regional-scale models provides an essential link between small-scale, mechanistic studies of land-use change that offer detailed insights into specific cases that cannot necessarily be generalised (Turner II et al., 1993; Meyer et al., 1992; Wiens, 1989) and integrated assessment models at the global level that often use very simplified relations between land use and its determinants, so that important driving factors are overlooked (Easterling, 1997; Wilbanks and Kates, 1999).

Appendix *Description of variables in data base*

Variable name	Description	Units	Source
Land-use types	*(% of the total area used for)*		
CULT91	Cultivated lands	%	INRRP/CLUE, 1998
ORCH91	Horticultural lands	%	INRRP/CLUE, 1998
FOREST91	Forestry lands	%	INRRP/CLUE, 1998
GRASS91	Grasslands	%	INRRP/CLUE, 1998
URBAN91	Lands for settlement and industry (built-up land)	%	INRRP/CLUE, 1998
UNUSED91	Unused lands: deserts, glaciers, saline lands etc.	%	INRRP/CLUE, 1998
Demography			
PTOT91	Total population density	persons/km^2	INRRP/CLUE, 1998
PAG91	Agricultural population density	persons/km^2	INRRP/CLUE, 1998
PURB91	Urban / non-agricultural population density	persons/km^2	INRRP/CLUE, 1998
PRURLF91	Rural labour force density	persons/km^2	INRRP/CLUE, 1998
PAGLF91	Agricultural labour force density	persons/km^2	INRRP/CLUE, 1998
PAGPER91	% of population belonging to agric. population	%	INRRP/CLUE, 1998
PRLPER91	% of population belonging to rural labour force	%	INRRP/CLUE, 1998
%AGLF91	% of population belonging to agric. labour force	%	INRRP/CLUE, 1998
PAGRUR91	% of rural labor force belonging to agric. labour force	%	INRRP/CLUE, 1998
Socio-economics			
ILLIT	Fraction of population that is illiterate (1990)	-	Skinner et al., 1997
INCOM91	Net income per capita	RMB/person	INRRP/CLUE, 1998
DISTCITY	Average distance to city	km	Tobler et al., 1995
Soil related variables	*(Fraction of the total land area with)*		
GOODDRAI	Well drained soils	-	FAO, 1995
MODDRAIN	Moderately drained soils	-	FAO, 1995
BADDRAIN	Badly drained soils	-	FAO, 1995
SHALLOW	Shallow soils	-	FAO, 1995
DEEP	Deep soils	-	FAO, 1995
S1IRRPAD	Soils very suitable for irrigated rice	-	FAO, 1995
S2IRRPAD	Soils moderately suitable for irrigated rice	-	FAO, 1995
NSIRRPAD	Soils not suitable for irrigated rice	-	FAO, 1995
S1MAIZER	Soils very suitable for rainfed maize	-	FAO, 1995
S2MAIZER	Soils moderately suitable for rainfed maize	-	FAO, 1995
NSMAIZER	Soils not suitable for rainfed maize	-	FAO, 1995
SMAXHIGH	Soils that have high moisture storage capacity	-	FAO, 1995
SMAXLOW	Soils that have low moisture storage capacity	-	FAO, 1995
FERT1	Poor soil fertility	-	CAS, 1978/1996
FERT2	Moderate soil fertility	-	CAS, 1978/1996
FERT3	High soil fertility	-	CAS, 1978/1996
TEXT1	Coarse soil texture	-	CAS, 1978/1996
TEXT2	Medium soil texture	-	CAS, 1978/1996
TEXT3	Fine soil texture	-	CAS, 1978/1996
Geomorphology			
MEANELEV	Mean elevation	m.a.s.l.	USGS, 1996
RANGEELE	Range in elevation	m	USGS, 1996
SLOPE	Slope	degrees	USGS, 1996
PHYSL	(Fraction of the area with) level land	-	FAO, 1994
PHYSS	(Fraction of the area with) sloping land	-	FAO, 1994
PHYST	(Fraction of the area with) steep sloping land	-	FAO, 1994
PHYSC	(Fraction of the area with) complex valley land forms	-	FAO, 1994
GEOMOR1	(Fraction of the area with) mountains	-	CAS, 1994/1996
GEOMOR2	(Fraction of the area with) loess	-	CAS, 1994/1996
GEOMOR3	(Fraction of the area with) eolian land forms	-	CAS, 1994/1996
GEOMOR4	(Fraction of the area with) tableland	-	CAS, 1994/1996
GEOMOR5	(Fraction of the area with) plain land	-	CAS, 1994/1996
EROSION	Index representing the extent and impact of human induced water erosion	-	based on Oldeman and Van Lynden, 1997
RIVERDIST	Average distance from major river	km	CAS, 1989/1996

Appendix *(cont.)*

Variable name	Description	Units	Source
Climate			
TMP_MIN	Temperature in coldest month	°C	Cramer
TMP_MAX	Temperature in warmest month	°C	(experimental data)
TMP_AVG	Average temperature	°C	
TMP_RNG	Difference between warmest and coldest month	°C	
TMP_10C	No. of months with temperature above 10 degrees	months	
PRC_TOT	Total yearly precipitation	mm	
PRC_RNG	Difference between wettest and driest month	mm	
PRC_50M	No. of months with precipitation above 50 mm	months	
SUN_TOT	Average percentage of sunshine	%	
Agricultural production[1]			
INDEX	Multiple cropping index	-	INRRP/CLUE, 1998
GRAIN[2]	% of total sown area sown to grain crops	%	INRRP/CLUE, 1998
CASHC	% of total sown area sown to cash crops	%	INRRP/CLUE, 1998
VEGE	% of total sown area sown to vegetables	%	INRRP/CLUE, 1998
OTHERS	% of total sown area sown to other crops	%	INRRP/CLUE, 1998
YGRAIN	Yield of grain crops	kg/ha	INRRP/CLUE, 1998
FERT	Application of chemical fertiliser	kg/ha	INRRP/CLUE, 1998
IRRI	% of the land that is irrigated	%	INRRP/CLUE, 1998
LABOUR	Labour force density on arable land	persons/ha	INRRP/CLUE, 1998
MANURE	Application rate of manurial fertiliser	ton/ha	Calculated[3]
MACH	% of cultivated land cultivated by machine	%	INRRP/CLUE, 1998

[1] Only used in Chapter 7

[2] In Chinese statistics grain includes rice, wheat, corn, sorghum, millet, other miscellaneous grains, tubers (potatoes), and soybeans

[3] Since there are no statistics on the application of manurial fertilisers we have calculated the data based on livestock numbers and manure production (see: Verburg and Thijssen, 2000)

Chapter

3

A spatially explicit allocation procedure for modelling the pattern of land-use change based upon actual land use

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Ecological Modelling 116 (1999): 45-61

Abstract

Modelling of land-use changes as a function of its biophysical and socio-economic driving forces provides insights in the extent and location of land-use changes and its effects. The CLUE modelling framework is a methodology to model near future land-use changes based upon actual and past land-use conditions. This paper describes how changes in land use are allocated in the model.

A statistical analysis of the quantitative relationships between the actual land-use distribution and (potential) driving forces or proxies of these forces underlies the allocation procedure. Based upon thus derived multiple regression equations, areas with potential for increase or decrease in cover percentage of a certain land-use type are identified. Actual allocation is modified by autonomous developments and competition between land-use types. A multi-scale approach is followed to account for the scale dependencies of driving factors of land-use change. This approach provides a balance between bottom-up effects as result of local conditions and top-down effects as result of changes at national and regional scales.

The modelling approach is illustrated with examples of scenario simulations of land-use change in Ecuador.

3.1 Introduction

Human use of land alters the structure and functioning of ecosystems, and influences how ecosystems interact with the atmosphere, aquatic systems and surrounding land (Vitousek et al., 1997). Changes in land cover through cropping, forestry and urbanisation represent the most substantial alteration through their interaction with most components of global environmental change (Ojima et al., 1994; Turner II et al., 1994).

Apart from its implications for environmental sustainability, land-use change can also have important consequences for food security. Conversion of cultivated land to non-farm uses such as housing, factories and infrastructure in combination with a growing population is for some countries regarded as a serious threat to future food availability (e.g. Brown, 1995a).

A large number of research groups have developed models to simulate and explore land-use changes (overviews are given by Lambin, 1994; Sklar and Costanza, 1991 and Baker, 1989). Differences in modelling techniques often relate to differences in the purpose of the study and the scale of study. Explorative models (e.g. Schipper, 1996; Stoorvogel et al., 1995; WRR, 1992) are developed to design alternatives for present land use. Derived land-use patterns therefore represent optimisations of land use based on biophysical potentials, sometimes including socio-economic estimates of inputs and goals. Another group of land-use change models (e.g. Hall et al., 1995, Zuidema et al., 1994 and Costanza et al., 1990) is developed to explore possible changes in land use in the near future as a function of driving forces. These models provide information about the scope and impact of land-use change, and can be used by resource planners to identify areas that require priority attention. The CLUE modelling framework (the Conversion of Land Use and its Effects) is such a dynamic land-use change model. Veldkamp and Fresco (1996) used this model to simulate land-use changes in Costa Rica. This paper describes the methodology to model changes in the pattern of land use with a new version of this model which can be applied to a wide range of land-use change situations.

3.2 Concepts of spatially explicit modelling of land-use changes

Land-use changes are the result of the complex interaction between human and biophysical driving forces that act over a wide range of temporal and spatial scales. Land-use changes at a given site can be measured and related to their driving factors more or less straightforwardly, but it is difficult to aggregate these changes and relations regionally and globally. Even more challenging is the modelling of regional or global land-use changes in a spatially (semi-) explicit way. Highly aggregated assessments obscure the variability of geographic situations through the high aggregation level of the data, and cause an underestimation of the effects of land-use change for certain regions and certain groups of the population. Spatially explicit assessments can identify critical areas of land-use change and give insight in the changes of the land-use pattern.

In analogy with the theories used in landscape ecology the pattern of land use can be described by its structure, function and change (Forman and Godron, 1986).

Structure refers to the spatial relationships between the components of a landscape. Human factors, like population, technology and economic conditions and biophysical constraints like soil, climate and topography determine the spatial pattern of land use as evolved over time (Turner II et al., 1993; Skole and Tucker, 1993). Population distribution and associated demographic characteristics, e.g. the ratio between urban and rural population, are often considered as most important factors affecting land-use distribution (Heilig, 1994; Turner II et al., 1993; Bilsborrow and Ogoth Ogendo, 1992). Spatially explicit land-use models (e.g. Hall et al., 1995) often use decision rules to describe the relationships between land use and human and biophysical factors. These decision rules are used to allocate land-use changes. For relatively obvious patterns, like deforestation along roads, this approach is suitable. However, when applied to more complex land-use patterns that have developed over large time spans, such decision rules will lead to a more or less incomplete description of the land-use pattern. In complex landscapes the land-use pattern is the result of many, non-linear, interactions between socio-economic and cultural conditions, biophysical constraints and the land-use history.

The IMAGE model (Alcamo, 1994) calculates the allocation of land-use changes in the near future based on the crop production potential of the land (Zuidema et al., 1994). Veldkamp and Fresco (1997a) give a number of reasons why the allocation approach based on yield potential is not feasible for exploring realistic changes in land-use pattern. Actual yields are most often far off from potential yields whereas yield potential does not necessary have a large effect on land-use distributions (Veldkamp et al., 1996).

Function of a landscape refers to the interactions between the spatial elements, such as the flow of energy, materials, and organisms among the components of the landscape. In land-use systems this is e.g. the flow of products from agricultural land-use types to residential land-use types on local to regional scales and the export of cash crops on the national scale. Flows between the different components of the system cause feedbacks within the system, e.g. nutrient depletion as result of unbalanced removal of agricultural products will influence the suitability of the land for agricultural production (Smaling and Fresco, 1993). Another interaction between the spatial elements of the landscape is the competition between different land-use types.

Change refers to the alteration of the structure and function of the land-use mosaic through time, caused by changes in the distribution of the population (e.g. urbanisation) and changes in the biophysical conditions (e.g. climate change or soil degradation).

The effects of spatial scale need to be considered in modelling land-use change. Because landscapes are spatially heterogeneous areas, the structure, function, and change of landscapes are themselves scale dependent. Landscape ecologists have recognised the importance of scale in relation to the level of organisation (i.e. the place within a biotic hierarchy) and regard it as one of the major research themes (Holling, 1992; Turner and Gardner, 1991; Ehleringer and Field, 1993). The structure of the land-use pattern, i.e. the relations between land use and the biophysical and socio-economic conditions, are depending on the scale of observation (Veldkamp and Fresco, 1997b; Walsh et al., 1997; De Koning et al., 1998). As an example the analysis of Hall et al. (1995) can be mentioned. In this study it was found that in areas with a rugged topography the land-use pattern is closely related to topography when analysed at fine scales while these patterns at coarser scales are primarily determined by climatic conditions. Usually coarse scales are useful to reveal the general trends and relations between land use and its determining factors. Factors that influence land cover over a considerable distance (like cities) can only be observed at these coarse scales. However, the high level of aggregation at these coarse scales can obscure the variability of units and processes and is therefore considered inaccurate for fine scale and local assessments.

Land-use models using cellular automata (Balzter et al., 1998; Engelen et al., 1995; White and Engelen, 1993) deal with scale dependency of the drivers in a deterministic way. Cellular automata in land-use models assume influence of driving factors of land-use change over a certain distance. The relations describing the relative impact of neighbourhood conditions (i.e. scale dependency) on land use are most often based on expert knowledge. These techniques attempt to mimic certain scale aspects but fail to unravel the system properties that cause these effects.

The approach used in the CLUE modelling framework to allocate land-use changes attempts to account for the entire system of complex interactions between historic and present land use, socio-economic conditions and biophysical constraints. Interactions between land-use elements and the scale dependency of both the structure and function of the land-use pattern are explicitly addressed as well. The following paragraphs describe the methodology and model structure in more detail. The function of the model is illustrated with examples of land-use change simulations for Ecuador taken from De Koning et al. (1999).

3.3 General structure of the CLUE modelling framework

The model consists of four main modules: a demand module, a population module, a yield module and an allocation module (Figure 3.1). The demand module calculates, at the national level, changes in demand for agricultural products taking into account population growth, changes in diet and import/export quantities. The calculations are based upon trends of the past in combination with projections of future food demand (e.g. Islam, 1995). The population module calculates changes in population and associated demographic characteristics based upon different projections (e.g. Lutz et al., 1994).

The calculated changes in demand and population will influence the spatial distribution and relative importance of different land-use types and associated productions. The yield module calculates, in a spatially explicit way, changes in yield level and yield distribution over the country. The changes in the distribution of different land-use types are calculated in the allocation module. In principal it is assumed that all changes in demand are satisfied by changes in land use following the theoretical framework of Boserup (1965), assuming that

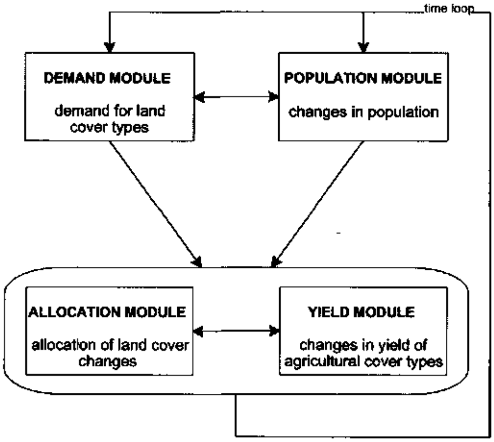

Figure 3.1 *General structure of the CLUE modelling framework*

agricultural production will develop in response to food demand.

The allocation module simulates the pattern of land-use change, not the total quantity of change, which is calculated at the national level in the demand module. All calculations are done on a yearly basis.

3.4 Multi-scale approach

The CLUE model includes two spatially explicit scales at which land use is allocated in addition to the aggregated national scale on which demands are calculated (Figure 3.2). These allocation scales are artificial aggregation levels consisting of grid based data at two different resolutions. A relatively coarse scale is used to calculate the general trends of the changes in land-use pattern and to capture the influence of land-use drivers that act over considerable distance. Based upon the general pattern of land-use change calculated at this coarse allocation scale, but taking local constraints into account, the land-use pattern is calculated at a finer scale level. Depending on the application, area studied and data availability the resolution of analysis will vary. For application in Ecuador a spatial resolution of ~9 x 9 km is chosen for the fine allocation scale while the coarse allocation scale consists of grid cells of ~36 x 36 km.

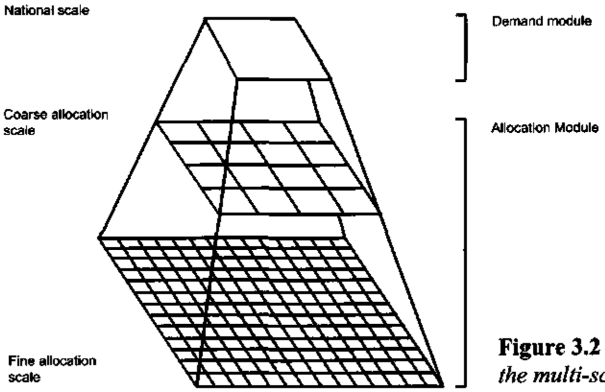

Figure 3.2 *Schematic representation of the multi-scale approach*

3.5 Spatial analysis

The allocation module is based upon a spatial analysis of the complex interaction between land use, socio-economic conditions and biophysical constraints. This interaction is captured by an empirical analysis of historic and/or present land use. This empirical analysis is used to identify the most important biophysical and socio-economic drivers of land use, as well as the quantitative relationships between these drivers and the surface area of the different land-use types. The next paragraphs describe the type of data used and the analysis performed.

Data

Spatially explicit data on the biophysical and socio-economic conditions are collected for the considered study area. Factors which can potentially explain the structure of land use are selected based on literature review and knowledge of the specific situation in the country. The data on land use and socio-economic conditions are obtained from the population and agricultural census or comparable surveys when no census is available. Census data are useful for this type of study because they contain relatively extensive sets of data covering the whole country. Biophysical data are obtained from maps or digital data-sets (e.g. UNEP/DEIA, 1997), containing information on soil conditions, relief and climate. Census data can be implemented in a Geographical Information System by mapping the administrative units for which the data are derived. Because these units only rarely coincide with biophysical units a grid-based system is used to facilitate analysis. Basic grid size is selected based on the average size of the administrative unit for which the census data are used.

In contrast with most grid-based approaches where land use for each cell is determined by the most dominant land-use type, we characterise land use by the relative cover of each land-use type in each grid cell, e.g. a grid cell can contain 30% cultivated land, 40% grassland and 30% forest. This way of representing the data is a direct result of the information contained in the census data.

To allow for a systematic analysis of spatial scale effects, grid data are aggregated into larger grids, of e.g. 16 basic grid units, creating an additional aggregated spatial scale. The new aggregated grid values are averages of the included basic grids. Aggregation of grid cells with dominant land-use types introduces bias as some class proportions will diminish and other will increase with scale depending on the spatial and probability distributions of the cover types (Moody and Woodcock, 1994). However, all information is retained in the sub-pixel information data structure as applied in this study.

Statistical analysis

A stepwise regression procedure is used to identify the biophysical and socio-economic factors that contribute significantly (at 0.05 level) to the explanation of the variability in land-use distribution. In this way it is possible to distinguish which factors have relevance for the spatial pattern of land use. These factors are used to derive multiple regression models of the type:

$$cover_{x,y,t,c} = \beta_0 + \beta_1 \cdot FACT_{x,y,t,1} + \beta_2 \cdot FACT_{x,y,t,2} + \dots$$

Where: $cover_{x,y,t,c}$ = the cover percentage of cover type c in year t for grid cell x,y

β_f = the regression coefficient belonging to factor f

$FACT_{x,y,t,f}$ = the value of factor f (e.g. population density) for grid cell x,y and year t

Expert knowledge and literature review are used to assess the relevance of the relations found. Figure 3.3 summarises the followed procedure. The whole procedure is repeated at the coarse allocation scale. At that scale new parameters are allowed to enter the regression equations if these parameters are significant for explaining the land-use distribution. Standardised bètas are calculated to allow a comparison of the relative importance of the different identified factors.

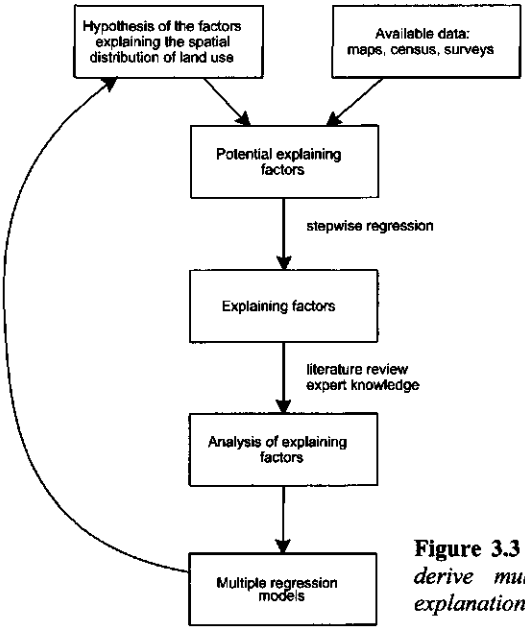

Figure 3.3 *Overview of the procedure used to derive multiple regression models for the explanation of the distribution of land use*

Table 3.1 illustrates the concept of multiple regression equations for the description of the spatial distribution of land use with equations derived for the distribution of arable crops in the coastal region of Ecuador for 1991 at the two scales considered in the model. Not all parameters relevant at the fine scale are also relevant at the coarse scale. The relative importance of the drivers differs with scale as well. An elaborated analysis of the statistical results for Ecuador is given by De Koning et al. (1998).

In each country we can distinguish regions that have clearly different biophysical, socio-economic and cultural characteristics and even more important, a clearly different land-use history. The countries studied are therefore divided in regions based upon biophysical, socio-economic and cultural characteristics in order to obtain better descriptions of the land-use pattern.

Table 3.1 *Multiple regression models at the two allocation scales for the area arable crops in the Coastal region of Ecuador*[a]

Fine allocation scale (r^2=0.38)		Coarse allocation scale (r^2=0.61)	
Variable	stb	Variable	stb
% High fertility soils	0.26	Rural population density	0.38
% Illiterate rural population	0.23	% High fertility soils	0.38
Distance to nearest river	-0.21	% Soils with slope > 16%	-0.23
% Soils with slope > 16%	-0.22	% Illiterate rural population	0.21
Rural population density	0.19	Distance to nearest river	-0.21
Total annual precipitation	-0.16		
Distance to nearest road	-0.08		

[a] Models are significant at the 0.001 level and individual parameters at the 0.05 level; stb: standardised regression coefficient

3.6 Calculation of changes in land use

3.6.1 Allocation at the coarse allocation scale

In order to reveal the pattern of land-use changes and identify 'hot-spots' of change, a first allocation of land-use change is made at the coarse allocation scale (Figure 3.2). The derived multiple regression models are assumed to give a good description of the land-use distribution under the actual biophysical and socio-economic conditions in a country. The regression models are used to calculate the cover percentage of the different land-use types under the biophysical and socio-economic conditions in a certain grid cell according to:

$$reg\_cover^{o}_{x,y,t,c} = \beta^{o}_{0} + \beta^{o}_{1} \cdot FACT^{o}_{x,y,t,1} + \beta^{o}_{2} \cdot FACT^{o}_{x,y,t,2} + \ldots$$

Where: $reg\_cover^{o}_{x,y,t,c}$ = the cover percentage as calculated by the regression equations for cover *c* in year *t* for grid cell *x,y* ('regression cover') at the coarse allocation scale

β^{o}_{f} = the regression coefficient belonging to factor *f* at the coarse allocation scale

$FACT^{o}_{x,y,t,f}$ = the value of factor *f* (e.g. population density) for grid cell *x,y* and year *t* at the coarse allocation scale

The results (further on referred to as 'regression cover') represent the average cover of the different land-use types expected on basis of the present biophysical and socio-economic conditions at the coarse allocation scale. Figure 3.4 gives the actual cover with permanent crops in Ecuador in 1991 (Figure 3.4A) and the 'regression cover' for the same land cover type as calculated by the multiple regression models under the prevailing conditions (Figure 3.4B). Under the assumption that all major determinants of the land-use distribution are included in the regression equations, two explanations can be given for the difference between the actual cover percentages and the cover percentages as calculated by the regression equations. Firstly, such a difference will arise if the value of one or more of the determining factors of the land-use distribution has changed after the year for which the regressions are derived. Especially the values of demographic variables will change over time due to population growth, migration, urbanisation and changes in the labour force situation. Changes in the biophysical conditions can be the result of e.g. changes in soil suitability due to erosion, and can be

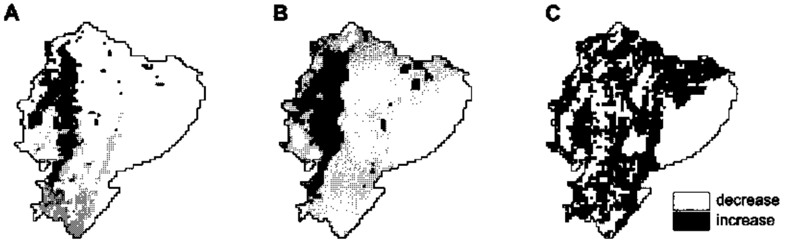

Figure 3.4 *(A) Actual cover with permanent crops in 1991 (dark colour high cover); (B) Cover calculated with the multiple regression models for permanent crops; (C) Direction in which the cover with permanent crops might develop based upon difference between actual and 'regression cover'*

implemented in scenarios. A second cause is the competition between land cover types. Although a certain location may have suitable conditions for a number of land cover types its available land area is limited. Hence the actual cover percentage can become lower than the cover percentage found with the regression equations. As demand for cover types changes, the competitive balance between cover types will also change. Therefore all deviations between actual land cover and the 'regression cover' are assumed to have relevance for land-use change. Areas where the actual cover of the considered land-use type is lower than the 'regression cover' are assumed to have preference for an increase in cover because the regression models indicate that at other places in the region more of the considered land-use type is found under similar conditions. The opposite is true for areas with a higher actual cover than the 'regression cover'. Figure 3.4C indicates the areas where an increase or a decrease in cover with permanent crops can be expected.

When the national demand for a certain land-use type increases (as calculated in the demand module) all grid cells that have a lower cover percentage than the 'regression cover' are selected. For all the grid cells the difference between the actual cover and the 'regression cover' is calculated. A fraction (ITF_c) of this difference in cover is added to the actual cover of the cells to increase their cover percentage according to:

$$cover^{o}_{x,y,t,c} = cover^{o}_{x,y,t-1,c} + ((reg\_cover^{o}_{x,y,t,c} - cover^{o}_{x,y,t-1,c}) \cdot ITF^{o}_{c})$$

Where: $cover^{o}_{x,y,t,c}$ = the cover percentage of cover type c in year t for grid cell x,y at the coarse allocation scale

ITF^{o}_{c} = the fraction actually allocated for cover type c at the coarse allocation scale

This fraction ITF_c is adjusted in an iterative method until the aggregated cover for all cells equals the demand for the cover type at the national scale:

$$DEMAND_{c,t} = \sum_{x} \sum_{y} (cover^{o}_{x,y,t-1,c} + ((reg\_cover^{o}_{x,y,t,c} - cover^{o}_{x,y,t-1,c}) \cdot ITF^{o}_{c}))$$

Where: $DEMAND_{c,t}$ = the demand for land use type c in year t calculated by the demand module for the national level

As a result, the change in land cover for individual grid cells is proportional to the difference between actual cover and 'regression cover'. Grid cells in which the actual cover only differs slightly from the cover calculated with the regression models will hardly face changes while grid cells with large differences between actual and 'regression cover' will face relatively large changes. Figure 3.5 illustrates this graphically for a hypothetical situation in which the 'regression cover' is only determined by one factor.

In case of a cover with a decreasing demand at the national level the opposite effect is obtained. Now the grid cells with a 'regression cover' that is higher than the actual cover will be selected, and a decrease in cover will be allocated relative to the difference between actual land cover and 'regression cover'.

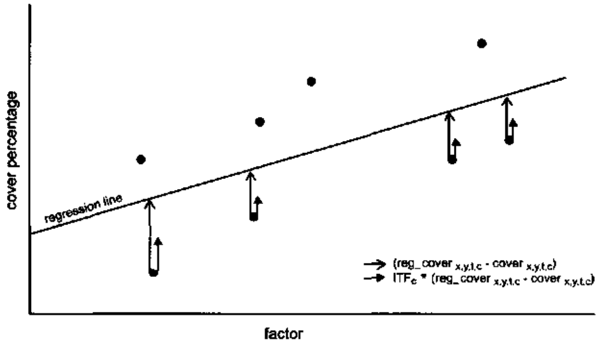

Figure 3.5 *Hypothetical relation between the actual cover percentage of a land-use type and a determining factor (points and regression line). Closed arrows indicate the allocated change in cover percentage of grid cells in case of an increasing demand for the considered land-use type if the determining factor stays constant*

3.6.2 Allocation at the fine allocation scale

As a first step land-use changes are calculated, as described above, at the coarse allocation scale. Based on this result, areas with relatively large changes ('hot spots') and areas with relatively small changes in land use are identified by comparing the changes of the individual grid cell with the average change of all grid cells.

At the fine allocation scale, calculations start with identifying differences between present land cover and land cover according to the regression equations. Again, an iteration procedure modifies the fraction of the difference between the present and regression cover until the demand at national level is equalled. However, at this scale, the fraction allocated depends on the calculated relative land-use change at the coarse allocation scale for the considered grid cell according to:

$$cover'_{x,y,t,c} = cover'_{x,y,t-1,c} + ((reg\_cover'_{x,y,t,c} - cover'_{x,y,t-1,c}) \cdot ITF'_c \cdot RCH_{x,y,t,c})$$

Where: $cover'_{x,y,t,c}$ = the cover percentage of cover type c in year t for grid cell x,y at the fine allocation scale

$RCH_{x,y,t,c}$ = a factor proportional to the relative change of cover c in year t for grid cell x,y calculated at the coarse allocation scale

If the grid cell is located in a fast changing area at the coarse allocation scale (large $RCH_{x,y,t,c}$), a relatively large percentage of the difference between actual and 'regression cover' is allocated. If the grid cell is located in a less than average changing area at the coarse allocation scale (small $RCH_{x,y,t,c}$), a relatively small part of the difference between actual and 'regression cover' is allocated.

In this way comparative advantages for allocation at the fine allocation scale depend on changes at the coarse allocation scale (Figure 3.6). Although the coarse allocation scale can have a large influence on the fine allocation scale, local factors like a specific grid cell that is

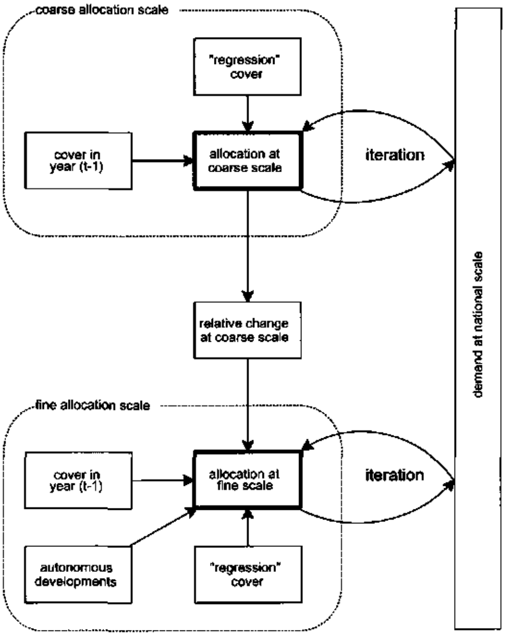

Figure 3.6 *Schematic representation of the allocation of land use changes at two scales*

unsuited for a certain land-use change, will cause that land-use change is not allocated to this grid cell (small or negative $reg\_cover'_{x,y,t,c}$ - $cover'_{x,y,t-1,c}$), even if the area has a relatively large change calculated at the coarser scale (large $RCH_{x,y,t,c}$). Thus, a balance is created between top-down influence of regional land-use change and bottom-up effects of land-use change due to local conditions.

For a baseline scenario of land-use change in Ecuador the resulting distribution of permanent crops was calculated at both the coarse and the fine allocation scale. Figure 3.7A shows the results for the coarse allocation scale and Figure 3.7B for the fine allocation scale. Figure 3.7C indicates the difference in simulation results for an allocation solely based upon the fine allocation scale and an allocation based upon the multi-scale approach. For a large number of grid cells the multi-scale approach results in a different cover change than for allocation solely based upon the fine allocation scale.

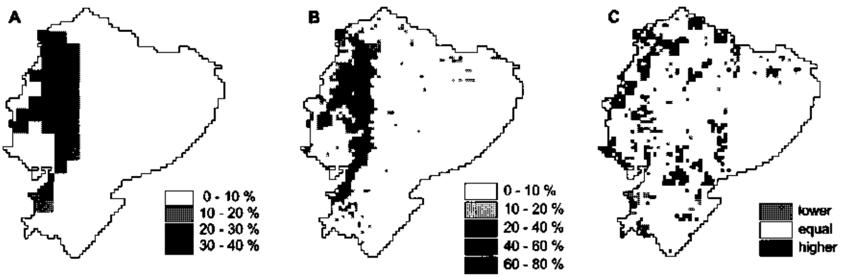

Figure 3.7 *(A) Simulation results for the allocation of permanent crops at the coarse allocation scale; (B) Simulation results for the allocation of permanent crops at the fine allocation scale; (C) Difference in simulated land cover percentage between a simulation with and without the use of the coarse allocation scale to modify allocation*

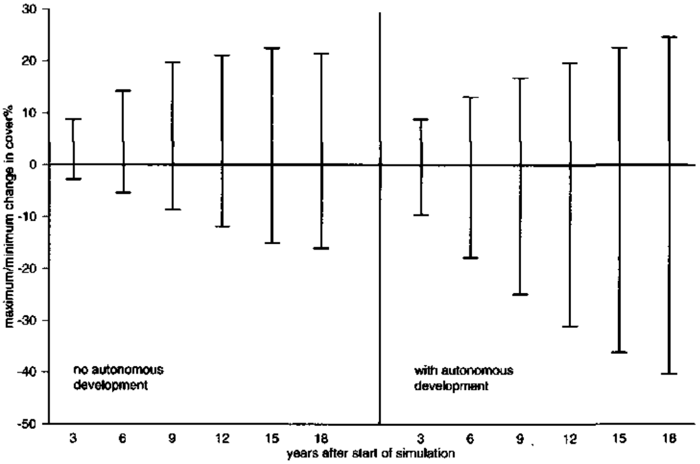

Figure 3.8 *Range over which the cover percentage of permanent crops changes for individual grid cells during the simulations as compared with the start of simulation for a baseline scenario; without and with modelling of autonomous developments*

3.6.3 Autonomous developments

In the previous procedure only changes in cover are allocated as they correspond with the direction of the change in demand at the national level, assuming a top-down driven land-use system. In reality, however, land-use systems also have bottom-up interactions. Therefore autonomous developments are implemented to account for changes exclusively based on the local biophysical and demographic grid conditions, i.e. independent of the national demand. Thus land use/cover in one local grid cell may change as a result of local conditions only. Therefore grid cells not selected for change in the normal top-down allocation procedure are attributed a change proportional to the specific difference between actual cover and 'regression cover'. The fraction of the difference allocated can be set by the user of the model and will in general be small compared to the change in the direction of the demand.

Autonomous developments will also result in changes in land use in periods with constant demand.

Figure 3.8 gives the range over which individual grid cells have changed under a baseline scenario for land-use change in Ecuador with and without implementing autonomous developments. From this figure it is obvious that autonomous developments cause the system to be much more dynamic. If grid cells are allowed to change opposite to the direction of demand, this needs to be offset by larger changes in the direction of the demand, resulting in a more dynamic system with both top-down and bottom-up interactions.

3.6.4 Competition between land-use types

As the area of land available is limited it is not always possible to allocate all changes calculated with the procedure described above. If the total cover percentage of all land cover types in a certain grid cell exceeds the total cell area (i.e. >100% cover) the allocation of changes needs to be modified. Competition between land-use types is implemented by modifying the changes in land-use types according to the competitive strength of the different land-use types. The competitive strength depends on both the difference between present cover and 'regression cover' and the change in demand. In case all covers are allocated a change in the same direction, competition may result in a change in opposite direction for the cover types with the smallest competitive strength.

The same procedure is used for situations in which all land-use types have a decrease in cover. Land-use types with a relatively small decrease can be attributed an increase in cover because of the larger decrease of the other land-use types in the same grid cell.

In this way competition between land-use types takes into account both national demands for the land-use types and their local suitabilities.

3.7 Discussion

3.7.1 Model behaviour and sensitivity

By including multiple driving factors, feedbacks and the multi-scale approach as described above, the model results in non-linear explorations of changes in land-use patterns in time. The multi-scale approach ensures that both top-down and bottom-up driven changes in land use are taken into account. Bottom-up effects become clearly visible if an area is suddenly defined unsuitable for certain land-use types, e.g. due to the establishment of a nature reserve or the construction of a reservoir. Because national demand needs to be fulfilled, the decrease of cover in a certain area due to such a local unsuitability will affect land use in other parts of the country. Figure 3.9 gives the difference in land cover percentage of permanent crops of a simulation without and with protection of nature reserves in Ecuador. Although nature reserves cover only small parts of the country, the land-use dynamics in the whole country are affected. Because less land is available for permanent crops due to the establishment of the nature reserves, more permanent crops are allocated elsewhere. However, there are also areas where less permanent crops are allocated. This demonstrates that the complex interactions between land-use types and changes in relative competitive strengths can cause non-linear changes in land-use distributions.

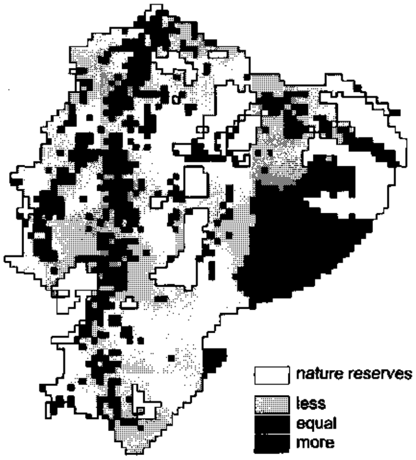

Figure 3.9 *Difference in the distribution of permanent crops in Ecuador after a simulation of 18 years respectively with and without the protection of nature reserves*

The sensitivity of the model depends on the situation modelled. The relation between determining factors and land-use types as described by the multiple regression equations will determine the sensitivity of the model for changes in these determining factors, like changes in population density and associated characteristics. Changes in demand calculated at the national level in the demand module determine the overall amount of change. The resulting pattern of land-use change also depends on the rate of change. This is illustrated in Figure 3.10 which gives the results for the distribution of grassland in Ecuador for two hypothetical scenarios with equal initial and final conditions. The two scenarios differ in the rate of change during the simulation period. Figure 3.10A and 3.10B give the initial and final distribution of grassland and Figure 3.10C displays the difference in final distribution of grassland between the two considered scenarios. This result shows that land-use history and the pathway of change do effect the simulation results.

The model behaviour, as illustrated in the examples above, corresponds with system dynamics as described by landscape ecologists (Forman and Godron, 1986). The *structure*, i.e. the relations between land use and the biophysical and socio-economic determinants, are mimicked by the multiple regression analysis. A realistic modelling of the *function* of the landscape is possible through the multi-scale approach that allows both top-down and bottom-up driven changes. The *change* in land use is the result of the alteration of structure and function in time. Interactions between function and structure, i.e. feedbacks, cause the change to be dependent on the pathway of alteration in function and structure (i.e. Figure 3.10). The holistic/integrative nature of the model is essential for modelling the non-linear behaviour of complex systems like ecosystems and landscapes (Jørgensen, 1994). The model behaviour illustrated in Figure 3.9 and 3.10 indicates that the model is capable to capture some of the important system properties of landscapes.

3.7.2 Limitations

It is assumed that the multiple regression equations give a rather complete description of the land-use system distribution. The user should therefore evaluate the statistical analysis on suitability for modelling the changes in land-use pattern. The R-squared of the multiple regression models gives a first indication of the goodness of fit. If the multiple regression models lack factors essential for explaining the differences in land use, any modelling exercise will be of no value because land use will be adapted without taking these major factors determining the land-use distribution into account.

The non-deterministic way of land-use allocation, based upon the actual land-use pattern, also limits the time horizon and scenario possibilities for simulations. As there is no principal causal dependency between the distribution of land use and its determining socio-economic and biophysical factors, the derived multiple regression models may change over time and can only be assumed stable for short time periods (e.g. ~20 years). Discontinuities in land use change, like the fast introduction of new land-use types or major natural disasters affecting large areas, cannot be simulated because of lack of empirical precedence, i.e. because the relations between the land-use types and socio-economic and biophysical factors are unknown. The stability of the regression models can be evaluated by analysing the historic spatial distribution of land use for two years with one or two decades in between. Such

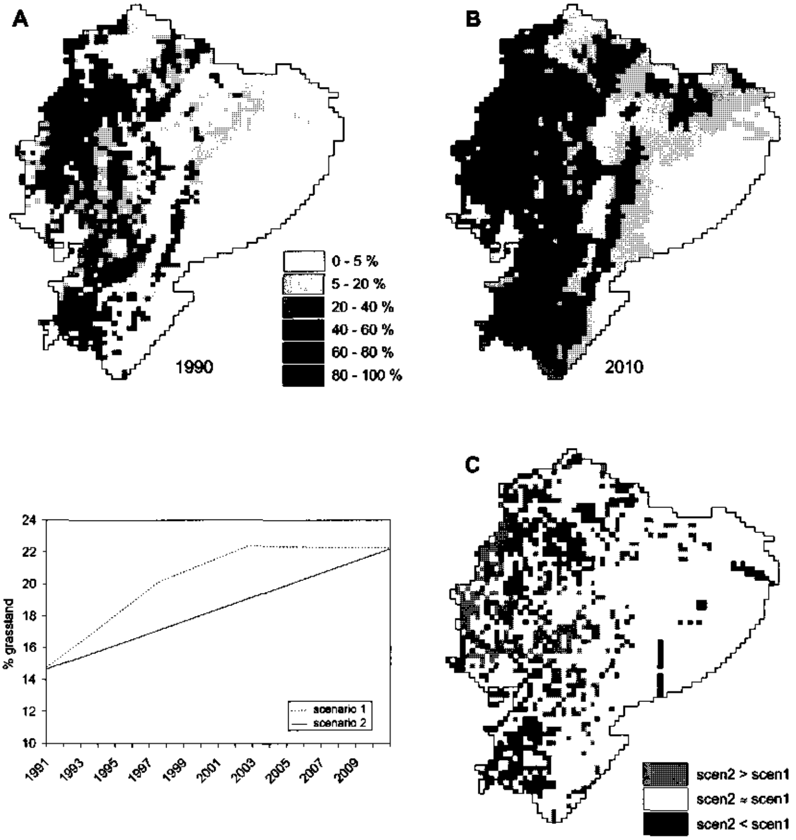

Figure 3.10 *(A) Actual cover with grassland in Ecuador in 1991; (B) Simulated cover with grassland in Ecuador in 2010 for scenario 1; (C) Difference in simulation results between scenario 1 and scenario 2 (which are only different in the rate of change at the national level)*

analysis, as performed for Costa Rica by Veldkamp and Fresco (1997b), resulted in relatively stable relations between land-use distributions and determining factors for a period of 20 years.

The present model assumes that all increases in demand can be fulfilled by changes in land use. However, during allocation it might be impossible to allocate all demand under certain conditions e.g. when no suitable land for a certain land-use type remains. For the time period considered and increasing possibilities for international trade it is assumed that in such situations the demand will be satisfied by increases in import. Feedbacks, e.g. through changes in population growth as proposed by Malthus (1967), are considered not relevant in the present areas studied by the model. For application in other areas these aspects might be important and should be included in the model.

3.7.3 Calibration and validation

Calibration and validation of models with a high spatial resolution is difficult and in some cases impossible, as it is impossible to validate future land-use patterns. However, historic analysis can give possibilities to calibrate the model and validate it. This means that at least for three points in time, preferably about a decade apart, the distribution of land use should be known. In many countries this will not be possible due to the absence of the appropriate data over such long time spans. In that case only expert knowledge can be used to calibrate and validate the model outcome.

For Ecuador high resolution spatially explicit land-use data are only available for 1991. So a full validation of model performance and spatial pattern matching (as described by Costanza, 1989) is not possible. However, for 1974 agricultural census data are available at the canton level (n=111). Backward validation from 1991 to 1974 enabled comparison between simulated and observed land-use distributions at the canton level for 1974. Correlations between observed and simulated land-use distributions range from 0.71 to 0.90 for the different land-use types. The validation indicates that the general pattern of land-use change is well simulated. A full description of the validation is presented by De Koning et al. (1999).

Although the user of the model must have prior knowledge about the land-use situation in the area studied, to select potential driving factors and to evaluate the multiple regression models, it is not necessary to quantify and/or calibrate the relations between land use and its determining factors by expert knowledge, as this is included in the statistical analysis of the land-use distribution. In contrast to many models describing complex systems the CLUE model has only two major parameters that need to be calibrated. The first is the relative magnitude of autonomous developments. Autonomous development, i.e. local land use change opposite to the national trend, will never be large, as national demands have to be fulfilled. Historic analysis of years in which the demand for land-use types remained constant can give indications for the magnitude of autonomous developments.

The second calibration parameter influences the multi-scale approach. If certain grid cells, at the coarse allocation scale, have an increase in a certain land-use type that is higher than the national increase, the model will increase the change of the grid cells at the fine allocation scale. Because not much is known about the interrelations between drivers at various scales, calibration with historic data is needed to define the appropriate interaction between scales. When calibration is not possible scales can be assigned equal weights.

3.8 Conclusions

The methodology presented offers opportunities to simulate the pattern of land-use change based upon actual land-use conditions fully respecting scale dependencies within a landscape. The model should be seen as a tool in addition to other models that base allocation upon decision rules and optimisations. While these methodologies give insight in the causal response of land-use allocation upon a limited number of conditions, the CLUE approach will give insight in the allocation of land use as a function of the complex interaction of a large number of socio-economic and biophysical, multi-scale, interactions.

The results of simulations with CLUE can be used to evaluate the consequences of land-use changes for environmental sustainability. For scientists and policy makers the results help to understand, anticipate and possibly prevent the adverse effects of land-use changes, by focussing policies on those locations that are most threatened.

Future developments of the CLUE modelling framework include the application of the model to different land-use change situations, e.g. China where a decrease in farmland area at the benefit of urban and industrial development is experienced, while at the same time demands for agricultural products are increasing, leading to an even further intensification of land use. Also with respect to the data used in the modelling approach advances are being made by including remote sensing data in the model, which will allow a higher spatial resolution. More attention to the economical parameters as one of the important factors for land-use allocation is needed to result in a better understanding and allocation of land use.

Chapter

4

Simulation of changes in the spatial pattern of land use in China

Peter Verburg, Tom Veldkamp and Louise Fresco

Applied Geography 19 (1999): 211-233

Abstract

This paper presents a model to simulate country-wide changes in the land-use pattern of China. The model is based upon an empirical analysis of the spatial distribution of land-use types in China. In this analysis socio-economic as well as geophysical variables are taken into account. The empirical analysis indicates that a reasonably complete description of the land-use distribution can be made by including demographic, soil related, geomorphological and climatic variables.

A multi-scale approach is followed to capture top-down as well as bottom-up factors affecting land-use allocation. Competition between different land-use types determines which changes will actually take place.

The most important land-use conversions in China, caused by urbanisation, desertification and afforestation, are simulated for a scenario that is based upon a trend analysis of present land-use dynamics. The spatially explicit results allow an analysis of the consequences of a decrease in cultivated area and related production capacity. A preliminary analysis shows that the average production capacity of the lost arable lands is somewhat less than the average production capacity of all agricultural lands together.

4.1 Introduction

Human influence has been affecting land cover in China at a large scale for a long period. Already during the early Han dynasty, in the 4th and 3rd centuries BC, the Chinese started systematic land reclamation and irrigation schemes, converting large areas of natural land into rice paddies. These activities reached a first climax in the 11th and 12th and another during the second half of the 18th and first half of the 19th century (Youtai, 1987; Heilig, 1997).

More recent changes in land use are dominated by losses of agricultural land. In particular, in the eastern part of China there has been an unprecedented conversion of arable land into non-agricultural uses following rapid industrialisation. This loss of agricultural land in combination with the trend towards a much higher demand for agricultural products for a growing and wealthier population, has resulted in a discussion about the long-term capacity of the country to feed itself, and the consequences for the global food market if China would not be able to feed its own population (Garnaut and Ma, 1992; Brown, 1995a; Smil, 1995; Alexandratos, 1996; Prosterman et al., 1996).

Most assessments of land-use change in China are based upon aggregated national values (Brown, 1995a; Smil, 1993; Crook and Colby, 1996). However, differences within the country are large as a consequence of the country's enormous physical and human diversity. Recent high rates of economic growth have been increasing these differences even more. It is therefore important to gain more insight in these regional differences and trends. This paper presents a methodology to simulate the spatial pattern of changes in land use under given scenarios of change at the national level. Spatially explicit assessments of change can indicate more specifically the consequences of land-use change by overlaying the changes with production capacities and management conditions. Such assessments will also enable the identification of 'hot spots' of change which allow the spatial concentration of the resources for policies aimed at mitigating adverse effects of land-use change. The simulations in this study are made with the CLUE (The Conversion of Land Use and its Effects) modelling framework (Veldkamp and Fresco, 1996; Verburg and Veldkamp, 1997). The characteristics of the model and its implementation for the Chinese situation are described in this paper.

4.2 Land use in China

Data uncertainty

The analysis of Chinese land-use statistics is difficult due to large inconsistencies between sources and the absence or unreliability of many critical variables. According to Wu and Guo (1994) about 15% of the total land area of China consists of cropland and horticultural land. Forests and grasslands together are covering more than 55% of the country. Most grasslands are of poor quality, either due to climatic conditions, bad management and overgrazing. Desertification of grasslands might have caused that the actual grassland area is already lower (Bo, 1997). Another large part of the country (23%) consists of unused land, being deserts, glaciers and bare lands. The built-up area is presently about 3% of the total land area.

Especially for the extent of the cultivated area a wide range of estimates is published (Table 4.1). The official statistics published in the statistical yearbooks are generally assumed to be underestimating the cultivated area (Crook, 1993a). In recent editions of the Statistical Yearbook of China a footnote to the data acknowledges that the data are known to be underestimated. Underreporting of cultivated area in Chinese statistics has a long tradition as a consequence of linkages between the statistical system, the tax system and production quota (Crook, 1991). More confusion is caused by variation in the area measure 'mu' depending on land quality (Crook, 1993a). Smil (1995) suggests that unreliability in Chinese statistics is also caused by reportage of inflated achievements in order to receive bonuses and promotions while other figures are denigrated in order to be eligible for additional financial aid. The high estimates based upon satellite image interpretation probably overestimate the cultivated area as a consequence of resolution and interpretation problems (Smil, 1993).

Today it is commonly accepted that the actual cultivated area is somewhere between about 125 and 137 million hectares (Heilig, 1997; Alexandratos, 1996). Huang (1997) agrees with this estimate but mentions that a recent household survey revealed that un-reported lands mostly fall under the categories of marginal, fragile and newly reclaimed land, and mainly belong to ‘private plots’ planted to vegetables and other minor crops for household consumption. However, several other researchers at the Chinese Academy of Agricultural Sciences do not agree with this thesis.

All this makes the analysis of land-use data for China not an easy task as the uncertainties can obscure the real trends in land-use change. Smil (1993) mentions that since there is no overwhelming reason to assume that the overall extent of inaccuracy has changed significantly during the last 30 years, the trends in land-use statistics are not affected by the under reporting issue. However, Brown (1995b) highlights the discrepancy between rates of arable land loss in official statistics and land surveys. He assumes that fear for agricultural taxation, which motivated earlier under-reporting, has been replaced by a fear of fees for the conversion of farmland. This would result in an under-reporting of losses of cultivated land.

Table 4.1 *Cultivated area in China (estimates)*

Data source	Cultivated area (ha x 10^6)
Wu and Guo (1994)	136.4
Sun et al. (1994)	133.3
Statistical Yearbook of China (1994)	95.1
Wang (1992)	139.6
State Land Administration and State Science and Technology Commission (1994)	125.2
Peoples University Press (1991)	132.8
Institute of Remote Sensing Applications (IRSA) vegetation map	189.9
Landsat interpretation mentioned by Smil (1995)	150.0

Land-use change issues

The cultivated area decreased between 1985 and 1995 from 96.8 to 94.9 million hectare, a decrease of 1.9% (State Statistical Bureau, 1986 and 1996). The main reasons for the decline in arable lands are the conversion of these lands to residential, industrial and infra-structural area, the conversion to orchards and fish-ponds and the loss of land due to degradation.

Heilig (1997) and Smil (1993) give overviews of the causes and drivers of the losses of agricultural land. They illustrate that the loss of arable land to residential, industrial and infra-structural area as well as the conversion to orchards and fish-ponds is mainly driven by the continuing increase of population, urbanisation, economic modernisation and industrialisation, changes in diets and lifestyles, and changing economic and political arrangements and institutions.

For the growing population China will need to provide housing. This alone will give a large claim on land, predominantly in the eastern part of the country where 90% of the population lives and where space can often be taken only from cultivated areas. The relation between population growth and space needed for housing is modified by a.o. the rate of urbanisation. Although the higher population density in cities (Table 4.2) seems to cost less land the opposite is true, because city dwellers in general need a much broader supply and service infrastructure than rural population ranging from water reservoirs and sewage treatments to shopping centres and recreational areas. Table 4.2 also indicates that the living space per capita gradually increases as a consequence of increasing wealth. Indirectly urbanisation has an even much larger effect on land use. Changes in diets and lifestyle cause an increase in the demand for horticultural products and meat, leading to the conversion of arable plots to orchards and fish ponds. Ping (1997) argues that these indirect effects of urbanisation cause a larger loss of arable land than the conversion into built-up area.

Degradation through wind and water erosion, salinisation and soil contamination does not directly take land out of production. Degradation first leads to decreases in agricultural output in large areas (Rozelle et al., 1997) while upon prolonged degradation the land is not usable any more. The large extent of degradation in China has worried many scientists (e.g. Smil, 1984, 1993; Huang and Rozelle, 1995).

Other large losses of farmland result from the reversion of fields on previously forested slope land and pastures to their former uses (Smil, 1993). Especially in north and north-west China large areas of land are prone to serious desertification and should be returned to pasture as soon as possible. On steep slopes erosion rates are that high that if not reforested soon they will be unsuited for any agricultural use within a few years. The government has issued a rule that all arable lands on slopes steeper than 25% should be converted back into their former land cover (pers. comm. Su Daxue (CAS)). Presently the Chinese government is undertaking large afforestation programs to serve as shelterbelts and windbreaks to protect crops and reduce soil erosion in agricultural areas. However, the success of such afforestation projects is generally low (Smil, 1993).

Table 4.2 *Living space per farmer, urban resident and per capita built-up area including residential, industrial, infrastructural and mining area (m^2)*

Living space	1978	1990
Per farmer	8.1	17.2
Per urban resident	3.6	6.6
Per capita built-up area	156	252

Source: State Statistical Bureau

4.3 The CLUE modelling framework

For the simulation of the spatial pattern of land-use change in China the CLUE modelling framework is used. The CLUE modelling framework is a grid based, multi-scale, spatially explicit land-use change model. Veldkamp and Fresco (1996) used this model to simulate land-use changes in Costa Rica. The version of the model used in this study consists of three modules (Figure 4.1). The demand module calculates, at the national level, changes in demand for different land-use types. Calculations can be based upon changes in demand for agricultural products, taking into account population growth, changes in diet and import/export quantities. Instead of these calculations projections of changes in land use at the national level can be used as well as trend extrapolations of time series, which are often available at the national level. The population module calculates changes in population and associated demographic characteristics based upon projections and historic growth rates.

The central part of the model is the allocation module. This module calculates for all grid cells the changes in land use on a yearly basis. In contrast to most grid-based approaches, where land use in each cell is determined by the most dominant land-use type, land use is characterised by the relative cover of each land-use type in a certain grid cell, e.g. a grid cell can contain 30% cultivated land, 40% grassland and 30% forest. It is assumed that all changes in demand at the national level are allocated by changes in the cover percentage of the individual grid cells.

The allocation itself is based upon a spatial analysis of the complex interaction between land use, socio-economic conditions and biophysical constraints. This interaction is captured by an empirical analysis of historic and/or present land use. Therefore a grid-based system containing land use, socio-economical and biophysical variables is used. Multiple regression

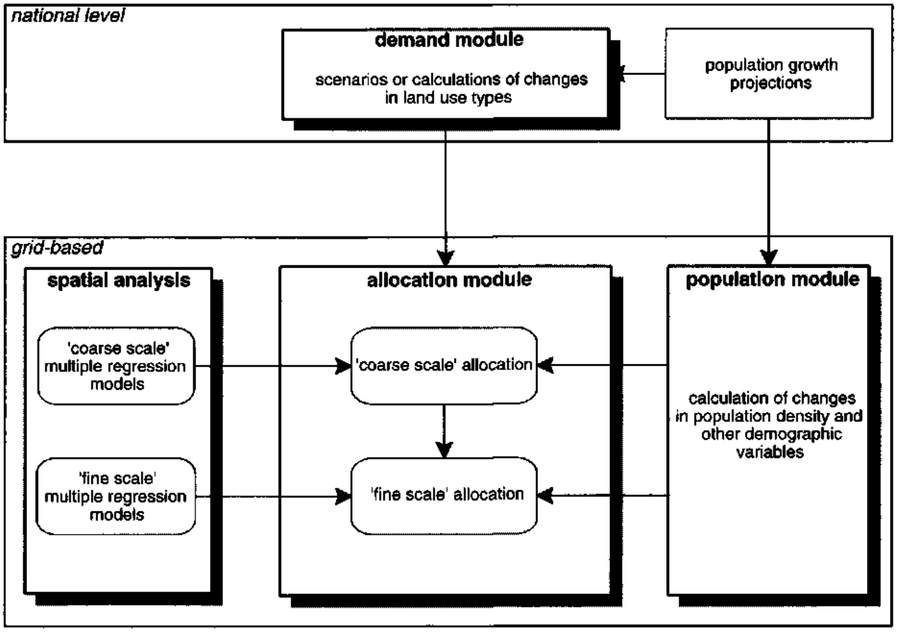

Figure 4.1 *Structure of the main components of the CLUE modelling framework*

models are calculated to quantify the relation between the distribution of land use and determining conditions.

The structure of the land-use pattern, i.e. the relations between land use and the biophysical and socio-economic conditions, are depending on the scale of observation (Veldkamp and Fresco, 1997b; Walsh et al., 1997). Usually, coarse scales are useful to reveal the general trends and relations between land use and its determining factors while finer scale assessments can reveal variability within regions and landscapes. Therefore the statistical analysis of the distribution of land use is repeated at two different aggregation levels (Figure 4.2) allowing different explaining factors at the different aggregation levels. The second aggregation level is created by aggregating nine basic grid cells using a focal function.

The thus derived multiple regression models are assumed to give a good description of the land-use distribution under the actual biophysical and socio-economic conditions in a country. Therefore they are used to determine which areas of the country have potential for an increase in cover percentage for the respective land-use types. These areas are found by comparing the cover percentages calculated with the multiple regression models with the actual cover percentages. The cover percentages calculated by the regression equations will change in time as the determining factors change, e.g. population density. It is assumed that grid cells of which the cover percentage according to the regression equations is higher than the actual cover of the considered land-use type, will experience an increase in cover percentage. In case the regression equations result in a lower cover for the grid cell considered, a decrease in cover for the land-use type considered is probable.

The actual change allocated is determined by an iteration procedure which adapts the fraction of the difference between actual cover and the cover calculated by the regression equations. This iteration continues until the aggregated cover of all grid cells equals the national level demand. The two distinguished aggregation levels ('allocation scales') for which the multiple regression models are derived, are used to capture general trends as well as changes caused by local circumstances. The general pattern is found by allocating land use at the coarse allocation scale as described above. Based on this result areas with relatively large changes and areas with relatively small changes in land use are identified by comparing the changes of the individual grid cells with the average change of all grid cells.

At the fine allocation scale the allocation procedure is repeated. However, at this scale, the fraction allocated is modified by the calculated, relative land-use change at the coarse allocation scale. If the grid cell is located in a fast changing area at the coarse allocation scale, a relatively large change is allocated. If the grid is located in a less than average changing area at the coarse allocation scale, a relatively small change is allocated.

Verburg et al. (1999a) give a more extended description of the model and its characteristics. The next paragraphs describe how this methodology is implemented for the Chinese situation and which data are used.

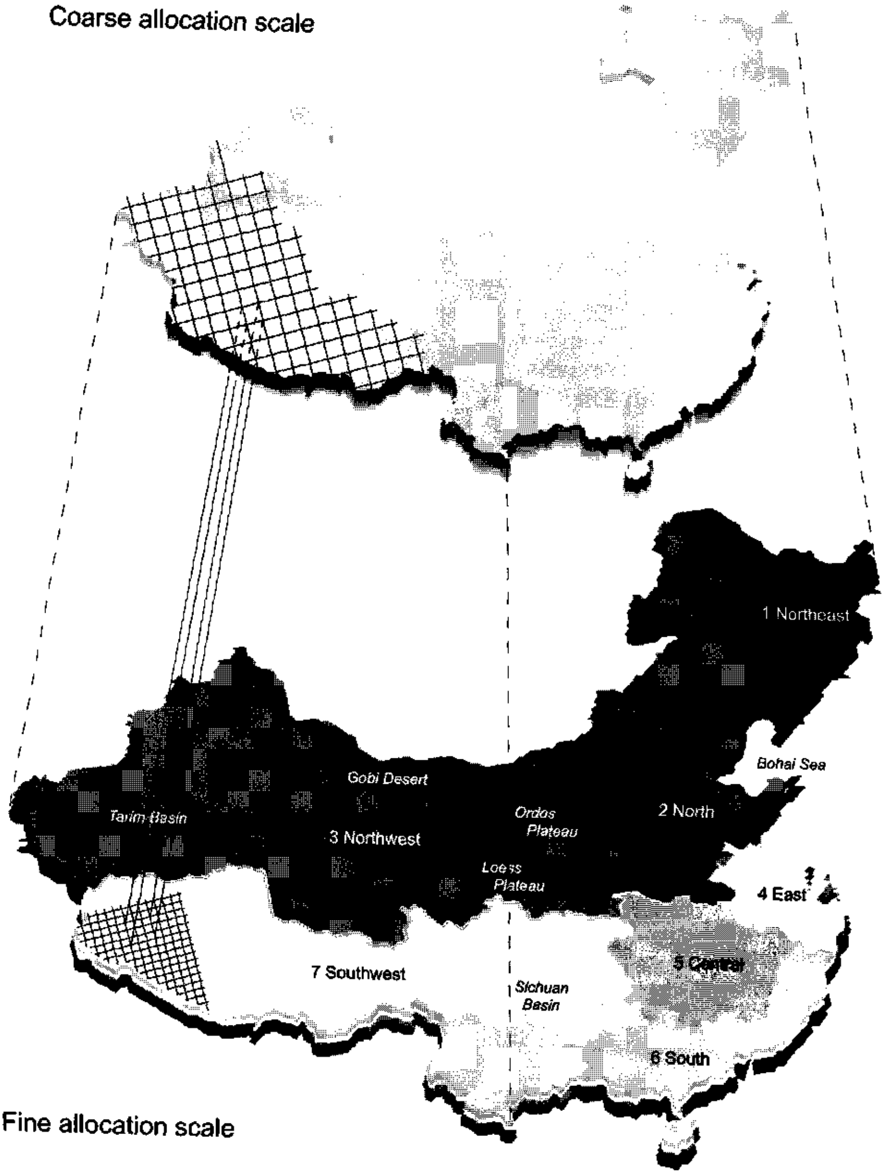

Figure 4.2 *Representation of the multi-scale data and modelling structure for China and subdivision into regions*

4.4 Implementation of the CLUE modelling framework for China

Data

The land-use distribution is assumed to be determined by demographic, socio-economic and biophysical conditions. To enable the analysis of the interrelations between these determining conditions and the land-use distribution a GIS database containing data on land use, demographic, socio-economic and biophysical drivers was made. Land use and demographic parameters can generally be taken from the national census. However, in the case of China, many figures of interest are still unavailable (Smil, 1993). Given these limitations we created a database which is based upon multiple sources. For land-use statistics an adapted version of the statistics contained in the LUC-GIS database of the International Institute for Applied Systems Analysis, Austria and the Institute of Geography, Chinese Academy of Sciences was used. Table 4.3 gives the land-use types contained in this database. This database is assumed to represent the land-use situation at the end of the 80's. The cultivated area in this database equals 133 million hectare which corresponds with the area generally assumed reliable. Demographic and labour force characteristics are taken from the 1990 population census (Skinner et al., 1997). These demographic and land-use statistics are available for approx. 2350 counties. However, counties in west China have an areal extent which is several orders of magnitude larger than counties in the eastern part of China. In order to achieve a more homogeneous data resolution a 1:4 million vegetation map (Chinese Academy of Sciences, 1979/1996) was used to exclude desert areas. Other land-use categories are assumed to be equally distributed over the remaining area. Population density in desert areas is assumed to be zero.

Data on soil texture and fertility are derived from the 1:4 million soil map of China (Chinese Academy of Sciences, 1978/1996); other soil attributes like depth, drainage and land suitability are from the 1:5 million Digital Soil Map of the World (FAO, 1995). Topographic parameters are derived from a 30 arc second digital elevation model (USGS, 1996) while the distance to the nearest city and the average distance to a major river are calculated from an infrastructure map (Tang et al., 1996) and a river system map (Cartographic Publishing House of China, 1989).

Geomorphology is based upon a 1:5 million physiographic base map prepared by FAO and ISRIC (FAO, 1994) and a 1:4 million geomorphology map (Chinese Academy of Sciences, 1994/1996). Climate data are calculated from long term monthly averages interpolated on a five minute grid (experimental data set; pers. comm. W. Cramer). All derived variables are listed in Table 4.3.

All GIS data are converted to an equal area projection and gridded. Basic grid size is 32 x 32 km (1024 km^2). For each grid cell land use is characterised by the relative cover of each land-use type in the grid cell. This way of representing the data is a direct result of the information contained in the census data. The same approach is followed for other classified variables, like soil texture. To facilitate the multi-scale approach an artificial aggregation level comprising 9 basic grid cells was created with the help of focal functions (Figure 4.2).

Table 4.3 *Complete set of variables used in the statistical analysis*

Variable name	Description	Unit
Land-use types	*(fraction of the total area)*	
Cultivated	Cultivated lands, including paddy and dry-land	-
Horticulture	Horticultural lands, including orchards, tea and mulberry plantations	-
Forest	Forestry lands, incl. timber, fuelwood, shelter and economic forests, sparse woodlands and shrubs	-
Grassland	Grasslands, including natural grasslands and artificial grasslands	-
Built-up	Land for settlement, enterprises, mining and transportation	-
Water	Water bodies and wetlands, including rivers, lakes, beaches, reservoirs and marshlands	-
Unused land	Other land, including glaciers, permanent snow, sandy land, deserts, saline land and bare land	-
Demographic factors		
Rurdens	Rural population density	Persons km^{-2}
Agdens	Density of agricultural labour force	Persons km^{-2}
Urbdens	Urban population density	Persons km^{-2}
Rurper	Rural population as a fraction of the total population	-
Popdes	Population density	Persons km^{-2}
Illit	Fraction of the population that is illiterate	-
Aglabour	Fraction of the total population that is in the agricultural labour force	-
Soil related factors	*(fraction of the total area)*	
Gooddrai	Well drained soils	-
Moddrain	Moderately drained soils	-
Baddrain	Badly drained soils	-
Shallow	Shallow soils	-
Deep	Deep soils	-
S1irrpad	Soils very suitable for irrigated rice	-
S2irrpad	Soils moderately suitable for irrigated rice	-
Nsirrpad	Soils not suitable for irrigated rice	-
S1maizer	Soils very suitable for rainfed maize	-
S2maizer	Soils moderately suitable for rainfed maize	-
Nsmaizer	Soils not suitable for rainfed maize	-
Smaxhigh	Soils that have high moisture storage capacity	-
Smaxlow	Soils that have low moisture storage capacity	-
Fert1	Poor soil fertility	-
Fert2	Moderate soil fertility	-
Fert3	High soil fertility	-
Text1	Coarse soil texture	-
Text2	Medium soil texture	-
Text3	Fine soil texture	-
Geomorphological factors		
Meanelev	Mean elevation	m.a.s.l.
Rangeelev	Range in elevation	Metres
Slope	Slope	Degrees
Physl	(Fraction of the area with) level land	-
Physs	(Fraction of the area with) sloping land	-
Physt	(Fraction of the area with) steep sloping land	-
Physc	(Fraction of the area with) complex valley landforms	-
Geomor1	(Fraction of the area with) mountains	-
Geomor2	(Fraction of the area with) loess	-
Geomor3	(Fraction of the area with) aeolian landforms	-
Geomor4	(Fraction of the area with) tableland	-
Geomor5	(Fraction of the area with) plain land	-
Accessibility		
Distcity	Average distance to city	Metres
Riverden	Average distance to river	Metres

Table 4.3 *Continued*

Variable name	Description	Unit
Climatic variables		
Tmp_min	Minimum temperature	°C
Tmp_max	Maximum temperature	°C
Tmp_avg	Average temperature	°C
Tmp_10c	No. of months with temperature above 10 degrees	-
Tmp_rng	Range in temperature	°C
Prc_tot	Total precipitation	mm
Prc_rng	Range in precipitation	mm
Prc_50m	No. of months with precipitation above 50 mm	-
Sun_tot	Average percentage of sunshine	%

Statistical analysis

The spatial distribution of land use is quantified by multiple regression models using the cover percentage of a land-use type as dependent and the socio-economic and biophysical characteristics as independent variables. It is our hypothesis that all socio-economic and biophysical characteristics listed in Table 4.3 can give a contribution to the explanation of the land-use pattern. However, correlation among variables and differences in explaining power makes that only part of the variables have a significant contribution to the multiple regression model. A stepwise regression procedure is used to avoid multicollinearity and select the most significant variables. For the distribution of built-up area only demographic parameters are taken into account because population and built-up area are directly linked. Table 4.4 gives the thus derived regression models for the coarse allocation scale. On general the explaining power of the regression models is reasonable to good. Only for the distribution of horticultural land the explaining power is less. This can probably be ascribed to the somewhat scattered distribution of horticultural land and the very variable environmental requirements of all crops lumped under horticultural crops (e.g. tea, mulberry plantations and orchards). For each land-use type the regression models contain one or more demographic parameters, some soil related variables, a geomorphological variable and climatic variables. This indicates that all these types of variables are important to explain the distribution of land use within the country. The relative importance of the variables (indicated by the standardised estimate) and the sign of the parameter estimate should be interpreted with great care as multicollinearity affects these measures.

The statistical analysis at the fine allocation scale is stratified according to seven individual regions used by the United States Department of Agriculture (Crook, 1993b) which represent regions differing in agro-climatic conditions and resource endowments (Figure 4.2). This stratification allows a better representation of region specific conditions affecting the land-use distribution. The resulting regression models for the distribution of cultivated area are shown in Table 4.5. For all regions the distribution of cultivated land can easily be explained. Although the variables are different for each region, all regression models contain demographic, soil, geomorphologic and climatic variables. So, also at this more detailed scale of analysis, it is only possible to describe the land-use distribution by an integrated data set containing both socio-economic and biophysical variables.

Table 4.4 *Variables, parameter estimates and standardised parameter estimates of multiple regression models explaining the distribution of the different land-use types at the coarse allocation scale (sorted according to decreasing absolute standardised parameter estimate)*[a]

Variable	Estimate	Std-est	Variable	Estimate	Std-est
Cultivated (r^2-adj = 0.86)			*Forest (r^2-adj = 0.79)*		
Intercept	-9.11	0.00	Intercept	5.57	0.00
Prc_rng	0.10	0.43	Prc_50m	5.20	0.70
Prc_tot	-0.02	-0.42	Prc_tot	-0.03	-0.63
Agdens	0.11	0.33	Meanelev	-0.01	-0.48
Popdes	0.02	0.25	Prc_rng	0.15	0.47
S1irrpad	0.51	0.21	Geomor1	0.28	0.37
Geomor2	0.35	0.19	Agdens	-0.10	-0.24
Rurper	15.50	0.18	Slope	1.63	0.19
Illit	-11.59	-0.14	Rurper	-17.84	-0.15
S2irrpad	0.22	0.08	Fert1	0.10	0.14
S1maizer	0.12	0.08	Distcity	0.02	0.13
Horticulture (r^2-adj = 0.39)			*Unused (r^2-adj = 0.74)*		
Intercept	-0.94	0.00	Intercept	30.22	0.00
Tmp_min	0.11	0.87	Prc_tot	0.06	0.95
Tmp_avg	-0.13	-0.82	Prc_rng	-0.31	-0.75
Meanelev	-0.00	-0.54	Prc_50m	-6.97	-0.72
Sun_tot	0.04	0.38	Gooddrai	-0.74	-0.30
Popdes	0.00	0.37	Nsirrpad	0.68	0.24
Prc_tot	0.00	0.30	Geomor3	0.40	0.22
Nsirrpad	0.01	0.14	Aglabour	-55.67	-0.21
Smaxhigh	-0.01	-0.11	Riverden	0.15	0.14
Geomor4	0.01	0.10	Physt	0.11	0.10
Fert2	0.00	0.08	Tmp_min	0.66	0.02
Grassland (r^2-adj = 0.53)			*Built-up (r^2-adj = 0.79)*		
Intercept	-40.19	0.00	Intercept	0.80	0.00
Shallow	0.72	0.60	Popdes	0.02	0.85
Smaxlow	-0.60	-0.52	Distcity	-0.00	-0.09
Illit	54.81	0.42			
Gooddrai	0.88	0.42			
Physl	0.23	0.30			
Tmp_min	-0.69	-0.26			
Rurdens	-0.04	-0.22			
Text1	0.16	0.19			
Fert3	0.15	0.18			
Geomor5	0.17	0.17			

[a] All significant at $P < 0.01$

Table 4.5 *Variables and standardised parameter estimates of multiple regression models explaining the distribution of cultivated land at the fine allocation scale (sorted according to decreasing absolute standardised parameter estimate)*[a]

Variable	Std-est	Variable	Std-est
Region 1: Northeast		*Region 2: North*	
(r^2-adj = 0.84)		*(r^2-adj = 0.87)*	
Intercept	0.00	Intercept	0.00
Rurper	0.61	Meanelev	0.61
Agdens	0.59	Rurdens	0.54
Aglabour	-0.41	Tmp_avg	0.38
Nsirrpad	-0.33	Slope	-0.29
Gooddrai	0.30	Geomor1	-0.20
Geomor1	-0.27	Sun_tot	0.16
Tmp_min	-0.25	Phys1	0.14
Prc_rng	-0.18	Baddrain	0.12
Tmp_10c	0.14	Aglabour	0.12
Distcity	-0.09		
Nsmaizer	-0.05		
Physc	-0.04		
Region 3: Northwest		*Region 4: East*	
(r^2-adj = 0.76)		*(r^2-adj = 0.91)*	
Intercept	0.00	Intercept	0.00
Rurdens	0.60	Prc_tot	-0.40
Geomor2	0.29	Fert3	0.27
Prc_rng	0.24	Geomor1	-0.22
Prc_50m	-0.21	S1irrpad	0.18
Rurper	0.10	Rurdens	0.17
Distcity	-0.08	Sun_tot	-0.13
Fert3	0.08		
Region 5: Central		*Region 6: South*	
(r^2-adj = 0.84)		*(r^2-adj = 0.81)*	
Intercept	0.00	Intercept	0.00
Rurdens	0.46	Tmp_avg	0.35
Geomor5	0.38	Agdens	0.34
Slope	-0.19	Shallow	-0.32
Tmp_min	-0.16	Geomor1	-0.27
Phys1	0.10	Smaxhigh	-0.27
Sun_tot	-0.09	Fert2	0.15
		Prc_50m	0.13
		S2maizer	-0.07
Region 7: Southwest			
(r^2-adj = 0.91)			
Intercept	0.00		
Rurdens	0.76		
Sun_tot	-0.26		
Fert3	-0.10		
Smaxlow	0.06		

[a] All significant at $P < 0.01$

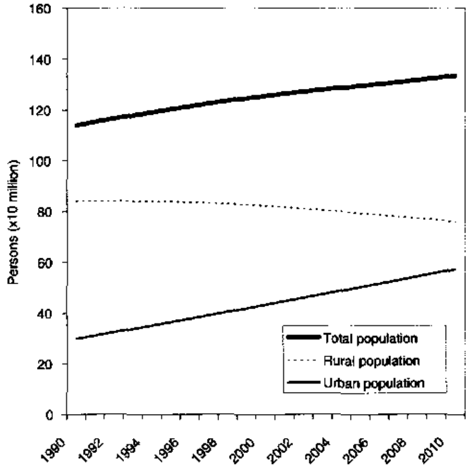

Figure 4.3 *Development of total, urban and rural population for China during the simulation period, based on US Bureau of Census (1997) and UN (1995b)*

Population module

The population module as implemented for China contains three demographic parameters: total population, percentage rural population and agricultural labour force. Rural and urban population densities are calculated from the total population and percentage rural population. Growth rates of population are clearly different throughout the country as a result of regional differences in natural growth rate and migration within the country. County based growth rates between 1982 and 1990 (Editorial Board of the Series National Atlas of China, 1996) were used to calculate population growth for individual grid cells. Relative growth rates are assumed to be stable. However, the absolute growth rate changes in time. Therefore, the individual growth rates are corrected to such a degree that the national total corresponds with population projections used. For the present study the population projection of the U.S. Bureau of the Census (U.S. Bureau of the Census, 1997) is used.

Changes in rural population are calculated in a similar way. County based growth rates, derived from changes between 1985 and 1990, are used and corrected for national scale urbanisation projections (UN, 1995b). Figure 4.3 illustrates the projections used. For the changes in the percentage agricultural labour force of the total population county level data are, for this study, only available for 1990. Therefore growth rates are based upon province level changes between 1984 and 1994 (State Statistical Bureau). These growth rates are assumed to be constant for the simulation period.

Demand scenario

In this study the spatial pattern of land-use change is calculated for a scenario of land-use change at the national level for the period 1990-2010. The scenario is based upon extrapolation of trends and estimates of land-use change by Smil (1993) for the period 1989-2000. Most available statistics of current land-use changes as well as the estimates given by Smil (1993) only account for changes at the cost of cultivated land while no data of other conversions are available (Table 4.6).

The increase in built-up area for the scenario used in this study is lower than the estimates of Smil (1993) and the statistical trends because it is assumed that part of the increase in built-up area comes from land already classified as built-up in our land-use data (e.g., courtyards, wasteland in between houses etc.). The conversion of cultivated land to forest and grassland and desertification is split up into increases of forest area and unused land. Grassland area is kept constant as it is assumed that the restoration of rangelands will be compensated by degradation of grasslands at other places. Furthermore, it is assumed that all increases in horticultural land come from land previously used for other crops. Therefore the average rate of conversion of cultivated land to horticulture during 1987-1995 (NLMA, 1995) is used as the rate of increase in horticultural area.

The area of inland water bodies is kept constant. In reality some dynamics in the extent of the inland water bodies are expected due to the construction of reservoirs, hydro-generation projects and fishponds and the reclamation of wetland areas (Streets et al., 1995).

In our scenario the cultivated area decreases 8.5% during the simulation period which corresponds well with other estimates of losses in cultivated land (Peoples University Press, 1991; Garnaut and Ma, 1992 and Ke, 1996).

4.5 Results

Land-use change patterns

The changes in land-use pattern for the different land-use types over the period 1990 - 2010 are shown in Figure 4.4. The results illustrate that although the total extent of the cultivated area decreases, still some areas with an increase in cultivated area can be distinguished. These dynamics are even more obvious for the changes in grassland distribution. Although the national demand remains constant several regions are found where the grassland area is changing. These spatial dynamics are a result of the competition among land-use types and autonomous developments. From Figure 4.4 a number of 'hot spots' of land-use change can be observed. In the Northeastern part of China a decrease in cultivated land can be seen as result of reforestation and increases in grassland area. In the northeastern part of this region grassland area increases at the cost of forest. Some increases in horticultural area are expected in the more favourable southern part of the region, bordering the Bohai sea.

Table 4.6 *Yearly land-use change rates at the national scale used in the simulations as compared to estimates of Smil (1993) for the period 1989-2000 and statistics of current trends*

	Scenario used in this study (1000 ha)	Smil (1993) for period 1989-2000 (1000 ha)	Statistics (1987-1995) (NLMA, 1995) (1000 ha)
Cultivated land	-574	-282 - -500	-267[d] - -631
Built-up land	+221	+261 - +283	+295
Urban	-	+23 - +45[a]	n.a.
Rural	-	+182[b]	n.a.
Others	-	+56	n.a.
Forest (reforestation)	+107	+114 - +227[c]	+209
Grassland (restoration)	0		
Unused land (desertification)	+64		+107
Horticulture	+182	n.a.	+182[e]
Inland water bodies	0	n.a.	n.a.

[a] Of which about 60% is expected to cause conversion of cultivated land

[b] Of which about one quarter is expected to come from cultivated land

[c] Only those conversions at the cost of farmland are mentioned

[d] Average between 1978-1991 according to statistical yearbooks

[e] Including area converted to fishponds

Degradation of arable land causes large losses of cultivated land on the Ordos Plateau of Inner Mongolia. In this area cultivated land is mostly converted or degraded into grasslands while part of the area is reforested to avoid sandification. The most dramatic land-use conversions are found on the Loess plateau. The simulation results indicate that while a large part of the cultivated area becomes unusable other parts of the area are reforested. The areas bordering the Gobi desert and Tarim basin face decreases in cultivated area due to desertification. Other 'hot-spots' of land-use change can be found in the main agricultural regions of East, Central, South and Southwest China as a result of the expansion of built-up area. In the highly populated Sichuan basin losses can be attributed to construction and urbanisation while in the southwestern mountains reforestation of marginal lands takes place. Prominent increases in the area devoted to residential and industrial construction are found in the eastern region (Zhejiang province), the southern coast north of Hong Kong and in the Central region (Hunan province). In the Southern region large increases in horticultural land appear in the model outcome. This result corresponds well with the high demand for horticultural products in the fast growing economy of the urban centres in this region.

Characteristics of cultivated land losses

The spatially explicit approach of land-use change modelling allows us to evaluate the possible consequences of changes in land use. As an example an assessment is made of the consequences of arable land loss for the food production capacity. This assessment is made by comparing the production characteristics of land lost for agricultural production with the production characteristics of all arable lands. As measures of the production capacity soil fertility, grain yield and multiple cropping index, taken from the 1990 statistics (Skinner et al., 1997), are used. Grain yield is an important measure of production capacity in China: in both ancient and modern times, China's leaders tend to define food security as grain security (Crook, 1997). These three measures of the agricultural production capacity and the cultivated area are assumed to be distributed homogeneously over the grid cells of 32 x 32 kilometre. Table 4.7 gives the average production characteristics for all cultivated land and lost cultivated land, aggregated for the whole country as well as for two groups of regions. On average the lost cultivated areas have slightly lower soil fertility, somewhat lower yields and a somewhat lower multiple cropping index than the overall values. However, for regions 2,4,5 and 6, comprising east, south and central China, more valuable land is lost. In these regions the grain yield of the lost lands is equal to the overall grain yield while the multiple cropping index is slightly higher. The differences between the regions in quality of the converted arable lands are probably due to different types of land-use conversions. In the northern and western regions, most arable lands are lost as a result of degradation and/or conversion to its former use. These areas are usually marginal for agriculture and have thus a lower production capacity. Cultivated land losses in the eastern and southern regions are mainly caused by competition between cultivated land and built-up area. This type of land-use conversion is indirectly related to the production capacity of the land because most of China's cities are situated in fertile areas.

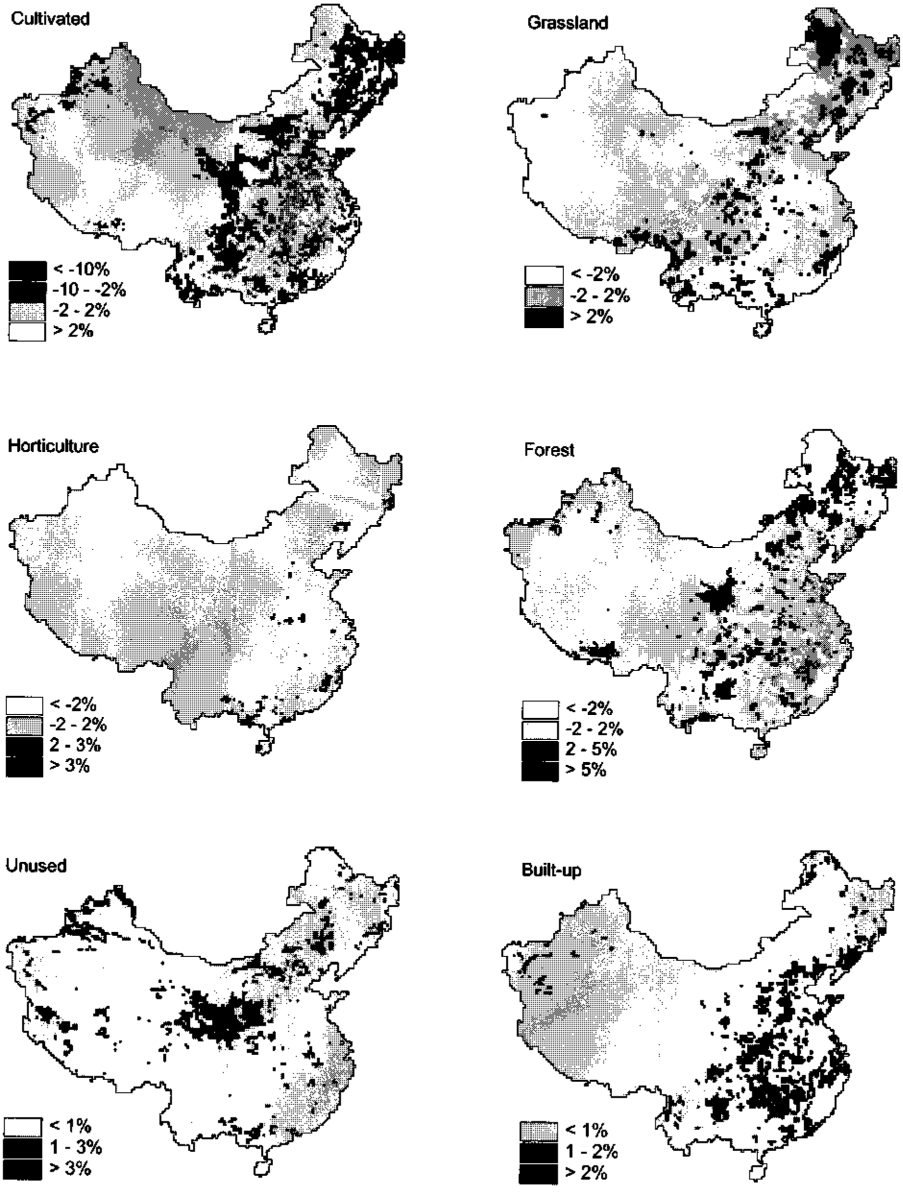

Figure 4.4 *Changes in percentage cover for the different land-use types during the simulation period (1990-2010)*

4.6 General discussion

The spatial analysis, on which the CLUE model is based, consists of an integrated assessment of the biophysical and socio-economic factors or proxies of those factors that determine the distribution of land-use types. The rather good fit of the multiple regression models confirms that no major factors influencing the land-use pattern are omitted. The results show that national trends in land-use change are not always followed in all regions: even in the case of large decreases in cultivated land at the national level there are still some areas where cultivated land tends to increase. These dynamics result from the modelling technique that takes competition between land-use types and autonomous, bottom-up, changes in land-use into account (Chapter 3). This type of dynamics corresponds well with our understanding of landscape dynamics (e.g. Baker, 1995; Wiens, 1995).

Validation of the model performance is only possible when the land-use distribution is known for two points in time with a considerable number of years in between. Even then, it is only possible to validate the model against historical changes. For China no land-use data of reliable quality are available for two separate years. It was only possible for us to derive relative changes in cultivated area over the period 1990 - 1993 from official statistical data (Skinner et al., 1997; Editorial Board of the Series National Atlas of China, 1996). A comparison of modelling results with these data is difficult because of the short time period and the consequently small changes in land use during this short period. Limitations also arise from the bad quality of the data used due to georeferencing difficulties. The differences in total cultivated area between this data set and the data used for the simulation will further restrict the possibilities for direct comparison.

If, given these limitations, the changes between 1990 and 1993 (Figure 4.5) are compared to the modelling results (Figure 4.4) it can be noticed that the modelling results put more emphasis upon changes in regions that are rather marginal for agricultural production, such as the Ordos and Loess plateau and the southwestern mountain area. The measured changes between 1990 and 1993 are more concentrated in the eastern part of China, probably mainly caused by increases in the built-up area.

Table 4.7 *Average characteristics of all cultivated land and characteristics of cultivated land converted during the simulation period (1990-2010)*

	grain yield (ton/ha, 1990)	multiple cropping index (1990)	poor soil fertility (% of area)	high soil fertility (% of area)
whole country				
all cultivated land (1990)	3.8	1.6	23	47
converted cultivated land (1990-2010)	3.5	1.4	26	43
region 1,3 and 7				
all cultivated land (1990)	3.4	1.3	21	49
converted cultivated land (1990-2010)	3.2	1.2	20	48
region 2,4,5 and 6				
all cultivated land (1990)	4.2	1.8	26	45
converted cultivated land (1990-2010)	4.2	1.9	40	32

The areas indicated by the model as 'hot spots' of decreases in cultivated area correspond with the areas indicated in literature as regions where the risk for cultivated land loss are the largest and where desertification and erosion have already a long history of arable land losses (Qinye et al., 1994; Han, 1987; Smil, 1993). The statistics of 1990 and 1993 show only limited changes in the cultivated area in these regions. Degraded arable lands might still be kept in production or have been compensated by bringing more marginal lands into production. On the longer term these losses cannot be compensated and marginal lands must be restored to earlier, less demanding uses through reforestation and pasture restoration (Rozelle et al., 1997). In this respect our simulations over a period of 20 years appear to be realistic.

On the other hand it might well be that the simulation technique overestimates cultivated land losses in these marginal areas and underestimates land loss in East China. The model assumes that in areas where the conditions for the actual amount of cultivated land are not optimal a decrease will occur as soon as these areas are more suitable for one of the other land-use types. In other areas, cultivated land will only decrease when competition with other uses is very large. This explains the simulated decreases of cultivated land on the Ordos and Loess plateaux and in South-west China. In the east of China, where most increases in built-up area are found, the conditions are also favourable for cultivated land. Therefore the model predicts that the increases in built-up area will largely result in decreases of forest area. However, when analysed at a more detailed scale than modelled, forest areas in the eastern part of China mainly consist of small patches at places unsuitable for any other land use. It is not likely that these areas can, and will be used for construction of residential and industrial sites. Most urban development is expected adjacent to present built-up area and for a large part at the cost of cultivated lands (World Bank, 1993). This type of detailed scale land allocation can not be assessed correctly by the present model because of its minimum resolution with grids of 1024 km^2.

A more thorough analysis of model performance is recommended as soon as more land-use data for China become available. Downscaling of the model results to certain regions in East China can give more insights in the bottom-up effects of the allocation of land and competition between land-use types.

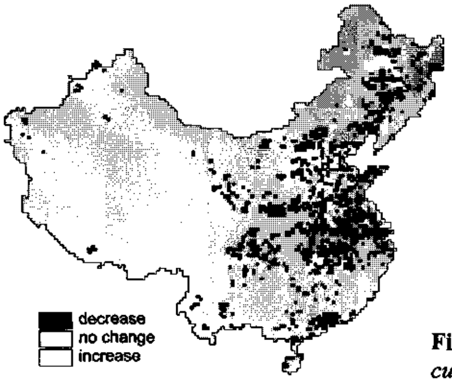

Figure 4.5 *Changes in percentage cover of cultivated land during 1990-3 according to official statistics*

Based on the modelling results, assessments can be made of the possible consequences of land-use change, like the effect on production capacity described above. This type of assessment is not possible when land-use changes are only studied at the national or regional level. Even at the spatial resolution of our study one should take care with the interpretation of the results. The results of this type of assessments are scale dependent because both land-use change and production characteristics need to be assumed homogeneously distributed over each grid cell. Representative case-studies in varying parts of the country might proof the reliability and scale dependency of the assessments made.

The results of the model are dependent on the amount and rate of land-use change during the simulation period. An analysis of model behaviour (Chapter 3) indicated that the spatial pattern of simulated changes in land use is different for scenarios that only differ in the pathway of change. Therefore the 'hot-spots' of land-use change as identified with the model will, to a certain extent, depend on the scenario specified. A more specific analysis of the changes in demand for agricultural products and built-up area with reliable estimates of reforestation policy will facilitate the formulation of realistic scenarios.

4.7 Conclusions

The CLUE modelling framework provides a methodology to simulate the spatial dynamics of land-use change in China. Although the model aims at a realistic description of land-use dynamics the results should not be interpreted as forecasts of future events. Rather, they indicate possible patterns of land-use change given the scenario simulated.

The exploration of possible land-use changes and the identification of 'hot-spots' of land-use change can be seen as a policy-supporting instrument. The model may also form a tool to assess pathways of development and related effects of land-use change. As an example of such effects production characteristics of the converted cultivated areas were calculated in this study. For the presented scenario the actual production characteristics of the areas taken out of agriculture are slightly worse than the average production characteristics of Chinese agriculture. In a similar way the results of the model simulation can be used to assess the effects of land-use change on greenhouse gas emissions. This type of analysis is not realistic with highly aggregated data at the national level. In this respect the CLUE model for China can be seen as an essential tool to link national scale studies with regional to local assessments.

Chapter

5

Exploring changes in the spatial distribution of livestock in China

Peter Verburg and Herman van Keulen

Agricultural Systems 62 (1999): 51-67

Abstract

China's livestock sector is very dynamic as a consequence of increasing demands for animal products. This paper explores the spatial distribution of different groups of livestock in China. Relations between the spatial pattern of livestock distribution and a large number of socio-economic and biophysical variables have been derived by correlation and regression analysis. The thus derived relations are used in a spatially explicit, dynamic simulation model to explore near future changes in land-use and livestock distribution. A baseline scenario and a scenario with improved management of grasslands are evaluated. The results indicate that for both scenarios most increases in livestock numbers are to be expected in China's agricultural region.

5.1 Introduction

Projections of tremendous increases of the consumption of livestock products in China (e.g. Garnaut and Ma, 1992; OECF, 1995) have caused discussions in the scientific as well as in the political arena. These discussions focus mainly on the ability of China to produce enough grains for human consumption and feeding of the increasing livestock population. However, the increasing scale of meat production will also affect the systems of livestock keeping, their spatial distribution and interactions with the environment.

Grasslands are one of the main natural resources used for livestock. The extended grasslands of Inner Mongolia have since long been used for large herds of sheep and horses (Wittwer et al., 1987). Of the total area of China, 35% is covered with grasslands (Wu and Guo, 1994). Due to its low natural productivity and low management levels the carrying capacities per hectare are rather low. Carrying capacities are also decreased through degradation of the grasslands. Overgrazing of grasslands has often been mentioned as one of the major causes of degradation and desertification (Smil, 1993). Although governmental policy is aiming at the restoration of grassland areas in regions that are very marginal for arable farming, there is a loss of good quality grasslands which are converted to cultivated lands as a consequence of the need to increase food production.

Changes in the spatial distribution and size of the livestock population will also have effects on other sectors of agriculture. Because feed-stuff and manure are generally not transported over large distances, changes in the spatial distribution of the livestock population will cause changes in the pattern of feed-crop production and manure availability. Although China's agriculture has a long tradition of using organic inputs to maintain soil fertility (Stone, 1990) structural changes and increasing inputs of chemical fertilisers have reduced the importance of organic fertilisers. With increasing numbers of livestock, the importance of organic manure is likely to increase again.

For an assessment of the interactions of the animal husbandry sector with the natural and agricultural environment, insight is needed in the distribution of different systems of animal husbandry throughout the country. The unequal distribution of livestock throughout the country will render aggregated assessments at the regional or national levels inadequate for assessing the impacts that changes in livestock numbers can have for certain areas. Therefore the analysis of livestock distribution as presented in this paper is based upon high resolution spatially explicit data. The objective of our analysis is to identify the (proximate) processes that determine the spatial distribution of livestock in China based on a spatial, empirical analysis. These representations of the proximate causality processes are used in a modelling framework for identifying locations of high rates of near-future changes in livestock numbers.

5.2 Livestock in China

According to FAO's production statistics for 1997 there are about 468 million pigs in China, making up for about 80% of the total meat production. About half of all other meat production comes from poultry, derived from a stock of about 3 billion chicken and 500 million ducks. Although their contribution to total meat production is much lower, the impressive number of 133 million sheep and 171 million goats has a huge impact on land use in a large part of China. Furthermore, sheep and goats are also important in wool, mohair and

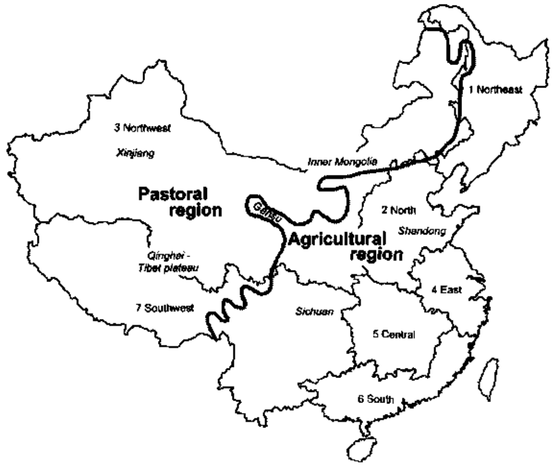

Figure 5.1 *Map of China with division into pastoral and agricultural regions (after Shen, 1989; Simpson et al., 1994) and the regional subdivision used by USDA (Crook, 1993b)*

cashmere production. Increasing popularity of beef and cow milk has resulted in immense increases in cattle numbers, from 52 million heads in 1980 to 116 million heads in 1997. Draft animals, including water buffalo's, horses, donkeys, mules and camels, count for about 76 million heads.

Throughout the country large differences in livestock systems are found. In the northern and western part of China, the 'pastoral region', we find grassland based livestock systems where the animals are mainly fed by grazing on rangelands (Sere, 1994; Shen, 1989). The east and south-east part of China, the 'agricultural region', is characterised by intensive arable farming in which livestock is kept in either mixed farming systems, in which the larger part of the total value of production comes from non-livestock farming activities, and land-less livestock production systems, in which animals are fed by products not produced at the same farm (Sere, 1994). Between these two regions, indicated in Figure 5.1, is a transitional area called the semi-pastoral belt characterised by a combination of grassland based livestock systems and mixed farming systems.

The pastoral region

The large differences in natural conditions, access to technology and culture have caused a wide variety in grassland production systems. The main animals used for grazing are sheep, goats, cattle, yaks, camels and horses. Sheep and goats are well adapted to harsh conditions, especially the breeds kept in the pastoral areas of the Qinghai-Tibet Plateau, have evolved in response to exceedingly harsh conditions. There is very little forage available during the long winters and, as a result, the sheep tend to deposit a large amount of fat during the summer to meet later nutritional needs. Yaks are even better adapted to harsh climates as they are found on the high cold mountains of west China where they graze the alpine grasslands in summer. Cows are kept under more favourable conditions and are still often used for meat as well as for milk. However, since demand for beef and milk products is increasing, the number of specialised farms is also increasing. Figure 5.2A and 5.2B show the distribution of sheep and goats as well as the distribution of large animals. In spite of the variety in animals grouped under large animals, e.g. horses, yaks, camels, cows and donkeys, they are included in the same category in Chinese county level statistics (Editorial Board of the Series National Atlas of China, 1996).

The agricultural region

About half of all goats are found in the agricultural region of China. In contrast to most other livestock found in this region, goats are usually fed, for a considerable part, by grazing. In the absence of rangelands the goats are usually herded on road-sides, in dry river beds and other pieces of wasteland between the arable lands.

Pigs make up the larger part of the livestock in the agricultural region. Traditionally, a large number of pigs are kept in 'back-yards', with 1 to 3 pigs per household as a secondary activity next to crop production. Although this production system is still found over the whole agricultural region, the increase in demand for meat has stimulated the development of specialised, commercial, pig fattening farms.

Draft animals, such as water buffaloes and donkeys, are found everywhere in the agricultural region. Especially in the southern part of China they play an important role in the preparation of paddy fields. Although their distribution is different from other large animals no separate

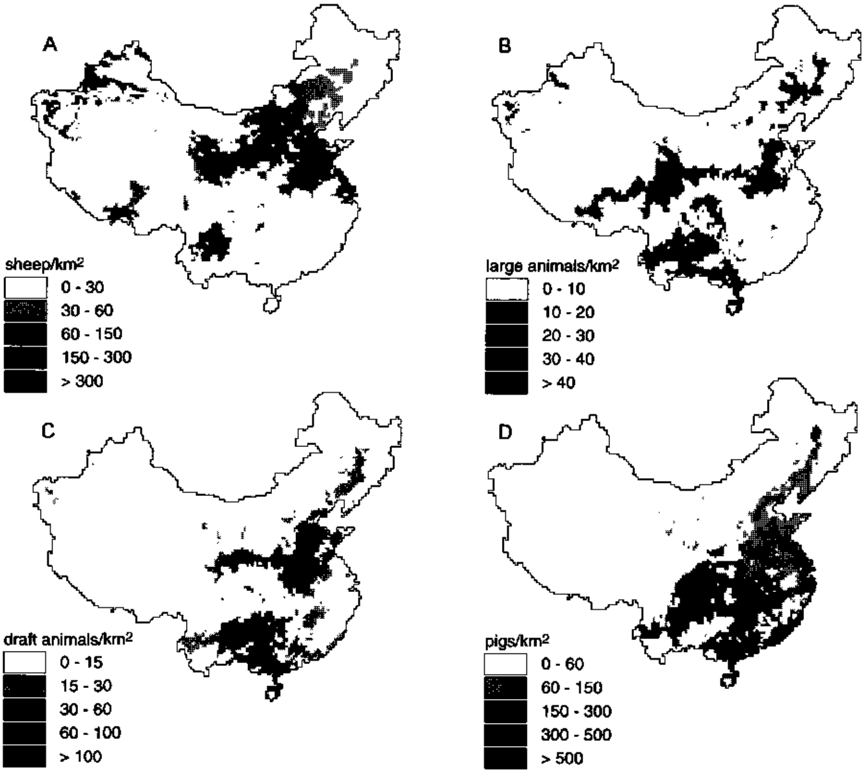

Figure 5.2 *Distribution of livestock types in China in 1990 based on data of the Editorial Board of the Series National Atlas of China (1996)*

statistics are available at county level. The distribution presented in Figure 5.2C is derived by multiplying the county-based distribution of large animals by the percentage of these large animals used for draft purposes calculated at the provincial level (USDA, s.a.).

Output from aquatic animal production systems has experienced annual growth rates of about 10% during 1980-1990. About 40 percent of all output is from freshwater. Most of the production of freshwater fish is nowadays from artificial fish ponds. This is also the type of production that will continue to grow and increase production. Spectacular increases in the area devoted to fish ponds, from 919 thousand ha in 1982 to 1.4 million ha in 1990, reveal that fish ponds should be regarded as a separate land-use type which will trigger conversions of agricultural land (Simpson et al., 1994). Analysis of remote sensing images of Jiangsu province by Streets et al. (1995) shows this conversion clearly. Because spatially explicit data of fish pond distribution are not available, no further analysis of aquaculture is made in this study.

5.3 Analysis of the spatial distribution of livestock

5.3.1 Methodology

The spatial occurrence of the different livestock types shown in Figure 5.2 is analysed in relation to maps of natural and socio-economic landscape variables. It is assumed that a large number of interrelated socio-economic and biophysical variables can be seen as the (proximate) causes for the distribution of livestock. Therefore a data-base containing approximately 60 potentially causative variables is used. The data-base contains demographic data (population, rural/urban population), socio-economic data (labour force, literacy) and data describing soil and climatic conditions, geomorphology and infrastructure (distance to city). The data-base also contains the distribution of different land-use types. An overview of all variables is given in Table 5.1 while a more detailed description of the data-base, its development and its sources is given in Chapter 4. All data are contained in a grid-based GIS with a cell-size of 32 x 32 km (1024 km^2; n = 9204).

Livestock numbers and their spatial occurrence are correlated to the variables contained in this data base. More comprehensive multiple regression models were constructed using a stepwise regression procedure which accounts for multicollinearity among the different variables. Because regional differences are large within China the analysis is stratified into seven regions according to the United States Department of Agriculture (Crook, 1993b) based on differences in agro-climatic conditions and resource endowments (Figure 5.1). This stratification allows a better representation of region specific conditions affecting livestock distribution.

A similar analysis is made for the distribution of grasslands in the country. As China is a huge country with an enormous variation in agro-climatic conditions a wide variety of grassland types is found, each with its own characteristics and potentials for use. Different classifications of China's grasslands are used (Daxue, s.a.; Zhu et al., 1985; Hu et al., 1992) to characterise the different types of grassland using vegetation pattern and species composition as criteria. In this study the 1:4million map of grassland resources as prepared by the Commission for Integrated Survey of Natural Resources of the Chinese Academy of Sciences is used to characterise the different grassland types. This map also contains a classification of the grassland resources based on grass production and quality for grazing. These two characteristics are used to calculate the carrying capacities of the grasslands in China (based on Daxue, s.a.; Figure 5.3A).

Table 5.1 *Variables used in the analysis of the spatial distribution of livestock*

livestock
sheep and goats
large animals
pigs
draft animals

land-use types
cultivated land
horticultural land
forest
grassland
built-up land
inland water
unused land

demographic variables
population density
rural population
urban population
agricultural labour force

climatic variables
temperature (min, max, avg, range)
no. of months above 10 degrees C.
precipitation (total, range)
no. of wet months (>50 mm precipitation)
percentage of sunshine

socio-economic variables
illiteracy
distance to nearest city
agricultural mechanisation

soil related variables
soil drainage (3 classes)
soil depth (2 classes)
soil moisture storage capacity (2 classes)
soil texture (3 classes)
soil fertility (3 classes)
soil suitability for irrigated rice (3 classes)
soil suitability for rainfed maize (3 classes)

landform related variables
mean elevation
range in elevation
slope
physiography (4 classes)
geomorphology (5 classes)

others
grassland carrying capacity
grassland grade (3 yield classes)
grassland class (3 quality classes)
distance to nearest large river

5.3.2 Results and interpretations

This section highlights the main results of the spatial analysis. As it is impossible to present the statistical results for all regions, grassland and livestock types, only the results are shown for the most important regions and most pronounced variables.

Grassland and carrying capacity. Grasslands are mainly found in the southwestern and northwestern regions of China. Smaller and more scattered grassland areas are found in the southern hilly area. Table 5.2 gives the variables with the highest correlations to the relative cover of a grid cell with grassland, both for the whole country as well as for the most important pastoral regions. The strong correlations with mean elevation and temperature at the national level indicate the dominance of grasslands in the Tibetan mountains. This relation is not valid for the northwestern region where the annual precipitation, soil fertility and occurrence of eolian landforms is essential for the distinction between grassland and desert. All results indicate that grassland areas are found in remote, uninhabited places (large distance to city, low population density) with a high illiteracy level. In this case we should interpret illiteracy as a proxy for the remoteness and development of the area. The correlations with the remoteness of the area indicate the problems that producers in the pastoral areas face with respect to poor transportation systems and vast distances that result in low prices for their livestock products.

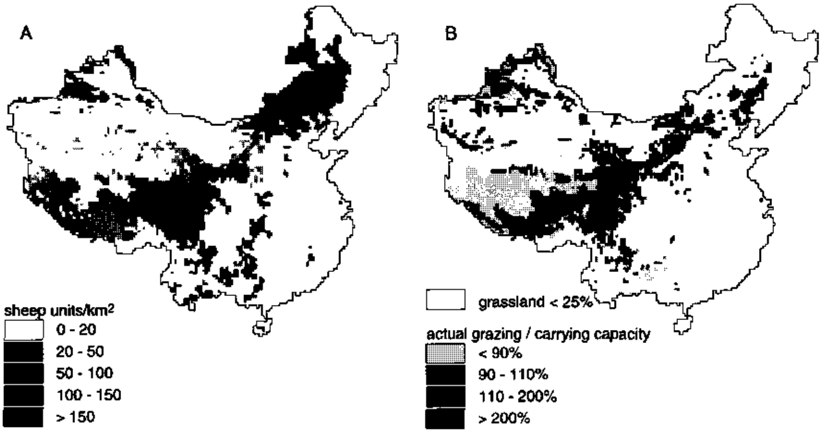

Figure 5.3 *(A) Carrying capacity (in sheep units/km^2) of grid-cells for grazing based on grassland distribution and grassland carrying capacity; (B) Percentage of carrying capacity used for grazing (only indicated for grid-cells with more than 25% grassland)*

Multiple regression models, which are corrected for multicollinearity among variables e.g., altitude and temperature, can explain 40 to 60% of the variation in grassland distribution in the main grassland regions.

High carrying capacities per unit area of grassland are found in the middle and southern parts of China where year-round rainfall and temperature patterns favour grassland productivity (Figure 5.3A). However, in these areas grasslands are almost exclusively confined to hill slopes with high susceptibility to soil erosion. The northeastern region also has reasonable grassland productions due to favourable temperatures and sufficient water in summer. Winters are however extremely cold which make year round grazing impossible. The northwestern part of China encompasses the larger part of the national grassland area, but has relatively low grassland production. Wind erosion, desertification and salinisation are major problems in the very dry climatic conditions in this region. Extremely low carrying capacities are found in the Tibetan Plateau area where most of the land is 3000 to 5000 m above sea level with related low temperatures. A correlation analysis between carrying capacity of grassland and potential explanatory variables illustrates our general understanding of production conditions: a negative correlation is found with altitude while positive correlations are found with precipitation, temperature and soil fertility. A remarkable correlation was found with illiteracy (-0.33), indicating the generally low carrying capacity of the undeveloped remote grassland areas.

By comparing actual stocking rates with the carrying capacity we can analyse which areas face overgrazing. In the calculations made it is assumed that in areas where grassland is the main land-use type all sheep, goats and large animals are fed by grazing or on hay harvested from the grasslands. Large animals are set equal to 5 sheep units, which is based on the legal definition of an animal unit in the Inner Mongolia Autonomous Region as well as in the United States for determining grazing permits (Simpson et al., 1994; Longworth and Williamson, 1993). Horses and mature bulls normally count for 6 sheep units, however, since no data splitting up the large animal category into different species are available, and the number of horses and bulls is relatively low, all large animals are considered equal to 5 sheep units. Figure 5.3B displays the pattern of overgrazing. This map confirms that the overgrazing situation in a large part of the grassland area in China is serious. Especially the southern part of Inner Mongolia autonomous region, Gansu province and part of Sichuan province exhibit very serious overgrazing.

Table 5.2 *Pearson correlation coefficients for the most important variables explaining the spatial distribution of grasslands in 1990*[a]

Whole country		Northwest - region 3		Southwest - region 7	
Variable	Correlation	Variable	Correlation	Variable	Correlation
Temperature (average)	-0.50	Precipitation (range)	0.42	Mean elevation	0.65
Mean elevation	0.46	Precipitation (total)	0.37	Temperature (average)	-0.62
Illiteracy	0.45	Soil fertility (high)	0.33	Precipitation (total)	0.59
Rural population density	-0.39	Temperature (minimum)	-0.33	Illiteracy	0.59
Soil depth (shallow)	0.34	Geomorphology (eolian)	-0.26	Agricultural labour force	-0.50
Distance to city	0.28	Illiteracy	0.25	Soil depth (deep)	-0.44

[a] all coefficients significant at 0.01 level

Table 5.3 *Pearson correlation coefficients for the most important variables explaining the spatial distribution of sheep and goats in 1990*[a]

Whole country		North - region 2		Northwest - region 3	
Variable	Correlation	Variable	Correlation	Variable	Correlation
Cultivated land	0.42	Agricultural labour force	0.53	Grassland	0.53
Rural population density	0.37	Illiteracy	0.51	Cultivated land	0.46
Agricultural labour force	0.36	Rural population density	0.50	Distance to city	-0.41
Grassland grade (moderate)	0.33	Cultivated land	0.49	Grassland class (good)	0.37
Population density	0.33	Geomorphology (plain)	0.47	Grassland carrying capacity	0.34
Grassland	0.13	Grassland	-0.30	Precipitation (total)	0.30

[a] all coefficients significant at 0.01 level

Table 5.4 *Multiple regression models for the distribution of sheep and goats in 1990*[a]

Whole country (adj-$r^2 = 0.42$)		North – region 2 (adj-$r^2 = 0.56$)		Northwest – region 3 (adj-$r^2 = 0.55$)	
Variable	Stb	Variable	Stb	Variable	Stb
Agricultural labour force	0.45	Illiteracy	0.46	Grassland	0.51
% sunshine	0.35	Mean elevation	0.40	Cultivated land	0.46
Cultivated land	0.30	Agricultural labour force	0.36	Grassland grade (low)	0.24
Grassland	0.24	% rural population	-0.32	Distance to city	-0.22
Distance to city	-0.22	Precipitation (range)	0.28	Soil fertility (moderate)	-0.09
Illiteracy	0.15	Temperature (average)	0.21		
Grassland grade (high)	-0.15	Wet months	-0.18		
Range in elevation	0.10	Soil texture (coarse)	0.15		
Geomorphology (tableland)	-0.10	Urban population	-0.12		
Soil fertility (moderate)	-0.09	Soil suitability rice (mod.)	0.10		
		Soil fertility (poor)	0.09		

[a] all models and coefficients significant at 0.01 level; stb: standardised beta coefficients

Sheep and goats. Table 5.3 gives the highest correlations found between a number of human and biophysical explanatory variables and the number of sheep and goats for the whole of China and for the two regions where most sheep and goats are kept. Table 5.4 gives the multiple regression equations for the same regions. Because of the large differences in livestock systems between the different regions large differences in explanatory variables and correlation coefficients are found, rendering the assessment of the country as a whole irrelevant. In the northern region sheep and goats are highly correlated to rural areas which are intensively used for arable crops (positive correlations with agricultural labour force, rural population and illiteracy). The animals are mainly fed on grain, fodder and all kinds of agricultural by-products (Simpson et al., 1994). Grazing is confined to small wasteland areas, along roads, dry riverbeds and arable fields after harvest. Grasslands are not important in this livestock system, as indicated by the negative correlation between the grassland area and number of sheep.

A totally different livestock system is found in the northwestern region. Here a strong correlation is found between grassland area and sheep distribution. Although a small part of the livestock in this area is still kept by nomads who move around the vast steppe regions with their herds, we find strong correlations between the cultivated area and sheep numbers. This reflects the transhumant life style of most of the herdsmen of Inner Mongolia. These herdsmen only leave their permanent home bases when seasonally abundant forage is conducive to pastoralism or move to pastures without water resources in the winter where the animals can take advantage of the snow (Simpson et al., 1994). Another reason for the correlation between livestock numbers and the area of cultivated land is the policy that called for local food self-sufficiency, causing the reclamation of grasslands for arable farming in the pastoral areas. Smil (1993) mentions that this policy led to large increases in the farmland area in the pastoral region between the late 1950's and 1980. Sheehy (1992) shows that also in more recent years herdsmen adopt a sedentary lifestyle and convert grazingland to arable fields. Positive correlations between carrying capacity, favourable climate and the number of sheep and goats per square kilometre need no further explanation. While most grassland areas are located far from cities and concentrations of population the opposite holds for the distribution of sheep. So, it is especially the less remote grasslands that are used for livestock. This strengthens the already mentioned importance of transportation distance and its influence on producer income.

Large animals The distribution of large animals is related to the same variables as the distribution of sheep and goats in the agricultural region. Because large animals in the agricultural region are mainly fed on grains and agricultural by-products the correlation with cultivated land is easily explained (whole country: 0.45). Other important variables are again the distance to the city and the density of agricultural labour force. Because different types of animals are lumped into the large animals group the relations found are not always straightforward and biased towards the distribution of cattle which make up the larger part of this group.

Draft animals Draft animals are strongly related to the distribution of cultivated land (0.69 in region 2) and agricultural labour force (0.74 in region 2). This is not a very surprising observation as draft animals are mainly kept for ploughing of arable fields and transport of agricultural products. Draft animal power is often, in the course of modernisation of agriculture, replaced by tractors (Campbell, 1989). Therefore the correlation between the fraction of the agricultural area ploughed by tractor and the number of draft animals per hectare of cultivated land was studied. Figure 5.4 shows the results at the provincial level. Provinces with a higher level of mechanisation clearly have a relatively low number of draft animals. The regression line in the figure is strongly influenced by the high draft animal density in Xizang Autonomous Region (Tibet). Without taking this point into account there is still a clear and significant relation between draft animal density and the fraction of the agricultural ploughed by tractor. The same analysis based on the gridded county-level data does only yield significant relations for a few regions. Obviously data quality is limiting in

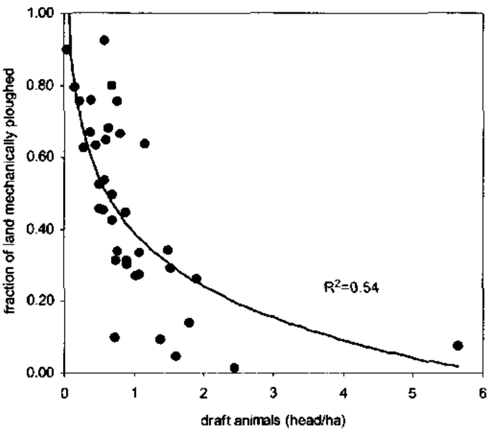

Figure 5.4 *Relation between the fraction of the cultivated area mechanically ploughed and the number of draft animals per ha of cultivated land in 1990 at province level*

case of draft animals, as the draft animal distribution has been derived by multiplying county level large animal numbers by provincial level fractions of large animals used for draft purposes.

Upon studying the distribution of draft animals (Figure 5.2C) it is found that especially Shandong province and the southern region have high concentrations of draft animals. Chinese agricultural scientists explain the high number of draft animals in Shandong by a long tradition of using animal labour in this province. High draft animal densities in the southern part of China are associated with rice farming, in which water buffaloes are an important source of animal labour.

Pigs Results of correlations between pig distribution and explanatory variables or proxies for explanatory variables are shown in Table 5.5 for the whole country and the two regions in which most pigs are found. Correlations with the distribution of population, especially the rural population, are very high and dominate the explanation of the pig distribution. Population density is important because meat is generally not transported over large distances, so production areas are close to consumption areas. Also the large number of rural households that keep some pigs in their 'backyard' is responsible for the correlation found, while correlations with cultivated area are associated with feed availability. At the national scale a significant, negative correlation with the average number of annual sunshine hours is found. When studied within the regions this correlation is not significant or very low. Instead of explaining the correlation as a preference of pigs for cloudy weather, we can attribute this to a historic preference for pig keeping in the southern part of China, where the number of annual sunshine hours is relatively low.

Table 5.5 *Pearson correlation coefficients for the most important variables explaining the spatial distribution of pigs in 1990*[a]

Whole country		South - region 6		East - region 4	
Variable	Correlation	Variable	Correlation	Variable	Correlation
Agricultural labour force	0.88	Agricultural labour force	0.83	Rural population density	0.65
Rural population density	0.86	Rural population density	0.75	Population density	0.60
Population density	0.79	Population density	0.64	Agricultural labour force	0.53
Cultivated land	0.69	Cultivated land	0.60	Geomorphology (plain)	0.57
Temperature (average)	0.59	Mean elevation	-0.52	Cultivated land	0.55
% sunshine	-0.58	% sunshine	0.08[b]	% sunshine	0.17

[a] all coefficients significant at 0.01 level

[b] not significant at 0.05 level

Because of large internal correlation between the demographic parameters only the density of the agricultural labour force, the percentage of illiterate population and the number of sunshine hours is retained in the multiple regression model. This multiple regression model is able to explain 80% of the variance in distribution of pigs.

5.4 Model explorations

5.4.1 Model description

The analysis of the spatial distribution of the different livestock types and the quantified relations with explanatory variables are used within a dynamic model to explore potential, near-future changes in the livestock distribution. The model is based upon the CLUE modelling framework (Veldkamp and Fresco, 1996). This land-use change model is able to calculate the spatial pattern of land-use change for different scenarios of change defined at the national level. In order to explore the changes in livestock distribution, a livestock module has been added to the modelling framework. The main assumptions and characteristics of the modelling approach are:

- Historic and present land-use distributions are essential to understand future patterns of land use. The relations between present land use and the explanatory human and biophysical variables are assumed constant during the simulation period.
- Both human and biophysical variables are used to calculate changes in the land-use pattern. Dynamic human variables will largely drive changes while biophysical variables determine the possibilities and constraints for changes. The relations between land use and these explanatory variables are quantified by multiple regression models, as described in the previous section of this paper.
- The model assumes that all demands for different land-use types, calculated at the national level and based upon changes in consumption, population, import and export, can be met from to the different grid cells.
- Competition between land-use types as a consequence of limited resources (land area, carrying capacity) in a certain grid cell will largely determine the resulting changes in land-use distribution. Competitive advantage is determined by the relative advantage of the local conditions for a certain land-use type as well as the relative change in demand for the considered land-use type at the national scale.
- Bottom-up effects as a consequence of local constraining factors as well as top-down driven changes in land-use preferences are mimicked in a multi-scale allocation procedure.

A more detailed description of the functioning of the model and its behaviour is given in Chapter 3 while the application of the model to the Chinese land-use situation is described in detail Chapter 4. The livestock module is based on the same principles. A major distinction is made between livestock systems that are based on grazing, and thus directly related to the prevailing land resources, and livestock systems that are relatively independent of the local grazing possibilities. It is assumed that sheep, goats and large animals, not used for draft purposes, are dependent on grazing of either grasslands or crop residues of arable lands. Pigs and draft animals are assumed to be independent of the carrying capacity for grazing as their number will not be determined by the limitations of the grazing area. If enough fodder is unavailable, farmers will supply draft animals with other feed. Pig breeding is totally independent from grazing practices and although crop residues are important feed for pigs, especially in backyard operations, the area of cultivated land in the near surroundings is assumed not to limit the number of pigs kept.

The multiple regression models describing the livestock distribution are used to indicate which areas have a potential for a change in livestock numbers, given a change in demand for livestock products at the national level. Three processes can be distinguished which might cause the livestock population in a certain grid cell to change. The most straightforward cause is a change in one of the determining conditions in a certain cell, e.g. as a consequence of population growth or urbanisation. The multiple regression models are used to indicate the livestock population that is found under similar conditions in other parts of the region/country. In this way spatial relations are used to predict future conditions. Even when national demands would be constant, changes in local determining conditions may cause some changes in livestock distribution.

Allocation of a change in livestock population is also based on the selection of grid cells that have, under the present conditions, a large deviation from the livestock population calculated by the multiple regression equations. It is assumed that, when the actual livestock population in a certain grid cell is lower than the population calculated by the multiple regression equation, there is potential for an increase in livestock population in that grid cell. The same holds true for decreasing demands and actual animal densities that are higher than indicated by the regression equations.

A third reason for a change in livestock population in a certain grid cell is a change in the competitive power between livestock types. If more than one livestock type uses the same limiting resource, like sheep and other cattle, and the competitive conditions for one of the two livestock types changes, e.g., through a change in demand or a change in local determining conditions, a new equilibrium in livestock numbers will be established.

For livestock types that use limited resources, all changes need to be corrected for the carrying capacity for grazing. All livestock numbers are converted to sheep units, as described above, after which the actual number of sheep units is compared to the carrying capacity of the grasslands and cultivated lands. If the carrying capacity is exceeded by a given percentage, no increase in livestock is allowed in the considered grid cell. Changes in the number of different livestock types as a consequence of changes in competitive power between the livestock types are of course possible. This correction has a large influence on the spatial pattern of changes.

In the livestock module an option is included to account for decreases in livestock numbers when carrying capacity in a certain area is already exceeded. The user can specify the annual percentage by which the number of livestock should be reduced until carrying capacity is no longer exceeded.

The livestock module is dynamically linked to the CLUE modelling framework so that changes in land cover will directly affect livestock distributions (Figure 5.5).

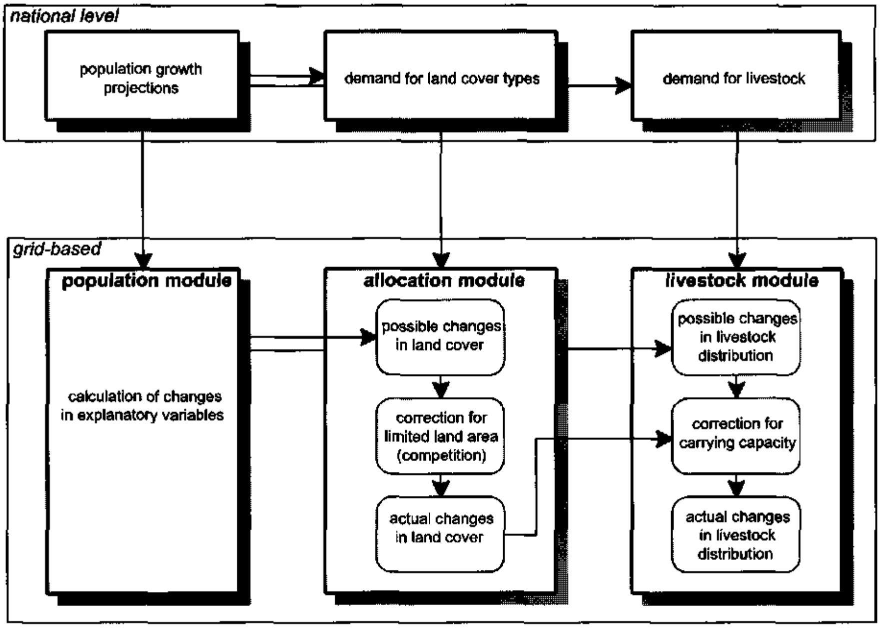

Figure 5.5 *Structure of the CLUE modelling framework*

5.4.2 Scenarios

Two scenarios have been formulated to analyse the effect of future demands and changes in land resources on livestock distribution. The first scenario is a baseline scenario in which most trends of the past ten years are assumed to continue. Zhu et al. (1985) have argued that agricultural output of grasslands could be increased given better management. The second scenario therefore, aims at an exploration of the effect of better grassland management on the use of grasslands.

Baseline scenario

The demand for livestock products, such as meat, milk and draft power, and the livestock numbers required to meet these demands are derived from Simpson et al. (1994). For their research they used a model developed for long-term projection of animal inventories. Their model captures human population dynamics as well as technological development. It is assumed that trade flows for livestock products remain small except for cow milk, so that all increases in consumption are derived from production within China. Based on elasticities and a scenario for income growth, demands for the different livestock products were determined. Per capita consumption is multiplied by the human population which is assumed to develop according to the high variant of the United Nations population projections (UN, 1995a). Total consumption is converted into livestock numbers using a number of production parameters like slaughter weight and off-take rates, again following Simpson et al. (1994) who assumed that development of production technology will lead to increased production efficiency. So, while total pork consumption is calculated to increase from 23 million tons in 1990 to 43 million tons in 2010, a 85% increase, the number of pigs will increase from 371 million heads to 430 million heads, only a 16% increase. Simpson et al. (1994) calculated livestock inventories for two different scenarios, titled 'sluggish economy' and 'robust economy'. In this study the projections of livestock inventories of the 'robust economy' scenario are used. In this scenario income growth rates of 9 percent for 1990 to 2000 and 8 percent for 2000 to 2010 were used.

Figure 5.6 gives the resulting scenario for the development of the number of pigs and the number of sheep and goats. More recent livestock inventories for the period 1990-1997 (FAO, 1998) indicate that already during this short time-span livestock numbers have exceeded projections for 2010. Simpson et al. (1994) have seriously underestimated increases in livestock consumption, partly as a consequence of a faster economic growth of China than anticipated.

The scenario for changes in land cover is based on extrapolation of trends and estimates of land-use change by Smil (1993) and described in Chapter 4. In this scenario the total area of grassland in China is assumed to stay constant. So it is assumed that losses of grassland through conversion to arable land or desertification of grasslands are compensated by restoration of grasslands at other places. It is also assumed that no attempts are undertaken to improve grassland management, so the carrying capacity is assumed stable.

The carrying capacity of arable land for sheep, goats and large animals is set to 300 sheep units per square kilometre of cultivated land. Because no information is available on differences in availability and quality of crop by-products this carrying capacity has been, arbitrary, applied uniformly to all cultivated lands.

Grassland scenario

Better rangeland management has been mentioned by various authors as a means to increase the output of livestock products from the pastoral region (Wittwer et al., 1987; Fu, 1989; Squires, 1989). The Chinese government has also provided a number of incentives to increase livestock production from the grasslands (Longworth and Williamson, 1993; Zhu et al., 1985). In this scenario the impact of better management of grassland resources for the livestock distribution is evaluated. The livestock inventory projections are identical to the baseline scenario. Grassland resources are, however, assumed to benefit from policies aiming at better management of the grassland resources. By assuming lower desertification rates through the establishment of shelterbelts and a higher rate of grassland restoration, the actual cover of grassland is assumed to increase by about 90 thousand hectares annually. Better management, through fertilisation, sowing of higher productive species, prevention of overgrazing and good rotations will cause increases in the carrying capacity of grasslands. In this scenario a 20% increase in carrying capacity between 1990 and 2010 is assumed. Simpson et al. (1994) indicate that grassland production increases are not possible and not

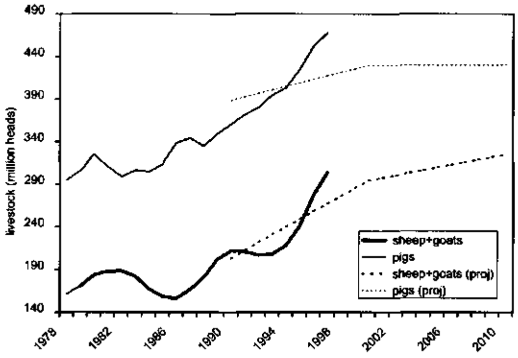

Figure 5.6 *Development of livestock between 1978 and 1997 and projections to 2010 made by Simpson et al. (1994)*

efficient on all types of grasslands. In their projections they assume that average grassland yields might increase 15% on the warm and sub-humid temperate grasslands between 1990 and 2010; 11% on the dry temperate grasslands and only 2 and 3% increases are attained on respectively arid and alpine grasslands. Grassland productivity increases do not linearly translate into increases of carrying capacity, but even so, our estimate of average increase in grassland carrying capacity seems to be rather high. It should therefore be regarded as the maximum attainable grassland productivity increase during this time period. All other assumptions are equal to the baseline scenario.

5.4.3 Results

Figure 5.7 gives the changes in relative grassland cover as calculated by the model for the two scenarios over the period 1990 to 2010. For both scenarios decreases in grassland area are found in Inner Mongolia and in the western part of China. This decrease is mainly caused by the degradation of grasslands into unused lands, e.g. deserts. Increases in grassland area are mainly found in the far north of China and in the semi-pastoral region, partly at the expense of cultivated land. The grassland scenario also shows a prominent increase of grasslands in the southern region.

The results of simulated changes in livestock density for the baseline scenario are shown in Figure 5.8. Most increases in livestock are found in the agricultural region of China. High dynamics in the distribution of sheep and goats are found in region 2, the North, where presently a high concentration of sheep and goats is found in the centre of the region. The results indicate that the distribution might become somewhat more equally divided over the region through small decreases in livestock densities in the centre of this region and increases in other parts. Large animal numbers are expected to increase especially around the urban centres on the southern and eastern coastline, around Beijing and Tianjin and in Sichuan province. Decreases in draft animal densities are evenly distributed over the area with presently high numbers of draft animals except for some localities where slight increases in draft animal numbers are predicted. The pattern of changes in pig density is similar to the pattern of population density changes except for the areas that already have a relatively large number of pigs, e.g. the Sichuan basin.

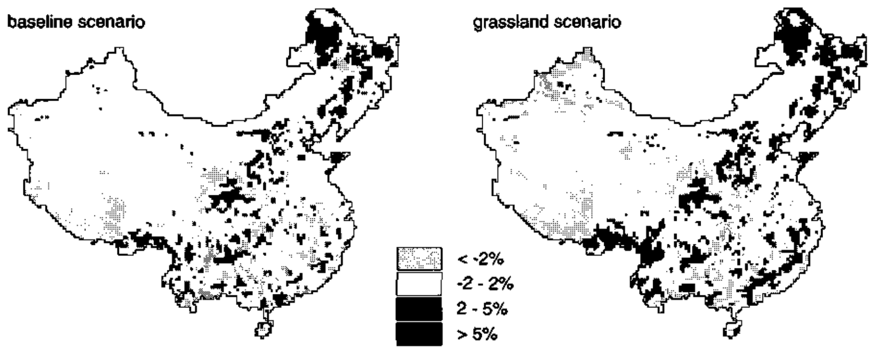

Figure 5.7 *Changes in relative grassland area simulated for 1990-2010*

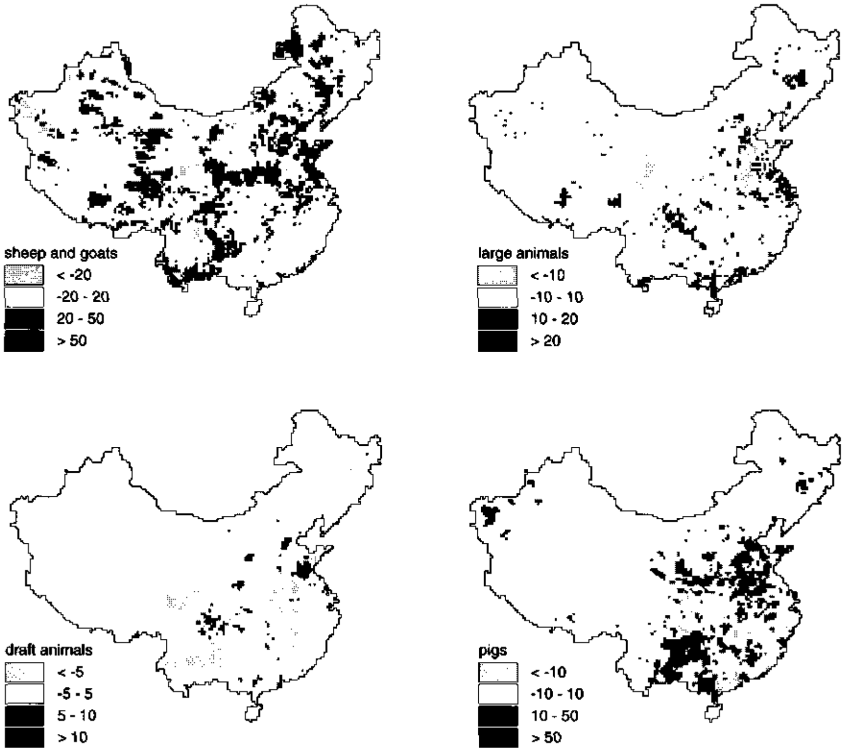

Figure 5.8 *Changes in livestock density (heads/km^2) simulated for the baseline scenario over 1990-2010*

The results of the grassland scenario are only slightly different from the baseline scenario. Because this scenario only differs with respect to grassland distribution and carrying capacities, results are only different for sheep and goats and for large animals. Table 5.6 gives the changes for these two types of animals for the pastoral and agricultural region respectively. It can clearly be seen that also in a situation with improved grassland management most changes will take place in the agricultural region.

Table 5.6 *Change in livestock population for two scenarios divided by region*

	Total increase in livestock (million head)	Increase in livestock divided by region	
		Agricultural region	Pastoral region
Baseline scenario			
Sheep and goats	121.0	69.9%	30.1%
Large animals	34.4	56.5%	43.5%
Grassland scenario			
Sheep and goats	121.0	70.0%	30.0%
Large animals	34.4	56.2%	43.8%

5.5 Discussion

The empirical analysis of grassland and livestock distribution, as described in this paper, gives us useful insights in the factors that determine the distribution of livestock. The regionalisation is essential as the large differences in farming systems between and within regions obscure the relations found at the national level. Although even within regions large differences in agricultural systems are found, the correlations between livestock distribution and the explanatory variables are generally clear. When interpreting the results one should keep in mind that the relations found are only valid at the scale of analysis and not necessarily causal. The determinants of livestock distribution at more detailed scales, e.g. at household or village levels, will probably be different. In our model exploration, we have used the relations at the scale from which they have been derived. Although much is known about the reaction of individual producers of livestock products to government incentives and changing conditions, these relations are not necessarily valid for large groups of producers living in heterogeneous biophysical and socio-economic areas of about 1000 square kilometres each, the minimum resolution of our analysis (Gibson et al., 1998).

Our analysis of the overgrazing situation of China's grasslands is rather rough. The carrying capacities, derived from the 1:4M grassland map (Daxue, s.a.), are disputable as is our assumption that all sheep, goats and non-draft large animals in the pastoral region are fed by grazing only. However, this type of assumptions are inevitable for analyses at high levels of aggregation. The areas identified as being overgrazed correspond well with the areas generally mentioned in literature (Longworth and Williamson, 1993). Simpson et al. (1994) mention that producer preferences for ownership of large numbers of livestock are one of the main reasons for overgrazing. This preference for large herds is inherent to the traditional livestock system that was adapted to the conditions characteristic of the grazing-land environment (Sheehy, 1992). High mortality as result of prolonged periods of deep winter snow or summer drought in some years was normal. The increasing population, especially through the migration of people of the Han nationality, and government policies have caused a trend towards sedentary agriculture. The most productive grasslands have been converted to arable fields while an increasing number of animals is kept on the decreased grassland area around villages. Also the communal use of the grasslands is targeted as one of the factors causing overgrazing as result of low individual responsibilities for the natural resource base. Longworth and Williamson (1993) argue that producer preferences for large livestock herds and improper use of communal grasslands are caused by market distortions and institutional uncertainties which cause farmers to optimise their short-term incomes.

When analysed at high aggregation levels, overgrazing seems to be much less serious. Simpson et al. (1994) mention an unpublished report by the Economic Policy Research Centre where provincial data for Inner Mongolia, Xinjiang and Tibet indicate that, as an average for the whole area, current livestock inventories are well below carrying capacities. This indicates that the overgrazing problem could at least be reduced, to some extent, through better allocation of the livestock. This suggestion does, however, not address the causes of the uneven livestock distribution in the grazing area. The presented statistical analysis clearly indicates that at the root of the problem are the poor transportation systems and vast distances, which cause low prices and high costs of inputs. The strong negative correlation of sheep, goats and large animal numbers with distance to the city indicates that people will be unwilling to reallocate their herds as long as these infrastructural and marketing conditions do

not improve. Especially dairy farms cannot be allocated on the grasslands at large distances from the major municipalities as access to fresh milk markets and the availability of high quality fodders in both summer and winter is essential (World Bank, 1987).
The modelling results of the 'grassland scenario' indicate that, even when grassland quality is improved and degradation is restricted, the relative importance of the grasslands for livestock will decline as most increases in livestock numbers are found in the agricultural region. The importance of infrastructure and marketing possibilities gets even more clear when a scenario is modelled in which the infrastructure and marketing conditions, approximated by the 'distance to city' variable, is improved. A model run was made in which the distance to city in region 3, the northwest, decreased 2% annually. Sheep and goat numbers increased by about 8% more than in the grassland and baseline scenarios. This indicates that the pastoral region becomes more favourable for livestock keeping when infrastructural conditions are improved. The grassland scenario, which implies enormous costs for increasing the grassland carrying capacities, also indicates that it will be very difficult to earn back investments. The predicted increase in livestock numbers is less than 1% higher than in the baseline scenario. However, upgrading of grassland might enable more sustained production levels on longer time scales.

The present model does not include an explicit feedback from overgrazing to degradation of grassland into unused land. The pattern of degradation to unused land is modelled directly based on a spatial analysis of land-use distributions (Chapter 4). Although the pattern of degradation corresponds well with our knowledge of the degraded areas in China (Sheehy, 1992), it is clear that overgrazing will more or less directly influence degradation into unused land. The time scale and type of processes involved are however difficult to quantify, as most degradation starts with a decrease in carrying capacity (Fu, *1989*) and the invasion of weeds (pers. comm. John Longworth, Univ. of Queensland). So, in the present version of the model only a feedback from overgrazing on livestock numbers is included. The exact calibration of this feedback mechanism needs further research at the appropriate scale.

Validation of the model results is not possible as the distribution of livestock is only available for one year. When more statistics become available, a comparison of model results with actual changes in livestock distribution will increase our understanding of the dynamics and driving factors of changes in livestock in China. For the time being, the presented analyses and model explorations should be regarded as a means to explore and increase our understanding of livestock systems in China rather than as predictions of the future livestock distribution.

5.6 Concluding Remarks

The analysis of livestock distribution and subsequent explorations of possible, near-future, changes in this distribution provide us with insights of the factors that govern livestock distribution and identifies regions and 'hot-spots' where changes in the livestock distribution are most likely to take place. The analysis also identifies the problems China is facing in the pastoral region with respect to overgrazing and limited increases in output of livestock products. The spatially explicit results can be used to calculate possible consequences of the changing livestock distribution for e.g. nutrient balances, feed requirements (Aubert, 1992) and greenhouse gas emissions (Hongmin et al., 1996).

Our spatially explicit methodology shows that GIS based modelling is useful for obtaining insights in land-use change and livestock distribution. The methodology used provides tools that are complementary to farming system analysis and stakeholder perceptions studied at fine spatial scales and non-spatial assessments of land-use change and food security at the national level.

Chapter

6

Land-use change under conditions of high population pressure

The case of Java

Peter Verburg, Tom Veldkamp and Johan Bouma

Global Environmental Change 9 (1999): 303-312

Abstract
A long history of increases in population pressure in Java has caused agricultural land use to expand and intensify. More recent land-use changes caused the conversion of prime agricultural land into residential and industrial area. Results of a dynamic, regional-scale, land-use change model are presented, defining the spatial distribution of these land-use changes. The model is based on multi-scale modelling of the relations between land use and socio-economic and biophysical determinants. Historical validation showed that the model can adequately simulate the pattern of land-use change. Future patterns of land-use change between 1994 and 2010 are simulated assuming further urbanisation. The results suggest that most intensive land-use changes will occur in Java's lowland areas.

6.1 Introduction

The island Java (Indonesia) is unique because of its high population density (>800 p km^{-2}) and intensive agriculture. The high population density has put a large pressure on land resources for a long time. Several studies have described the process of economic and agricultural growth during the past 200 years (Bottema, 1995; Van der Eng, 1993; Booth, 1988; Boomgaard, 1989). The process of economic growth and increasing population numbers has shifted agricultural expansion to the outer Indonesian islands while Java is changing into a more urbanised society (Bottema, 1995).

Studies that analyse and model these types of land-use change are carried out at different scales. The scale of study does affect the insights gained by modelling (Sklar and Costanza, 1991; Lambin, 1994). Local-level studies tend to highlight the complexity of the specific geographical and historical situations, demonstrating the uniqueness of particular causes of land-use change. Factors like agricultural prices, rural wages, credit supply, land markets and tenure security are often mentioned. The immense diversity in situations, the scale-specific nature of the relations and the general unavailability of quantitative information make it impossible to use such locally found relations for regional or global assessments. Methodologies for regional assessments must therefore be based on more generally available macro variables, which are often closely related to the immediate causes or are the underlying causes of land-use change. Most economic models, developed for regional scales, lack an explicit spatial dimension, therefore, they cannot answer the 'where' question (Lambin, 1994). An assessment of regional variability is, however, essential to capture feed-back effects, non-linear behaviour and diversity (Easterling, 1997).

A need for spatial models of land-use change was therefore identified (Hall et al., 1995; Mertens and Lambin, 1997). This paper introduces a spatially explicit methodology for regional scale assessments of land-use change. The methodology is applied to the island of Java to analyse recent and near future developments in land-use pattern under conditions of increasing population pressure.

6.2 Land-use change on Java

Recent and near-future land-use changes on Java are better understood when seen in the light of the development of agriculture in Java. In Figure 6.1 the change in land use and population from 1880 to 1995 is shown (based on yearly data collected by Van der Eng, 1993). From this figure we can derive different stages of agricultural development. The data for the last part of the nineteenth century and the first decade of the twentieth century show several of the classic features of a period of rapid agricultural expansion. The area of arable land was growing just fast enough to keep up with population growth. But as the expansion of arable land mainly occurred in upland fields, a decrease in average productivity was inevitable (Van der Eng, 1993; Booth, 1988). The increase in upland agriculture was facilitated mostly by improved communications and transport facilities, which lowered the threshold for people to migrate from the densely populated lowlands of Java to remote mountainous areas (Van der Eng, 1993). Geertz (1963) describes that during the same period the wet rice cultivation systems had to absorb ever-increasing numbers of people which worked harder and harder on the plots. However, with little improvement in the methods of cultivation, food production per person did not increase. By 1920 the frontiers of land extension

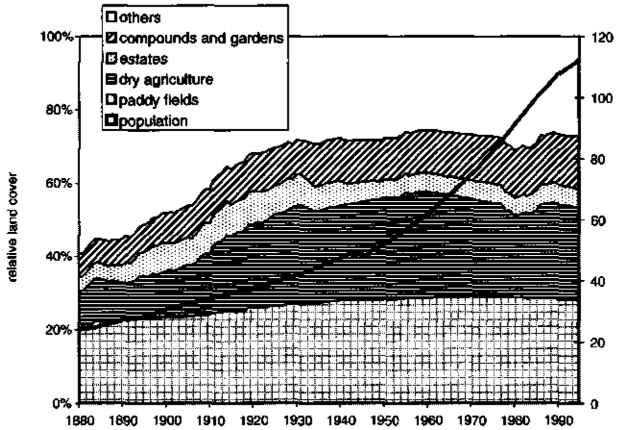

Figure 6.1 *Relative cover of different land-use types in Java (source: Van der Eng, 1993)*

were almost reached. The colonial authorities discouraged further extension, since it was likely to affect the hydrological situation in the upland forest reserves, and indirectly the supply of irrigation water in the lowlands. Following Boserup's theory, further increases in demand for food caused by population growth were satisfied by agricultural intensification (Boserup, 1965). The four decades from 1920 to 1960 can be seen as the era of intensification of Javanese agriculture, where intensification is defined as an increase in the cropping ratio. This resulted in a steady decline of arable land per capita and per agricultural worker and an increase in output per unit of land. A third stage in agricultural development of Java starts after 1970, when very rapid growth in food production can be observed, largely due to yield increases which accelerated throughout the period, particularly in the years after 1979. In the seventies there was also the first clear evidence of a decline in the proportion of the labour force being employed in agriculture. This decline, together with the rapid growth in rice production due to yield increases, led to a rapid growth in output per worker. Increasing labour productivity in agriculture implies that the agricultural surplus expands. Agricultural production will be sufficient to sustain a growing number of non-agricultural people who can be released from agriculture. Increasing labour productivity can also imply that more agricultural produce is available for export. Both consequences can be important preconditions for structural change and growth of the economy at large. In recent years Java is moving increasingly towards labour-intensive manufacturing and services as a means of employing a higher proportion of its population. Together with continuing population growth and larger demands for recreational facilities (e.g., golf courses) this will lead to a decrease in the area of prime agricultural land (Dyson, 1996). In Figure 6.1 this process is visible for the most recent years. Since possibilities for further intensification on existing agricultural fields are limited, Java is likely to become a net importer of food and agricultural raw materials both from the rest of the country and from the rest of the world. Booth (1988) stresses that Java and the Outer Islands are increasingly functioning as an integrated economy with free movement of goods and factors. The inevitable tendency will be to locate most industries, except those based on natural resource extraction and processing, in the densely populated inner core (Java), while keeping the rest of the country orientated towards agriculture and resource extraction. The described history of land-use change only has the intention of placing recent changes in a historic context. Lambin (1994) remarks that the evolutionary 'stages' do not necessarily grade into one another as simply as described. In reality, these processes of agricultural change can occur simultaneously within a region. Many finer-scale processes interact with the broad-scale trends driven by population pressure. The spatial modelling approach presented below is a methodology to assess the variability of these processes and to translate the broad-scale trends into finer-scale patterns.

6.3 Methodology

6.3.1 Spatial land-use change modelling

The CLUE modelling framework is a dynamic spatially explicit simulation methodology that uses actual and historical land-use patterns in relation to biophysical and socio-economic determinants for the exploration of land-use changes in the near future. The model was first applied to Costa Rica (Veldkamp and Fresco, 1996), while recently the methodology was tested for countries in Central-Andean America and Asia, showing different land-use change patterns (Verburg et al., 1997). The model uses a regular grid for which land-use changes are simulated. Essential is the way land use is represented in each grid cell. Instead of using a fine-mazed grid where grid-cells represent the dominant land-use type for a certain area, our grid-cells are relatively large and represent land use by designating the relative cover of the different land-use types. We assume that this relative cover, at a certain spot, is in a temporary balance with biophysical and socio-economic conditions that determine land use. This balance is primarily based on the relative competitive power of the different land-use types found at that location. The competitive power is influenced by macro variables, such as the demand for a certain land-use type, as well as by regional and more locally specific conditions, such as biophysical suitability and labour availability. Changes in one of the factors that affect the competitive power of one or more land-use types will cause the relative land-use configuration to change.

The CLUE methodology uses a multi-scale approach to determine the competitive power of the different land-use types at a certain location. A multi-scale approach is important as land use is affected by factors acting over a wide range of scales (Turner II et al., 1995). Land-use patterns identified on a scale with coarse resolution might disappear when a finer resolution is applied or vice versa (Gibson et al., 1998). In the model three different scales are used, including the national or regional scale and two spatially explicit scales. These two spatially explicit scales consist of grid based data at two different resolutions of which the finest resolution is chosen based on the data availability and quality. At the highest level, the level of the region or country modelled, the demand for the different land-use types is determined for a certain scenario of economic development. The demand for agricultural products, as well as for other land-use types, e.g. residential areas, is a major determinant of the relative competitive power of the individual land-use types. In this study this demand was based upon a review of different studies, described in the scenario below. This demand needs to be allocated by changing the relative cover of land-use types in the individual grid-cells. These changes are calculated based on the competitive advantages for the relatively coarse-scale grid and for the finer-scale grid. The determinants of the competitive advantage of the different land-use types are studied by relating the actual land-use distribution to a number of biophysical and socio-economic parameters which are generally considered to be determinants of, or proxies for, the land-use distribution (Turner II et al., 1993). These relations are quantified by a stepwise multiple regression procedure (Veldkamp and Fresco, 1997b). Upon changes in one of the determining factors the most likely new relative land-use configuration can be calculated from these multiple regression equations. As all land-use types are simulated synchronously, and total available land area is restricted, competition will determine the ultimate change based on the relative change in demand for the land-use types and the relative advantage of the local situation. The changes that are calculated for the coarse grid are used to promote changes at the nested detailed scale. All changes are simulated with one year intervals. A more detailed description of the allocation methodology and model sensitivity is given in Chapter 3.

6.3.2 Data

Land-use data are derived from agricultural surveys of the Central Bureau of Statistics of Indonesia. By aggregating some of the categories in these surveys six main land-use types were identified. These land-use types are described in Table 6.1. Only the 1979 survey contains statistics on forest areas. More recent statistics do not include this category. Therefore, forest, together with other small land-use types, is calculated for later years by correcting the area in 1979 for changes in other land-use types. The agricultural surveys contain statistics for 112 districts (kabupaten/kotamadya). The size of these districts is highly variable. In order to enhance the data resolution the land-use distribution is recalculated by combining the statistics with provincial maps designating the forested area.

A large number of variables are selected which are assumed to have importance for the distribution of land use (Turner II et al., 1993). Included are demography, economy and infrastructure, climate, geomorphology and soil related variables (Table 6.1). These data are derived from a large number of statistical publications, maps and digital data sets. All data are converted into an equal area projection and gridded. The basic grid size is based on the average data resolution and equals 20x20 km (400 km^2). For all 329 grid cells land use is characterised by the relative cover of each land-use type within the grid cell. In a similar way we represented classified variables, such as soil texture, by assigning the relative cover of each class within the grid cell.

To facilitate the multi-scale approach an intermediate aggregation level was created. Grid size of this aggregation level was chosen at 40x40 km (1 600 km^2), a simple aggregation of 4 basic grid cells. This artificial scale enables us to study coarser-scale patterns while still having a sufficient number of grid cells to perform statistical analysis.

6.3.3 Validation method

Validation of land-use change predictions is only possible for historical land-use changes. For Java spatially explicit land-use data are available for 1979 and 1994. This allows the evaluation of both the stability of the statistical relationships between land use and its determining factors as well as a means to validate the allocation algorithm of the model. As input for the yearly changes in demand for Java as a whole, a linear interpolation of land-use change between 1979 and 1994 was used. Most biophysical determining factors can be assumed constant during the validation period. This is not the case for the demographic and socio-economic conditions. Unfortunately only information of the total population and rural population was available for 1979. Labour force and gross regional domestic product were only available for 1994 and were therefore assumed constant at the 1994 level during the entire validation period.

Table 6.1 *Land-use classes and variables used to explain the spatial distribution of land use*

Variable	Description	Source
Land use		
Shifting cultivation	Agricultural land resulting form clearance of private woods and more or less forested land, mainly grown to annual, secondary crops	BPS (1979,1994)
Paddy fields	Wetlands mainly used for irrigated rice but also including rain-fed rice fields	
Dry agriculture	Garden land outside the home-yard and upland agriculture, mainly used for the production of seasonal crops (palawija)	
Housing and gardens	Land for building and its surroundings	
Estates	Government and private estate land on which commercial estate crops are cultivated, such as rubber, palm oil, tea, coffee, sugarcane, coconut, tobacco, cotton, cocoa and spices	
Forest and others	Forest and other smaller land-use categories (grasslands, swamps, ponds, temporary fallow, lakes and roads)	
Demography		
Population density	Density of total population (persons km^{-2})	BPS (1971, 1980,
Rural population density	Density of rural population (persons km^{-2})	1990, 1995)
Fraction rural population	Fraction of the total population that is classified as rural	"
Labour force density	Density of people aged 10 years and over who were working	"
Agricultural labour force density	Density of people working in agriculture (persons km^{-2})	"
Fraction agricultural labour force	Fraction of total labour force that is working in agriculture	"
Economy and infrastructure		
Gross regional domestic product	Gross regional domestic product at current price (million Rp)	BPS (1996)
Distance to nearest city	Direct distance to nearest city (m)	topographic map
Distance to nearest river	Direct distance to nearest major river (m)	ESRI (1993)
Distance to nearest road	Direct distance to nearest main road (m)	ESRI (1993)
Climate		
Sunshine	% of time without clouds	Cramer
Range in precipitation	Difference in precipitation between wettest and driest month (mm)	(experimental data)
Total precipitation	Average yearly precipitation (mm)	"
Average temperature	Average yearly temperature (°C)	"
Number of wet months	Number of months with more than 50 mm precipitation (months)	"
Agro-climatic zone	Agro-climatic zonation based on seasonality of precipitation	Oldeman (1975)
Geomorphology		
Mean altitude	Mean elevation (m AMSL)	USGS (1996)
Range in altitude	Range in elevation within grid based on 1km DEM	USGS (1996)
Mean slope	Mean slope (based on 1km DEM)	USGS (1996)
Geological unit	Geological classification based on parent material	CSAR/FAO (1959)
Soil		
Soil fertility class	Soil fertility (low, moderate, high)	CSAR/FAO (1959)
Soil drainage class	Soil drainage (well, moderate, poor)	PPT (1966)
Soil permeability class	Soil permeability (rapid, moderate, slow)	PPT (1966)
Soil texture	Soil texture (coarse, medium, fine)	PPT (1966)

Statistics on the area of forest were not available after 1979. Therefore forestry was reclassified with other minor land-use types into a separate land-use class. The dynamics of this land-use class are difficult to simulate as forest dynamics on Java are highly influenced by policy designation of reserves while other dynamics in this land-use class originate from e.g. the construction of artificial dams. Therefore, the changes in this land-use class during the simulation period were imposed on the model. The remaining five land-use types leave enough degrees of freedom to allow a proper validation.

Statistics and simulations can be compared at the level of individual cells. However, when validation is performed at the level of individual cells only, no index is given for the validity of the patterns that emerge at higher levels of aggregation. Costanza (1989) suggests a multiple resolution procedure to validate scale-dependent patterns. He proposes to calculate correlations between measured and simulated patterns at a number of artificial aggregation levels. If the correlation between measured and simulated patterns increases with aggregation level, the pattern is well matched, even though the initial fit at the base grid is relatively low. For Java we validated the model simulation at three aggregation levels, comprising the two grids at 20x20 km and 40x40 km and an additional aggregation level based on agro-ecological zones (Figure 6.2). Agro-ecological zones constitute a relevant, independent aggregation level not used in the modelling exercise. The agro-ecological zones are designated according to a map designed by Las and his associates (1991) at the Agency for Agricultural Research and Development. The zones are based upon regional mapping of water availability and elevation. The five distinguished zones are: lowland, dryland: wet climate, dryland: dry climate, upland and tidal/swamp lands. The first 4 zones cover all about one quarter of Java's surface area while the areal extent of tidal/swamp lands is only 0.5% of Java's land surface. This zone is therefore ignored in the validation.

6.3.4 Scenario to 2010

In this study, a scenario is evaluated which is assumed to be representative for future land-use changes in Java. The scenario is based on a study by the World Bank (1992). As this World Bank study was made before the recent Asia Crisis it projects a continuation of economical growth. The effects of the crisis on land-use change and the relevance of the scenario presented are discussed

Figure 6.2 *Agro-ecological zones (adapted from Las* et al.*, 1991)*

in more detail in the discussion paragraph.

The major land-use change represented in the World Bank scenario is caused by an increasing demand for non-agricultural land, e.g. land for urban and manufacturing development. Also the expanding number of farm families in the rural areas will require new land for house plots. Based on demand-supply studies it is expected that within agriculture there will be shifts away from paddy towards horticultural crops and other cash crops. The expanding and wealthier urban population will demand more fruit and vegetables, of which the larger part is expected to be cultivated on Java. Table 6.2 gives the resulting yearly changes based on the combination of the different land-use changes mentioned in the World Bank projections. The World Bank report does not mention changes in the areal extent of shifting cultivation. However, based on recent trends it is assumed that the area of shifting cultivation will gradually decline through a gradual conversion into more permanent agriculture. As a large part of Java's remaining forest is located in reserves, dynamics in forest cover are assumed to be relatively small (De Gier and Hussin, 1996). Some expansion of agriculture at the boundaries of these reserves will lead to a decrease in forest cover. It is assumed that the total area occupied by the land-use category 'forest and others' will remain constant as the losses of forest will probably be compensated for by afforestation at other locations and the construction of infrastructure (included in the others land-use class).

Taking the scenario as a whole it should be mentioned that, although the trend in land-use dynamics is similar to the trend between 1985 and 1995, the absolute changes are much larger. The changes in the scenario are, however, very modest compared to the view of some authors who foresee that in twenty-five years time from now, all Java, except the eastern and western parts, will be totally urban (Collier et al., 1993).

Table 6.2 *Total area of the different land-use types in 1994 and the annual change in area used in the scenario*

Land-use type	Total area 1994 (1000 ha)	Annual change (1000 ha)
Shifting cultivation	232	-5.0
Paddy fields	3396	-26.5
Dry agriculture	2849	-21.0
Housing and gardens	1732	+47.5
Estates	620	+5.0
Forest and others	3274	0

The biophysical determinants of land-use change were assumed to stay constant during the validation period. The change in population during the simulation period is based on projections to 2000 by the statistical bureau of Indonesia (BPS, 1994). For Java as a whole they project population growth at an average annual rate of 1.5% until 2000. All major population projections forecast further decreases in growth rates after 2000 for Indonesia as a whole. Therefore it was assumed that for Java the growth decreases to 1.25% yearly for the period between 2000 and 2010. The spatial distribution of population growth is derived from relative growth rates at district level projected for 1995-2000 (BPS, 1994). The same projection indicates that urbanisation increases from 39% in 1994 to 47% in 2000. For 2010 it is presumed that urbanisation will cause 57% of the population to be classified as urban. This rate of urbanisation corresponds well with projections of the United Nations (UN, 1995b) for the whole of Indonesia. The spatial distribution of urbanisation rates within Java is based upon observed urbanisation rates between 1990 and 1995. As no projections of labour force were available, the fraction of the population that belongs to the labour force is assumed to be constant while the fraction of the labour force that is active in agriculture is assumed to decrease between 1994 and 2010 from 36% to 29%. Table 6.3 summarises the changes in all land-use determining variables for this scenario.

Table 6.3 *Summary of changes in land-use determining variables used in the scenario*

Variable	Year	Value
Biophysical variables	1994-2000	Constant
Yearly population growth	1994-2000	1.5%
	2000-2010	1.25%
Urbanisation	1994	39%
	2010	57%
% labour force	1994-2010	Constant
% agricultural labour force	1994	36%
	2010	29%

6.4 Results

6.4.1 Validation

For the validation of the model performance, the observed and modelled changes in land use between 1979 and 1994 are compared at different aggregation levels. When measured and simulated land use in 1994 are compared, correlations range between 0.76 and 0.98 for the different land-use types at the '20x20' grid level. These high correlations can partly be explained by the relatively small changes in land use during the validation period. The comparison of measured and simulated changes in land use between 1979 and 1994 therefore provides a better measure of model performance. Table 6.4 and Figure 6.3a present the results of the validation. For all land-use types and aggregation levels there are positive and significant correlations between measured and simulated land-use changes. At the '20x20' grid level the change in paddy fields and estates is poorly simulated compared to the other cover types. Except for paddy fields, all correlations are higher at the '40x40' artificial aggregation level. Figure 6.3a presents the results of the validation for the different agro-ecological zones. The observed and simulated values are highly correlated (0.93).

In a number of grid-cells land-use change is moving against the general trend, e.g. although the total paddy area decreases there are some areas where paddy area increases. As a measure for this spatial variation, the standard deviation of change within the agro-ecological zones can be used. Figure 6.3b shows the observed and simulated standard deviation of the change within each agro-ecological zone for the different land-use types. In general there is a reasonable correlation (0.58) between the observed and simulated variability. However, especially for the more dynamic areas there is an underestimation of the variability in the model simulations.

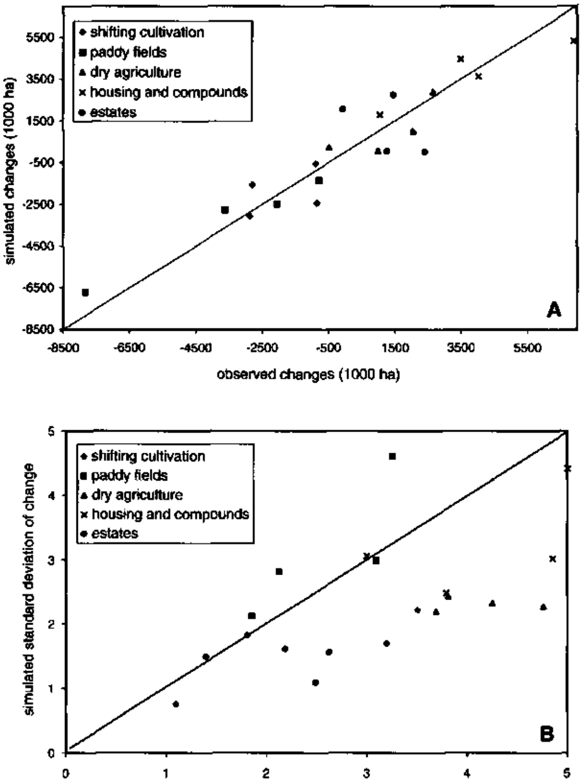

Figure 6.3 *(A) Simulated vs. observed change in land use for agro-ecological zones; (B) Simulated vs. observed standard deviation of change in land use within agro-ecological zones*

Table 6.4 *Correlations*[a] *between simulated and measured changes in land cover between 1979 and 1994 at different aggregation levels*

Land-use type	'20x20' grid (n=329)	'40x40' grid (n=97)	agro-ecological zones (n=20)
shifting cultivation	0.60	0.66	
paddy fields	0.31	0.30	
dry agriculture	0.45	0.47	
housing and compounds	0.46	0.56	
estates	0.20	0.22	
overall			0.93

[a] all significant at 0.05 level

6.4.2 Scenario to 2010

The results of the scenario simulations are presented in Figure 6.4. The maps indicate the major patterns of land-use change as they are predicted for the period 1994-2010. The most obvious pattern is the decrease in paddy fields in the northern coastal plain of Java, due to increases in housing area, estate crops and some increases in dryland agriculture. Other hot-spots of land-use change are found in the neighbourhood of the urban centres of Surabaya and Bandung, the major cities of Java. The model also predicts some land-use changes in the presently undeveloped areas in the western and southern part of West Java.

When summarised by agro-ecological zone most changes in land use are found in the lowlands. Land-use dynamics in the uplands are much lower, except for shifting cultivation.

6.5 Discussion

The validation of the land-use simulations as performed in this paper indicates that the model is able to capture a considerable part of the land-use dynamics. Especially at higher levels of aggregation the model results correspond well with the observed changes in land use. The CLUE modelling framework was already successfully validated for Ecuador (De Koning et al., 1999), under conditions of agricultural expansion. The analysis presented in this paper indicates that the model is also able to simulate land-use dynamics under conditions of high population pressure and strong competition among land-use types.

Differences between observed and simulated changes originate from a range of sources. Lack of appropriate data for the whole period for all dynamic parameters hampers the validation. Especially the changes in agricultural labour force, a major determinant of land-use patterns in an urbanising society (Booth, 1988), could not be modelled as spatially distributed labour force statistics were not available for 1979.

The model overestimated the increase in area used for housing in the upland areas while the increase was underestimated in the lowland areas. This is especially due to a serious underestimation of the increase in residential area in the environs of Jakarta ('the Jabotabek' area). At the start of the simulations in 1979, the area devoted to housing and its surroundings was well related to the rural population density, as a logical consequence of the large compounds which are characteristic for the Javanese rural area. Because rural population density is decreasing in the

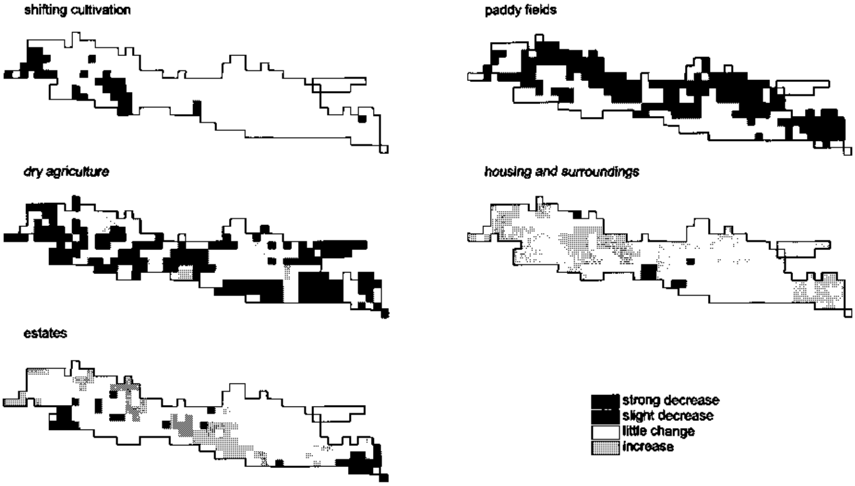

Figure 6.4 *Simulated changes in land use between 1994 and 2010*

Jabotabek area the increases in housing in urban areas are not well represented. Other reasons for differences between simulated and observed changes might be the omission of some determining factors, e.g. the land tenure situation. The land tenure situation could be important as it determines access to or control over land resources (Turner II et al., 1993). However, for models at this scale it is very difficult to obtain data representing the tenure situation and simulate its influence on land-use changes correctly.

A rather unique feature of the model is the realistic simulation of the spatial variability in land-use dynamics. The spatially explicit approach enables large differences in land-use change intensities within each zone. The validation indicates that the simulated variability corresponds reasonably well with the observed variability.

From the validation we can conclude that we should not interpret the results of the model on a cell-to-cell basis, as deviations between simulated and observed changes for individual cells can be considerable. Instead, the model results can be used to explore the pattern of land-use change and indicate regions that might become 'hot-spots' of land-use change. Although the period for which the model performance could be validated is short, it equals the time period for which predictions are made.

Model predictions for land-use changes during the period 1994-2010 indicate 'hot-spots' of land-use change. The land-use change activities along the northern coast of Java correspond well with recently observed trends in land-use change and several authors mention the region as a dynamic area (Bottema, 1995; World Bank, 1992). The observed change of paddy fields into residential and industrial area is straightforward. The increases in estates and dryland cropping are a reaction to the growing urban demand for horticultural crops (included in dry agriculture) and other cash crops. Because the largest decreases in paddy fields are found in the most productive area, the impact of the decrease in paddy area on rice production will be large.

Different studies (World Bank, 1992; Adnyana and Rachim, 1992) indicate that with rising incomes the demand for individual crops might change considerably. A decreasing share of staple crops within total food consumption is often found in urbanising countries (Heilig, 1995). Changes in the share of the individual crops will affect the relations between the land-use types and the socio-economic and biophysical determinants. In the presented model simulation we did not account for this effect as the individual crops are grouped into land-use types.

The model simulation indicates that land cover change in the uplands of Java will be limited as forests are assumed to be well protected and urbanisation is mainly occurring in the lowlands. This does not mean that land use in the uplands is not affected by the changes in the lowlands. As the agricultural production capacity of the fertile lowlands will be drastically reduced, food demands will need to be fulfilled for a relatively large part either by import from other islands and other countries, or from increased agricultural output of the upland areas of Java. This could have disastrous effects on the land quality of the upland areas, which are very susceptible to erosion (Whitten et al., 1996). The long history of high population pressure has already led to enormous soil losses. Even higher intensities of land use will be unsustainable unless enormous efforts are made to improve management. The loss of lowland paddy fields also carries with it potential for future calamities: a climate extreme or a new resistant pest could cause enormous rice shortages. For example, the drought brought about by the El Niño climatic event in 1997 in combination with financial problems due to the Asia Crisis currency devaluation, caused major food shortages.

The scenario presented in this paper does not take the effects of the Asia Crisis into account. The wave of exchange rate devaluations, stock market declines and severe credit shortages affecting

Southeast Asian economies started in 1997 and is expected to slow down economic growth until 2000. Recent projections by the United States Department of Agriculture expect economic growth rates to return to previously projected growth paths by 2001 (USDA, 1998). Slower rates of urbanisation, loss of purchasing power and declines in import demand will certainly affect land-use change. Intuitively it is most likely that demands for residential, industrial and estate crop land will not be as high as evaluated in this paper. A model run was made to evaluate the possible effects of the financial crisis on the land-use patterns presented. Therefore the scenario was adapted between 1997 and 2000. Demands for residential land are assumed to increase only slightly while other land-use types remain constant during these years. Urbanisation is also assumed to be halted between 1997 and 2000 while the total size of the labour force decreases. Resulting land-use change patterns between 1994 and 2010 mainly differed from Figure 6.4 in intensity. The location of the 'hot-spots' of change is almost identical for both simulations. The small differences in resulting land-use change patterns can primarily be attributed to the small period over which the rate of land-use changes is assumed to change. More prolonged changes in the economy will certainly have a larger impact on the land-use change patterns.

The quantification of impacts of this type of un-forecasted events on land use is not possible. This indicates the inherent uncertainty of any land-use change scenario and stresses that results of land-use change models should never be treated as predictions for future land use but rather as explorations of the potential dynamics of the land-use system.

6.6 Conclusions

The CLUE modelling framework has been successfully used to explore land-use changes for a scenario of further urbanisation on Java. The model can be used to explore the pattern of land-use change for different development pathways. The user can e.g. specify different demands for land-use types as well as different population growth distributions. The resulting patterns can be used to identify 'hot-spots' of land-use change and assess the possible impacts on natural and human resources. The scenario results presented in this paper show that the change into a more urban society is not taking place at equal pace over Java. Land-use change will especially occur in the lowland areas, either directly through construction of housing and industries or indirectly through the demand for higher value crops. The upland areas will, for the considered scenario, stay primarily rural.

This type of quantitative, spatial modelling is complementary to empirical observations of rates of land-use change, descriptive studies and non-spatial economic models. Local-scale, descriptive case-studies can provide important insights which are presently difficult to capture in quantitative models, and can inspire model builders to include new elements in their models. Regional-scale modelling exercises, such as presented in this paper, can integrate results from different disciplines and identify the need for new fields of research adding up to a better understanding of land-use change and its drivers. Understandings of land-use drivers, patterns and sensitivities thus obtained, will enable scientists to support the evaluation of land-use policies and associated impacts.

Spatial explorations of land-use change and grain production in China[1]

Peter Verburg, Youqi Chen and Tom Veldkamp

Abstract

Studies on land-use change and food security in China have often neglected the regional variability of land-use change and food production conditions. This study explores the various components of agricultural production in China in a spatially explicit way. Included are changes in agricultural area, multiple cropping index, input use, technical efficiency and technological change. Different research methodologies are used to analyse these components of agricultural production. The methodologies are all based on semi-empirical analyses of land-use patterns in relation to biophysical and socio-economical explanatory variables. The results indicate that different processes and patterns of land-use change are found in various parts of the country. Large inefficiencies in the use of agricultural inputs and relatively low input use in some of the rural, less endowed, western regions of China indicate that in these regions of China increases in grain yield are well possible. The spatially explicit results might help to focus agricultural policies to the appropriate regions.

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[1] Based on:

- Verburg, P.H., Chen, Y., Veldkamp, A. Spatial explorations of land-use change and grain production in China. *Submitted to* Agriculture, Ecosystems and Environment
- Verburg, P.H., Veldkamp, A. The role of spatially explicit models in land-use change research sequences: a case study for cropping patterns in China. *Submitted to* Agriculture, Ecosystems and Environment

7.1 Introduction

Land-use change is central to the interest of the global environmental change research community. Land-use changes influence, and are determined by, climate change, loss of biodiversity, and the sustainability of human-environment interactions, such as food production, water and natural resources and human health. Land-use changes not only include changes in land cover, but also the manner in which the land is manipulated and the intent underlying that manipulation (Turner II et al., 1995). Manipulation of land refers to the specific way in which humans use vegetation, soil, and water for the purpose in question: for example the use of fertilisers, pesticides, and irrigation for mechanised cultivation.

Land-use change in China is often seen in the light of its impact on food security. With a rising demand for agricultural products, as a consequence of population growth and changing consumption patterns, it is essential for China to increase its food production. In recent years much discussion is devoted to China's ability to maintain food self-sufficiency (Garnaut and Ma, 1992; Brown, 1995a; Rozelle and Rosegrant, 1997; Lin, 1998). China might become a major importer of food products as a consequence of its losses of agricultural land through urbanisation and degradation, and its limited possibilities to increase output per unit area. Brown (1995a) takes the most extreme position, claiming that China's grain production will fall in absolute terms while demand will rise, creating a shortfall of more than 200 million metric tons by 2030. Other authors, using more sophisticated analyses, have shown that shortfalls in production are probably lower (Paarlberg, 1997). The largest uncertainties in the projections of changes in China's food economy are found on the supply side of the food balance, largely as a consequence of differences in the analysts' perception of prospects for technological change and other factors affecting growth of cultivated land and productivity (Fan and Agcaoili-Sombilla, 1997). Almost all of these assessments of the impact of land-use changes on food supply in China are based upon an analysis of the economy at the national level. Such aggregated assessments lack the analysis of regional variability in land-use change and potentials to increase production. The highly diverse natural and socio-economic conditions in China cause land-use change to have differential impacts across the country. Spatially explicit assessments are needed to identify areas that are likely to be subject to dramatic land-use modifications in the near future. Such information is especially important for land-use planners since, in order to focus policy interventions, one needs not only to know the present rates and localities of land-use change, but also to anticipate where conversions are most likely to occur next. Such predicative information is essential to support the timely policy response.

This paper studies potential near-future changes in China's agricultural production from a spatially explicit perspective. The different components of land-use change influencing grain production, are studied in order to identify potential 'hot-spots' of change. Regional variability is related to its explanatory factors, to identify the processes underlying the changes in land use.

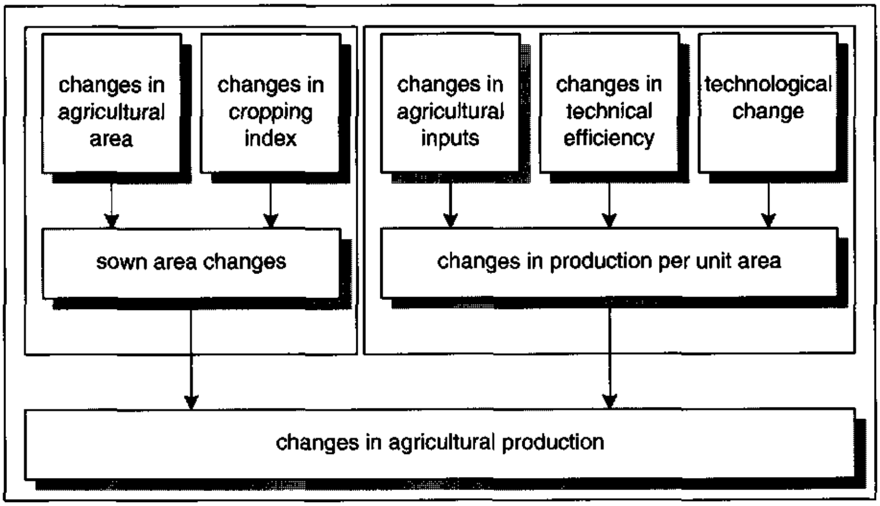

Figure 7.1 *Land-use change components that determine changes in grain production*

7.2 Methodology and data

7.2.1 Overview

Changes in agricultural production result from changes in one or more of the components of the land-use system. Changes in agricultural production can either originate from changes in the sown area or from changes in the production level per unit of land (yield). For regions where it is possible to sow the land more than once a year, changes in sown area can be divided into changes in agricultural area and changes in the multiple cropping index. Changes in yield can be subdivided into three components. First, the traditional source of growth stems from increases in agricultural inputs, e.g., irrigation and fertilisers. The second source of growth comes from increases in the efficiency of production. Increases in production efficiency make more output available with the same amount of inputs. Institutional innovations can be an important source of efficiency growth, as these eliminate restraints in resource allocation. The third source of growth is technological change, which shifts the production function upward. So, similar to efficiency increases, more outputs become available out of the same amount of inputs. New, improved varieties can be an important source of technological progress. Figure 7.1 shows the thus derived 5 sources of change in agricultural production. These different sources of change in agricultural production all have their own drivers and constraints. Therefore we have analysed them separately by different methodologies, described in more detail hereafter. Some of these methodologies have been described elaborately in other papers, so only the main characteristics are repeated here. All these methodologies have in common that they use data on the spatial variability of production conditions and (proximate) driving forces to analyse the dynamics of the land-use system. Another similarity between the methodologies is the use of statistical methods which are used to establish relationships between the pattern of land use and its supposed driving factors. The following paragraphs describe the data sets used in the study and the different methodologies.

7.2.2 Data

We have used a nation-wide, spatially explicit database containing biophysical, demographic and agricultural data. The data set is based on a large set of maps and statistical data gathered from various sources. Demographic and agricultural data are based upon statistics for 1986, 1991 and 1996 linked to administrative units (county-level). Soil, geomorphology and climatic characteristics are based on maps and interpolated climate data respectively, land cover data were unfortunately only available for 1986 and 1991 whereas data on agricultural inputs and production are also available for 1996. Therefore the base-year for all calculations is 1991, whereas 1986 and 1996 data are used to capture the temporal dynamics. The data and their various sources are summarised in the appendix of Chapter 2. All data are converted into a regular grid to match the representation of the different data and facilitate the analysis. The basic grid size, to which all data are converted, is 32×32 km (~1000 km^2), which equals the average county size in the eastern part of China. There has been considerable discussion about the reliability of Chinese land-use statistics, especially with respect to the amount of cultivated land (Crook, 1993a). Official statistics have always underestimated the area of cultivated land. However, the cultivated area in the agricultural survey we have used, equals 133 million hectares, which corresponds with the area generally assumed to be reliable (Alexandratos, 1996). For grain yield we had to use official statistics. Underreporting of arable land in official statistics has led to inflated estimates of grain yields and the appearance that China's yields are high by world standards. Statisticians have admitted that they have overstated grain yields to compensate for the underreported land area. They rely on sample survey cuttings to determine actual yields, and then inflate them 20 to 30 percent (Crook and Colby, 1996). The same overestimation holds for fertiliser application rates as these are also calculated with arable areas derived from official statistics. Unfortunately it is not possible to correct for the unreliability of the Chinese land-use statistics. Any calculation presented in this paper should therefore be seen in the light of this problem. However, we believe that it is still possible to use the data to indicate 'hot spots' of change and make conclusions on the relative importance of the processes throughout the country.

7.2.3 Methodologies

Changes in agricultural area

Changes in agricultural area can result from the reclamation of land, e.g., forest and grassland, into agricultural land as well as from the conversion of agricultural land into other land-use types through, e.g., encroachment of cities or desertification. Whereas the former conversion is constrained by availability of suitable land resources, the latter is the result of competition between land-use types. To explore these changes in agricultural area for China a dynamic, spatially explicit land-use change model is used. This model, the CLUE modelling framework, has been described in more detail in Chapter 3 whereas the application of the model for China has been described in Chapter 4. For the present application a special module is added to the model that allows the simulation of spatial patterns of different crop types.

Figure 7.2 schematically illustrates the structure of the modelling framework. At the national level demands for different land-use types are determined. Projections for future demands are directly obtained from other studies that use trend analysis or economic models to predict

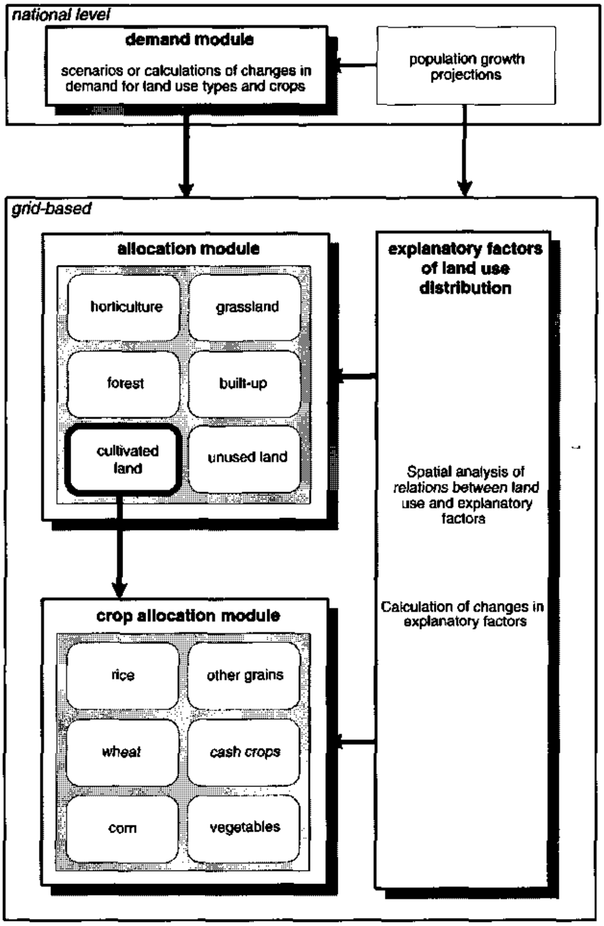

Figure 7.2 *Structure of the CLUE modelling framework*

changes in demand for the different land-use types. These demands are allocated on a yearly basis to the different grid cells in the allocation modules which use the relations between land use and the explanatory factors obtained by the spatial, empirical analysis. The appendix of Chapter 2 gives an overview of the demographic, socio-economic, soil related, geomorphologic and climatic variables evaluated in the analysis for China.

Simulations presented in this paper allocate land-use changes in a nested procedure. First changes in the different land cover types are simulated. In China we have subdivided the total land area into seven categories, including six land cover types and a category representing inland water bodies. In the simulation these different land cover types compete for the total land area available. It is assumed that the area occupied by inland water bodies is stable. Thereafter, nested within this simulation, follows the allocation of different agricultural crops or groups of crops. Included are wheat, rice, corn, a group containing other grains (incl. millet, sorghum, other miscellaneous grains, tubers and soybeans), cash crops (incl. fiber crops, oil crops, tobacco and sugar crops), vegetables and a miscellaneous category which includes all minor crops and green manure crops. In the model these crops compete for land within the agricultural area. No direct competition between individual crops and other land

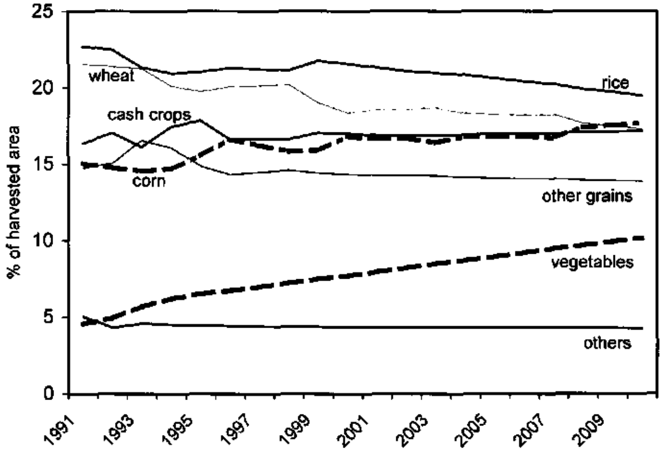

Figure 7.3 *Scenario for development of relative share of different crop types used in CLUE simulations*

cover types, such as built-up area and grassland, is taken into account because it is assumed that agricultural activities compete with other land-use activities indifferent of the actual crops cultivated. The simulations do not account for specific cropping sequences and intercropping systems. At the scale of analysis the data represent a mixture of cropping sequences and systems and do not allow the identification of individual cropping systems. In the simulations to be presented it is assumed that the multiple cropping index, i.e., the number of times a piece of land is sown to crops during one year, as well as the spatial variability of the cropping index are constant during the simulation period. For the allocation of changes in the different crop types simulations are only made for grid-cells where at least 5% of the land area is used for agricultural production in 1991. This effectively limits the simulation to about half of the area of China.

The scenario used for the simulations in this paper is a baseline scenario of which the demands for the different land-use types and population growth assumptions are presented in Table 7.1. These demands are based on an extrapolation of recent trends and estimates of land-use change at the national level for the period 1989-2000 by Smil (1993). The population growth rates, which stem from international projections, are differentiated throughout the country based on observed growth rates between 1986 and 1996. Also income was assumed to grow steadily with growth rates proportional to the growth rates observed in the grid cells between 1986 and 1991.

The demand for the different crop types is based on projections to 2007 by the United States Department of Agriculture (USDA, 1998) which provide yearly projections for all major crops. No projections are given for potato (included in the other grain category), some cash crops, vegetables and crops grouped in the category other crops, e.g., fodder and medicinal crops. For these crops projections are made based on trends and literature (e.g., Lin and Colby, 1996). China is expected to become a large vegetable exporter as China has a comparative advantage in producing vegetables for export, primarily because of its abundant rural labour resources (Crook, 1996). As China invests in transportation and storage infrastructure and as firms improve grading and packaging standards, China is likely to become a fierce competitor in world vegetable markets (Guoqiang, 1997; Lu, 1998). Domestic vegetable consumption is also expected to increase due to rather high income elasticity for vegetables, especially in the rural areas (USDA, 1998; Han and Wahl, 1998). Therefore we have assumed a doubling of the area sown to vegetables between 1991 and 2010. Figure 7.3 summarises the scenario for the different crops types. Up to 1997 observed data have been used, which can be seen from the fluctuations in relative harvested area.

Table 7.1 *Baseline scenario for CLUE simulations*

Demand for land cover types	*Area in 1991 (million ha)*	*Yearly change (1991-2010; 1000 ha)*
Cultivated land	132	-574
Horticultural land	5	182
Forest	195	107
Grassland	256	0
Built-up land	25	221
Water	34	0
Unused	296	64
Population growth assumptions	*Value*	*Source of projection*
Total population	17% increase (1991-2010)	US Census (1997)
% urban population	27% (1991) to 43% (2010)	UN (1995b)
% rural labour force of rural population	constant	Shen and Spence (1996)
% agricultural labour force of rural labour force	78% (1991) to 65% (2010)	trend and author's estimates

Cropping index

The cropping index denotes the number of times a year that a piece of land is sown to a crop. The possibilities for multiple cropping are constrained by climatic conditions and water availability. The temperature in winter is in a large part of China too low to support crop growth. Other parts, with more favourable temperatures, but with a distinct dry season, lack the water resources needed for crop growth unless irrigation is available. To understand the spatial variability in cropping index it is therefore essential to study both the actual and the potential cropping index. Agro-climatic and crop growth models can be used to calculate the variation in potential cropping indices throughout the country (Cao et al., 1995). However, this requires detailed information on crop growth and hydrological conditions. Because at many places China's cropping systems already operate at the maximum possible cropping index, it is also possible to obtain the maximum cropping indices by an analysis of the actual cropping index with a frontier function approach. Following the stochastic production function literature (Coelli et al., 1998) the following model was specified:

$$CI_i = f(X_i, \beta) + v_i - u_i$$

where CI_i is the average cropping index in the ith grid cell, X_i denotes the vector with climatic and hydrological factors determining the cropping index; v_i is a random error term which is assumed to be identically and independently distributed as $N(0,\sigma_v^2)$; and u_i are non-negative truncations of the $N(0, \sigma_u^2)$ distribution (i.e., half-normal distribution). The frontier function is represented by $f(X_i,\beta)$, and is a measure of the maximum cropping index for any particular vector X_i. Both v_i and u_i cause the actual cropping index to deviate from this frontier. The random variability, e.g., measurement errors or temporary constraints, is represented by v_i. The non-negative error term u_i represents deviations from the maximum potential cropping index attributable to inefficiencies. Inefficiency means in these circumstances a non-optimal use of the agro-climatic conditions. The basic structure of the stochastic frontier model is depicted in Figure 7.4 for a hypothetical relation between CI and X. Figure 7.4A indicates how the frontier function might relate to an ordinary least squares function (OLS) while

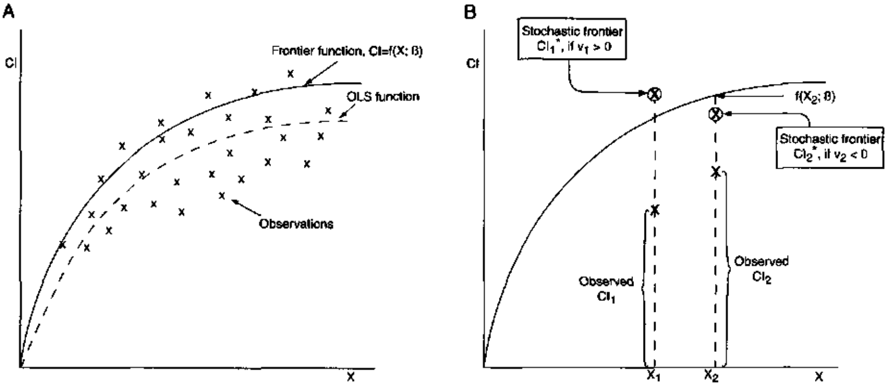

Figure 7.4 *Schematic representation of frontier function approach; (A) Frontier function as compared to ordinary least squares (OLS) function; (B) Observed multiple cropping index (CI) versus stochastic frontier value of the cropping index (after: Battese, 1992)*

Figure 7.4B focuses on the condition of two grid-cells, represented by *1* and *2*. In grid-cell *1* a cropping index CI_1 is found for the agro-climatic conditions X_1. The stochastic frontier cropping index, CI_1^*, exceeds the value of the frontier function, $f(X_1,\beta)$, because the random error, v_1, is positive. The cropping index in grid-cell *2*, CI_2, under conditions X_2, has a corresponding stochastic frontier cropping index, CI_2^*, which is less than the value of the deterministic frontier function, $f(X_2,\beta)$, because the random error, v_2, is negative. The efficiency in an individual grid-cell is defined in terms of the ratio of the observed cropping index to the corresponding stochastic frontier cropping index, conditional on agro-climatic conditions. Thus the efficiency in the context of the stochastic frontier function is:

$$TE_i = CI_i / CI_i^*$$

where TE_i is the efficiency in grid cell *i*.

In this study the vector *X* consists of the (long-term average) yearly temperature (TMP_AVG), the difference in temperature between the warmest and coldest month (TMP_RNG), the number of months that the average monthly temperature is above 10°C (TMP_10C), the number of months that more than 50mm rain is collected (PRC_50M), the average percentage of sunshine (SUN_TOT) and the fraction of all cultivated land in a certain grid cell that is irrigated (IRRI). The logarithm of the cropping index was used, because it resulted in a significantly better model fit. The frontier function is estimated for the three years that data were available with Maximum Likelihood procedures using FRONTIER4.1 software (Coelli, 1994). The actual changes in cropping index between 1986 and 1996 are used to evaluate the relevance of the calculated inefficiencies for future changes in cropping index.

Agricultural inputs

Farming systems can be characterised by their inputs and outputs. Therefore, each grid cell is classified by the average farming intensity calculated from an analysis of agricultural inputs and outputs. A disjoint cluster analysis is used to summarise the different inputs and outputs into groups of farming systems. In the cluster analysis grain yield (YGRAIN), chemical fertiliser input (FERT), irrigation (IRRI), labour availability (LABOUR), mechanisation (MACH) and manure application (MANURE) are used to characterise the farming system groups. To understand the spatial distribution of the distinguished farming systems, we have studied the spatial differences of the individual inputs and the farming system groups as a whole in relation to a number of environmental and socio-economic factors. The relation between grain yield and agricultural inputs is studied by fitting a production function with a Cobb-Douglas functional form given by:

$$\ln(Y_i) = \beta_0 + \beta_1 \ln(FERT_i) + \beta_2 \ln(IRRI_i) + \beta_3 \ln(LABOUR_i) + \beta_4 \ln(MANURE_i) + \beta_5 \ln(MACH_i)$$

Production efficiency

The notion of stochastic frontier functions and efficiency, as described above, originates from economic literature where frontier functions are used to determine the efficiency with which a firm produces a certain output given the level of inputs (Farell, 1957; Battese, 1992 and Bravo-Ureta and Pinheiro, 1993). The same holds for agricultural firms, or groups of agricultural firms in a certain area. Output, in this study defined as grain production per unit area (Y_i), is a function of agricultural inputs and the efficiency with which these inputs are used. Therefore we can write:

$$\ln(Y_i) = f(X_i, \beta) + v_i - u_i$$

where $f(X_i, \beta)$ presents the frontier production function where X_i denotes the vector of agricultural inputs similar to the Cobb-Douglas function (described above). v_i is the random variability in production that cannot be influenced by the producers and is identically and independently distributed as $N(0,\sigma_v^2)$. The non-negative error term u_i represents deviations from the frontier output attributable to technical inefficiency. Instead of giving these deviations a fixed distribution, as we do in the function for the cropping index, we follow the specification of Battese and Coelli (1995) where the inefficiency effects (μ_i) are expressed as an explicit function of a vector of grid-cell specific variables and a random error. Therefore u_i is assumed to be independently distributed as truncations at zero of the $N(\mu_i,\sigma_u^2)$ distribution. For this study the inefficiency function is defined by:

$$\mu_i = \delta_0 + \delta_1 TMP\_AVG_i + \delta_2 PRC\_TOT_i + \delta_3 SOIL_i + \delta_4 MEANELEV_i + \delta_5 DISTCITY_i + \delta_6 ILLIT_i + \delta_7 \%AGLF_i + \delta_8 INCOME_i + \delta_9 EROSION_i$$

All variables in this function are assumed to be determinants of the inefficiency in grain production. Climatic conditions (*TMP_AVG; PRC_TOT*) are included because it is hypothesised that the large differences in climate over the country will influence crop growth and therefore the efficiency in grain production. Soil fertility (*SOIL*) is assumed to be important because in areas with a high natural soil fertility less fertiliser is needed to obtain the same crop yield. Furthermore the elevation (*MEANELEV*) is expected to be negatively related to the efficiency as rugged terrain asks for relatively more labour and hampers cultivation practices. A second set of variables relates to the socio-economic conditions. Agriculture in areas which are relatively distant from cities (*DISTCITY*) is assumed to be hampered due to poor access to information and appropriate inputs, causing inefficiencies. In a similar way it is assumed that the illiteracy level (*ILLIT*), representative for the received education, influences efficiency. The percentage of the total population that is part of the agricultural labour force *(%AGLF)* is supposed to be indicative for the opportunities for off-farm labour, which is thought to be related to the efficiency of grain production. Average income (*INCOME*) is supposed to influence efficiency by the ability the farmer has to invest in his land (e.g., terracing) and the possibilities to buy a balanced set of appropriate inputs. The extent and impact of water erosion (*EROSION*) is assumed to be negatively related to efficiency as erosion can damage the crops, remove nutrients and have a negative effect on soil structure.

The frontier function and efficiencies are again calculated with the use of Maximum Likelihood procedures through FRONTIER4.1 software (Coelli, 1994).

Technological progress

Technological progress can be defined as a shift of the production function upwards. So, out of the same amount of inputs more output becomes available. This shift can easily be defined by including a time trend variable in the production function following:

$$\ln(Y_i) = \beta_t t + f(X_i, \beta)$$

where t is a time trend variable. The production function is calculated with data for the years 1986, 1991 and 1996. Data for years in between, which would make the estimates of the coefficient for the time trend variable more robust, are not available.

7.3 Results and interpretations

7.3.1 Changes in agricultural area

The results of the simulation of changes in the agricultural area with the CLUE model are presented in Figure 7.5 and 7.6. Figure 7.5A shows the spatial distribution of cultivated land in 1991, the reference year, as derived from the agricultural survey. The distribution of changes in cultivated area as simulated for the period 1991 to 2010 are indicated in Figure 7.5B. The results suggest that although the total extent of the cultivated area decreases, some regions showing an increase can still be distinguished. A more extended analysis of a similar model run, as presented in Chapter 4, indicates that in different areas different land-use conversions are responsible for the decrease in cultivated area. Degradation of arable land

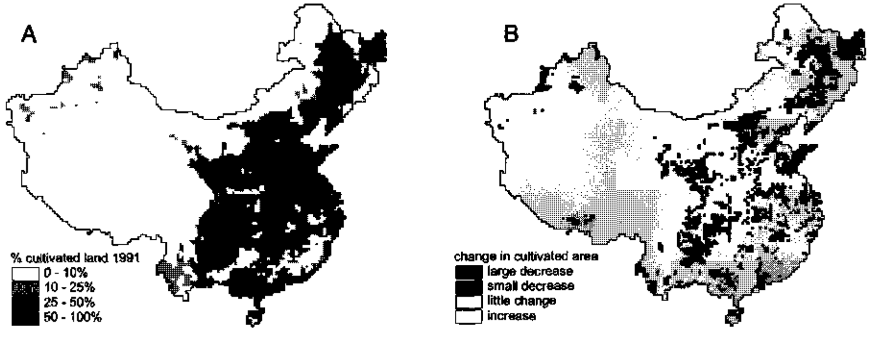

Figure 7.5 *(A) Cultivated land in 1991; (B) Predicted changes in cultivated area between 1991 and 2010 by the CLUE model*

causes large losses of cultivated land on the Ordos Plateau of Inner Mongolia and on the Loess Plateau. These are areas that are well known for their marginal agriculture and susceptibility to degradation (Qinye et al., 1994; Smil, 1993). Other 'hot spots' of land-use change can be found in the main agricultural regions of east, central, south and southwest China as result of the expansion of the built-up and horticultural area. Especially the larger area surrounding Shanghai is expected to face large decreases in cultivated land.

Figure 7.6 presents the results for the different crop types or groups of crops. Results for the group of miscellaneous crops have been omitted. The maps represent the relative share of the considered crop within the totally cropped area, i.e., a figure of 40% for rice means that at that location 40% of all sown area is occupied by rice.

Rice is mainly grown in southern China, where high temperatures and high precipitation favour the cultivation practices. From the map some rice far up north in the North Eastern plain and in the Beijing-Tianjin area can be distinguished. This rice cultivation does not follow the climatic subdivision of grain crop cultivation. In these areas special varieties are grown that can tolerate the cool climate. Yields are, however, low. Reasons for growing rice in these areas, which are more productive for other grains, are mainly historic and because of consumer preference for the high quality varieties from this area. Because of the large demand for these 'good tasting' varieties, prices are high and therefore the cultivation is profitable in spite of the low yields (Ren, 1991). Simulation results show that the decrease in demand for rice area is causing a decrease in the share of rice within the cropping system throughout the whole rice growing area. Because no distinction is made between rice varieties grown in the northern part of the country and in the southern part of the country, the impact that increasing incomes might have on the demand for the 'northern varieties' is not well represented. Increasing consumer preference for the northern rice varieties might keep rice production in the northern part of China more important than anticipated by the model.

Wheat is traditionally grown in the valleys of the yellow river and the large North China floodplain of the same river. The increasing cultivation of corn and cash crops in these areas will decrease the importance of wheat in the cropping system, especially in the southern part of the wheat growing area. In a large part of the wheat growing area labour-intensive cropping systems combining winter wheat cultivation and cash crop cultivation (e.g., partial intercropping of winter-wheat and cotton) are found. Increasing cash crop cultivation for the domestic and international market will make cash crop cultivation the most profitable part of the cropping system.

Corn is mainly grown in three regions, namely, the spring-sowing maize belt in the north; the summer-sowing maize belt in the plains of the Yellow river; and the southern maize belt in the upland areas of the provinces Sichuan, Guizhou, Guangxi and Yunnan. In 1994 sixty-four percent of all produced maize was used for animal feeds, while twenty percent was being used for direct consumption. The remaining sixteen percent was used for seed, processing, other uses and wastage (Guoqian, 1997). Very fast growth of the livestock population is responsible for the fast growth in demand for corn (Simpson et al., 1994; Verburg and van Keulen, 1999). Simulations show large increases in the share of corn production in the southern part of China, also in areas where corn is presently almost not cultivated. This increase in corn production in these areas seems rather realistic as in these areas a large amount of pig fattening farms is found. Results for cash crops show that in a large part of the agricultural area of China cash crops are going to make up a substantial part of the cropping system.

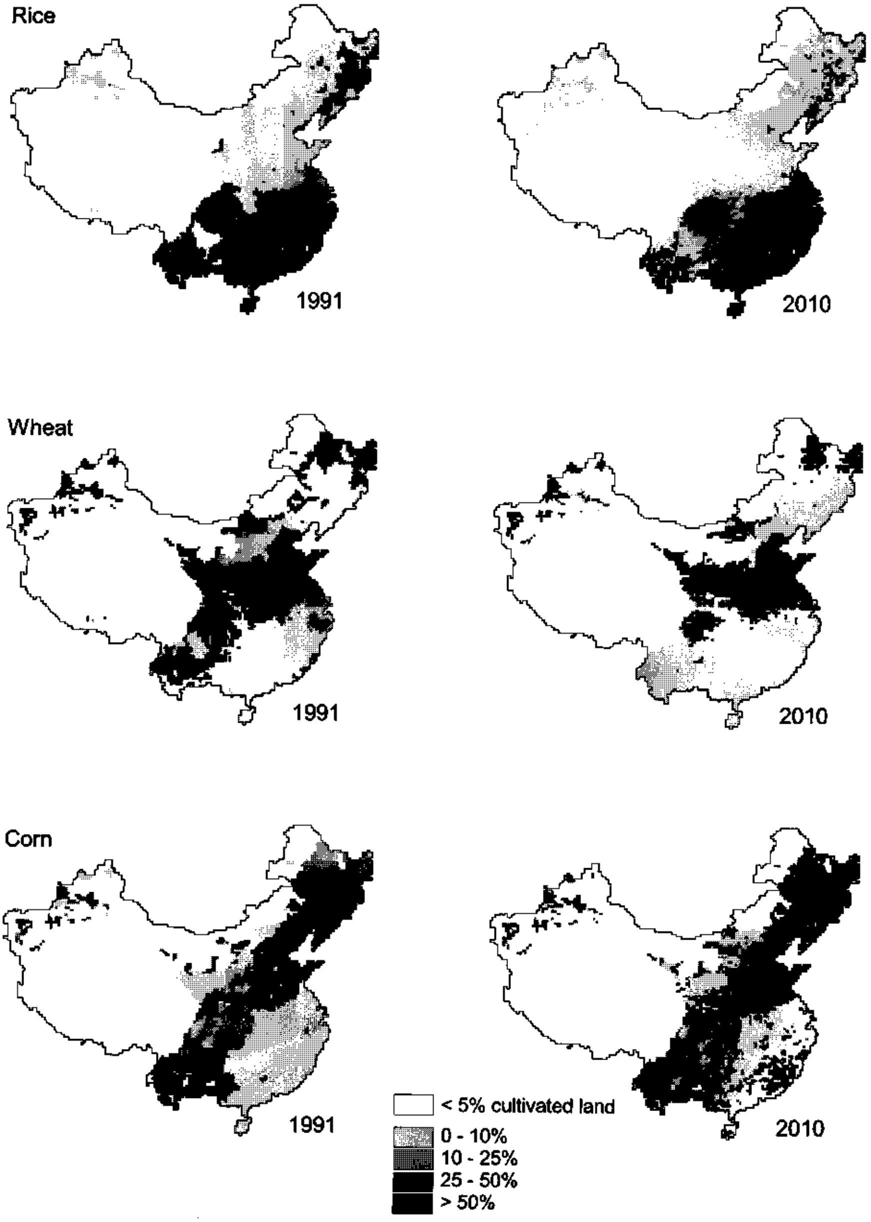

Figure 7.6 *Percentage of the harvested area allocated to different (groups of) crops for 1991 and simulation results for 2010*

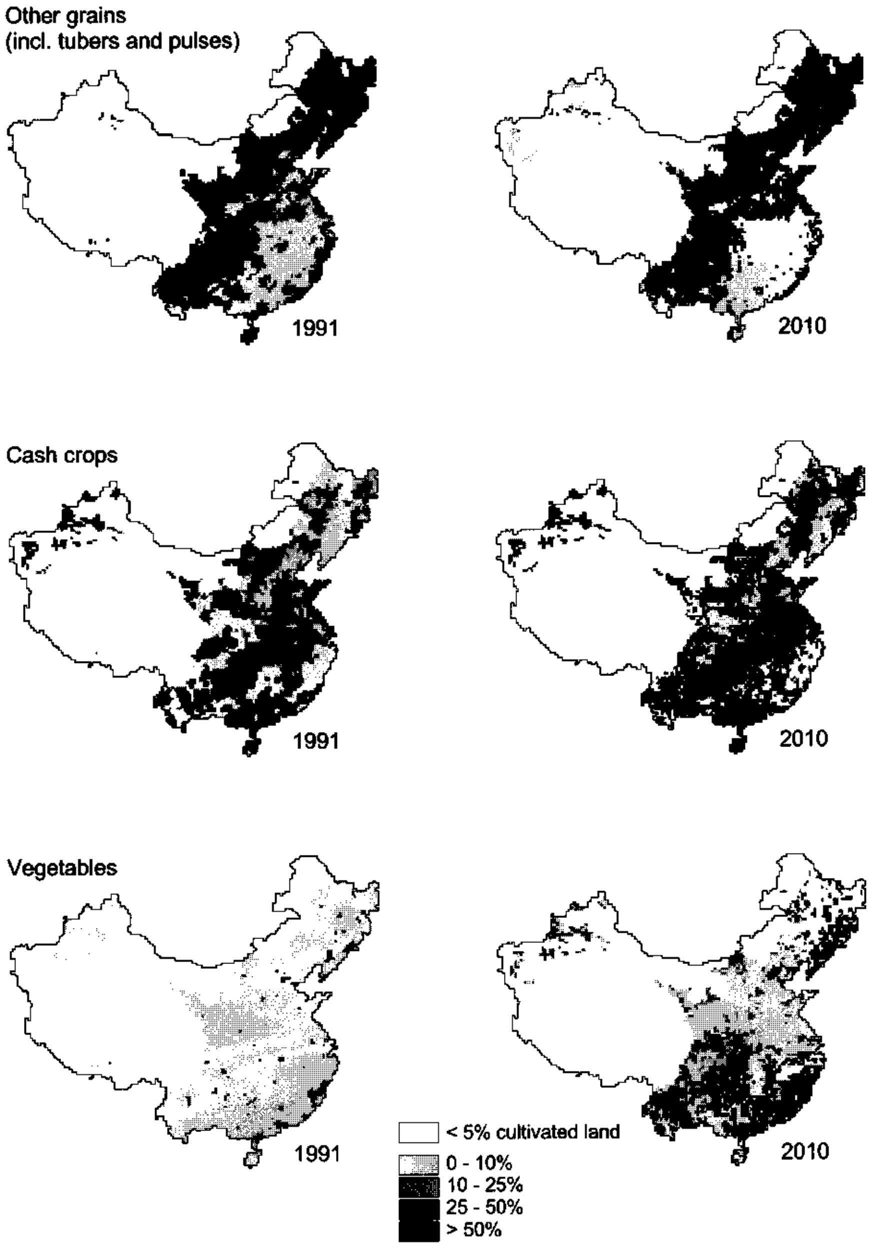

Figure 7.6 ***cont.*** *Percentage of the harvested area allocated to different (groups of) crops for 1991 and simulation results for 2010*

Of course, large differences in climatic conditions and resource endowments cause large regional differences in the type of cash crops. In the scenario large increases were defined for the vegetable area. Most of these increases are allocated in the southern part of China. Recent developments, however, show also increases in vegetable area in other parts of eastern China, mainly around the major urban centres (Guoqian, 1997). The model might therefore overestimate increases in the southern part because of the historic occurrence of vegetables in this part of China, which determines the spatial relation between land use and its explanatory factors used in the model. Fast growing vegetable producing zones, as designated by the Chinese government, include (in correspondence to the simulation results) the six southern provinces where vegetables are grown for consumption in the northern provinces; the winter and spring vegetable zone in the floodplain of the Yellow river (not well represented in the simulation results); and the low season vegetable zone in north China.

7.3.2 Cropping index

Table 7.2 presents the results of the calculation of the frontier function for the cropping index as for 1986, 1991 and 1996. Higher cropping indices are found at higher temperatures, longer rainy periods and a larger proportion of the cultivated area that is irrigated. The number of months with temperatures above 10°C and the range in temperature modify this relationship. The frontier functions for the different years are very much similar, indicating a stable relation between the agro-climatic variables and the cropping index. The Likelihood Ratio test statistic is calculated for testing the absence of inefficiency effects from the frontier (Coelli et al., 1998). For all three years the value is highly significant, hence the null hypothesis of no inefficiency effects is rejected. The gamma statistic is indicative for the partitioning of the deviations from the frontier. A zero-value for γ indicates that the deviations from the frontier are entirely due to noise, while a value of 1 would indicate that all deviations are due to inefficiency. The values found in this study (0.72 – 0.80) indicate that still a considerable proportion of the deviations from the frontier in this study can be attributed to noise.

Figure 7.7 presents the results in a spatially explicit way. Figure 7.7A and 7.7B respectively indicate the actual and frontier cropping index in 1991. The observed pattern corresponds fairly well with the climatic variability throughout the country whereas local variations are mainly due to differences in irrigation. The difference between the actual cropping index and the stochastic frontier cropping index is the inefficiency, which is indicated in Figure 7.7C. This figure shows that most potential for higher cropping indices is found in the central and southern regions of China. However, in these areas the cultivated areas are generally small, hence the increase in sown area upon an increase in cropping index is small. When the inefficiencies in cropping index are multiplied by the cultivated area the potential increase that can be attained in sown area is indicated (Figure 7.7D). This identifies the North China plain area as the main area where considerable increases in sown area are possible. The total sown area that could be gained by increasing the cropping index to its stochastic frontier value is about 25 million ha, which would mean an increase of about 12% in sown area.

The feasibility of increasing the cropping index can only be determined by an analysis of the reasons underlying the deviations from the frontier cropping index. Correlation analysis between the estimated efficiencies and the available socio-economic and biophysical variables did not result in strong conclusions. Best relations were found with the mean elevation (-0.10,

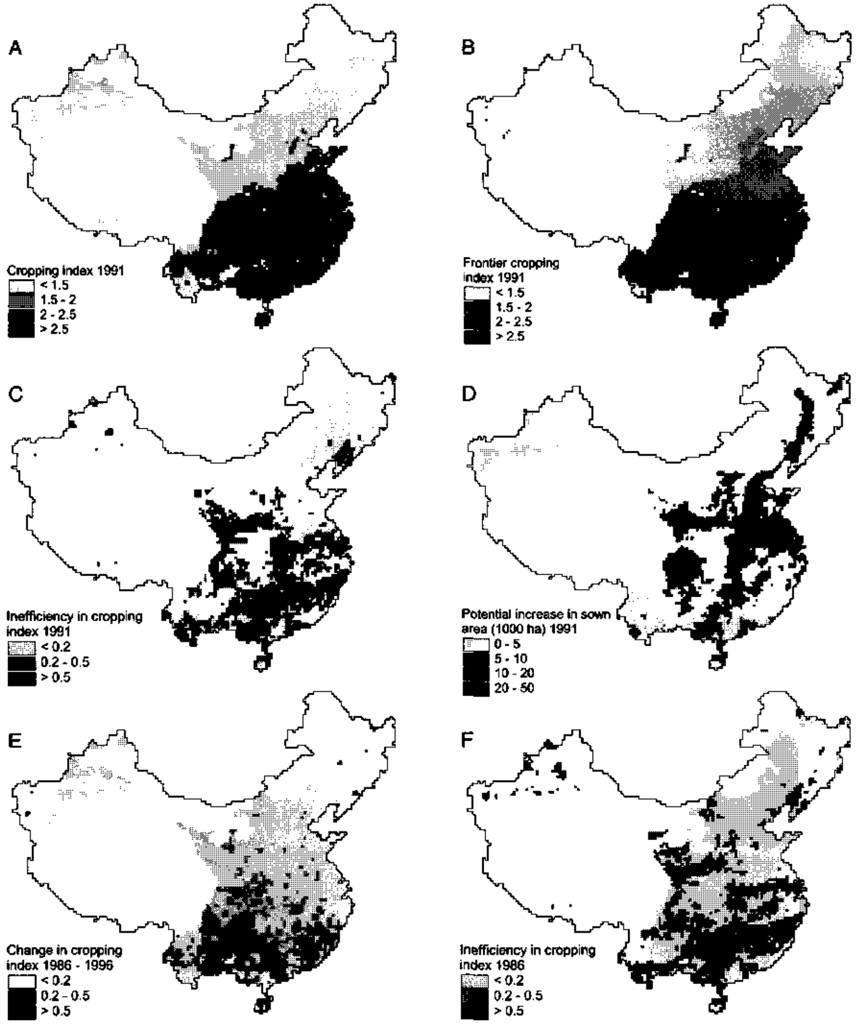

Figure 7.7 *(A+B) cropping index in 1991 and frontier cropping index in 1991; (C+D) inefficiencies in 1991 expressed in cropping index (C) and multiplied by cultivated area, indicative for potential expansion of sown area (D); (E+F) real changes in cropping index between 1986 and 1996 and difference between actual cropping index and frontier cropping index (inefficiencies) in 1986*

significant at 0.01 level) and the available labour per unit area of cultivated land (0.14, significant at 0.01 level), meaning that mountainous areas might hamper high cropping intensities and that labour shortage might cause less intensive use of the land. Another reason for lower than optimum cropping intensities might be found in the choice of crops. Some crops, e.g., sugar cane, have a longer growing season, inhibiting multiple cropping. This hypothesis is confirmed by a significant, negative correlation (-0.07) between the relative share of sugar in the cropping system and the efficiency. It was expected that inefficiencies would also be higher near urban centres, with large possibilities for off-farm labour. However, no evidence was found in the data. It can be hypothesised that regulations by county governments, that specify minimum cropping indices, overrule this effect.

Table 7.2 *Stochastic frontier functions for cropping index in China for 1986 and 1991 (t-ratios between parentheses)*

	Coefficient 1986	Coefficient 1991	Coefficient 1996
Frontier function			
Intercept	0.168 (7.31)*	0.367 (15.8)*	0.611 (22.8)*
TMP_AVG	0.0438 (39.9)*	0.0416 (37.4)*	0.0369 (25.9)*
TMP_RNG	0.00442 (10.5)*	0.00253 (5.86)*	-0.000240 (-0.462)
TMP_10C	-0.0462 (-20.6)*	-0.0410 (-18.0)*	-0.0306 (-10.6)*
PRC_50M	0.0347 (28.9)*	0.0342 (28.1)*	0.0279 (18.6)*
SUN_TOT	-0.00505 (-16.7)*	-0.00719 (-23.5)*	-0.00941 (-24.7)*
IRRI	0.00180 (23.6)*	0.00126 (15.1)*	0.00141 (13.8)*
Statistical parameters			
Sigma-squared ($\sigma_s^2 = \sigma_u^2 + \sigma_v^2$)	0.0375 (26.6)*	0.0349 (25.8)*	0.0587 (33.4)*
Gamma ($\gamma = \sigma_u^2 / \sigma_s^2$)	0.790 (40.7)*	0.723 (30.8)*	0.803 (65.3)*
Log likelihood function	2733	2683	1768
LR test of the one-sided error	171.5**	122.5**	539.0**

*significant at the 0.01 level

**significant at the 0.01 level (mixed chi-square distribution)

The potential for increases in cropping index can be seen as an indicator for near future increases of the cropping index. In Figure 7.7E and 7.7F the observed changes in cropping index between 1986 and 1996 are compared with the potential for increase in cropping index determined for 1986. If evaluated for individual grid-cells, the correlation is relatively low (0.34, significant at 0.01 level). However, the general pattern is very similar. When evaluated at the aggregated level of the 7 main geographical regions of China, a correlation between the observed changes in cropping index and the potential for change of 0.83 is found. This indicates that it is probable that also for longer time periods most increases in cropping index will be found in southern China.

7.3.3 Agricultural inputs

Four different farming system groups are distinguished based on the disjoint cluster analysis. The characteristics of the different groups are presented in Table 7.3. The groups indicate the intensity of the farming systems. Farming system groups 1 and 2 are characterised by high inputs and high yields while farming system groups 3 and 4 are characterised by low inputs and low yields. Only labour availability does not obey the general pattern. Figure 7.8 shows the spatial distribution of the different farming system groups. From this map it can be seen that the farming system groups have a clear distribution throughout the country. The high input farming systems of group 1 and 2 are mainly located in the central and eastern part of China, whereas the low input farming systems are mainly found in the western region, far from the main cities. Although farming conditions in this region are generally less favourable for very intensive farming, as a consequence of higher altitudes and lower precipitation,

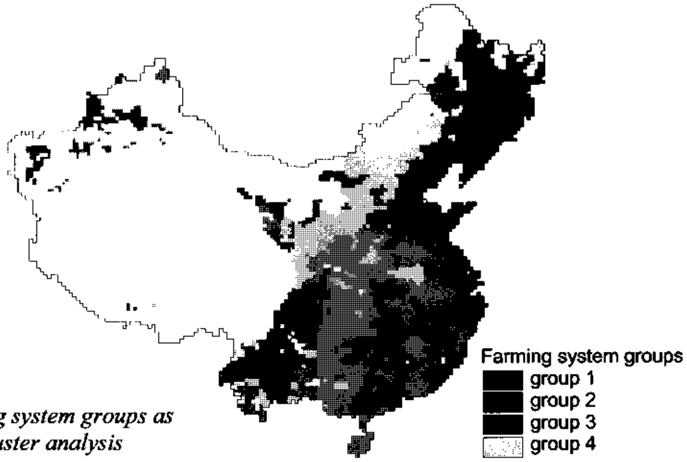

Figure 7.8 *Farming system groups as distinguished by cluster analysis*

socio-economic conditions are the main determinants of the lower land-use intensities. This can be seen from Table 7.4 that presents correlation coefficients between the quantity of agricultural inputs and a number of biophysical and socio-economic conditions. The use of chemical fertiliser, irrigation and agricultural machinery tends to decrease with the distance to a city and increasing percentages of illiterate population. In areas with higher population densities generally more inputs are used, probably a consequence of strong competition for land resources. The correlation of fertiliser and irrigation with the average temperature is a result of the location of intensively managed, irrigated rice cropping systems in the southern part of China. Because rice cultivation is not as mechanised as the cultivation of other grains, we find a negative correlation coefficient with temperature for mechanisation and a positive one for the labour use intensity. The connection between management intensity and soil quality is expressed by the positive correlation between soil suitability for rice cultivation and input quantities. The distribution of manure application does not obey the general pattern found. Inputs of manure are mainly determined by the availability of manure, and thus the distribution of livestock (Verburg and Van Keulen, 1999). Increasing labour intensities in agriculture with the distance to city are indicative for the decreasing opportunities for off-farm labour.

Table 7.5 presents the Cobb-Douglas production function as was derived for grain yield in 1991. Except for LABOUR, all estimates in the production function have the expected positive sign. The very small, but negative coefficient for agricultural labour force is somewhat surprising. However, low elasticities for labour are also found in other labour-rich Asian countries (Huang and Rozelle, 1995). Besides, Bhattacharyya and Parker (1999) and Rawski and Mead (1998) have argued that Chinese statistics massively overestimate the number of farm workers. This might well explain the negative value of the coefficient for labour in the production function. Chemical fertiliser is the most important input factor, followed by manure and irrigation. The elasticity for agricultural mechanisation is, however, small. These results are consistent with other studies (Fan, 1997; Yao and Liu, 1998) that also found low elasticities for machinery, probably a result of abundance of cheap agricultural labour. From the production function it is clear that chemical fertiliser is the most important input in Chinese agriculture. Inputs of chemical fertiliser have rapidly risen during the recent past. However, increases in fertiliser use have not made an equal pace throughout the country. Table 7.6 presents the changes in fertiliser application during the period 1986 to 1996 for the different farming system groups (Figure 7.8). From this table it can be clearly seen that the largest (absolute) increases in fertiliser use are found in areas that already have a high fertiliser use. So, in spite of the doubling of fertiliser use in areas classified as farming systems group 3 and 4, the differences in fertiliser use between the groups have increased. In the areas of farming system groups 3 and 4 both grain transportation and grain storage facilities are very backward and limited, the rural population not only has to produce food locally, but it also has to devote most of the arable land to food production for survival (Lin and Wen, 1995). So, under the present economic and infrastructural conditions in these areas, individual households are not able to increase their agricultural inputs (Lin and Li, 1994). Another reason for lower increases in fertiliser use in the areas of farming system groups 3 and 4 can be the allocation policy of subsidised fertiliser. The largest category of allocation is the 'procurement-linked fertiliser', its uniform price nation-wide being set by the central government. The central leadership allocates this fertiliser, which, as its name suggests, is directly linked to the quantity of state crop procurement. As a result, most of the subsidised urea flows into prosperous areas, where the state purchases most of its grain, cotton and oilseed crops. In contrast, farmers in poorer areas receive little or no subsidised urea because they have few surplus crops (Ye and Rozelle, 1994). Recently these subsidies have largely disappeared.

Table 7.3 *Mean value of agricultural parameters for farming system groups in China as determined by a cluster analysis (standard deviations between parentheses)*

Farming systems group	Number of cells	Grain yield (kg/ha)	Fertiliser application (kg/ha)	% irrigated	Labour (persons/ha sown area)	% machine cultivated	Manure application (ton/ha)
Group 1	61 (1%)	7205 (495)	292 (74)	58 (35)	2.43 (2.47)	63 (21)	8.97 (4)
Group 2	1485 (32%)	5089 (565)	218 (84)	65 (23)	3.73 (2.02)	49 (28)	9.59 (6)
Group 3	2385 (51%)	3270 (611)	139 (67)	39 (25)	2.58 (1.77)	38 (30)	8.64 (5)
Group 4	712 (15%)	1467 (512)	70 (80)	15 (13)	1.14 (1.00)	34 (26)	6.31 (5)
Mean	4643 (100%)	3627 (1404)	156 (91)	44 (28)	2.74 (2.07)	41 (29)	8.59 (5)

Table 7.4 *Pearson correlation coefficients between agricultural inputs and a number of biophysical and demographic factors*

	Chemical fertiliser application	% irrigated area	% machine cultivated area	Manure application	Agricultural labour force per sown area
Agricultural population density	0.48*	0.39*	0.17*	0.01	0.47*
Average temperature	0.38*	0.46*	-0.39*	0.21*	0.70*
Mean elevation	-0.34*	-0.25*	-0.27*	0.22*	-0.21*
Suitability rice	0.25*	0.12*	0.36*	-0.19*	-0.05*
% illiterate population	-0.28*	-0.27*	-0.44*	0.11*	0.01
Distance to city	-0.23*	-0.05*	-0.33*	0.07*	0.15*

*significant at 0.01 level

Table 7.5 *Production function for grain yield in 1991*

Variable	Parameter	Average function
Intercept	β_0	5.450 (132)*
FERT	β_1	0.390 (44.0)*
IRRI	β_2	0.133 (18.7)*
LABOUR	β_3	-0.023 (-2.91)*
MANURE	β_4	0.132 (13.4)*
MACH	β_5	0.012 (2.56)**
F-statistic model		1430*
Adj. R^2		0.61

Figures in parentheses are t-ratios of the estimates

*significant at the 0.01 level

**significant at the 0.05 level

Table 7.6 *Input use (standard deviations between parentheses)*

	Fertiliser application (kg/ha)			Change in fertiliser application 1986-1996 (kg/ha)	% change in fertiliser application 1986-1996
	1986	1991	1996		
Group 1	232 (60)	292 (74)	378 (108)	146	63
Group 2	166 (60)	218 (84)	290 (139)	124	75
Group 3	101 (50)	139 (67)	205 (139)	104	104
Group 4	44 (32)	70 (80)	99 (70)	56	127

Given the functional form of the production function and the already high levels of fertiliser use, diminishing returns upon further increases of chemical fertiliser input in the areas of farming system groups 1 and 2 can be expected. Furthermore, excessive use of agricultural chemicals has already caused severe damages to the natural environment, e.g., groundwater pollution and deterioration of soil fertility (Jin et al., 1999; Smil, 1993). The low inputs and yields in large parts of western China suggest that there is still a vast potential for raising grain output by using more land-augmenting inputs such as fertilisers and irrigation in these medium and low yield regions.

7.3.4 Production efficiency

The parameters that are calculated for the frontier production and inefficiency function are given in Table 7.7. The values of the frontier production function are very similar to those of the average production function (Table 7.5), indicating that the frontier function consists of a near-neutral upward shift of the average function. The diagnostic statistics indicate that inefficiency effects explain a relatively large part of the variation whereas the likelihood-ratio statistic is highly significant, rejecting the hypothesis of no inefficiency effect in grain production in China.

Table 7.7 *Stochastic frontier production function for grain production in China*

Variable	Parameter	Stochastic frontier
Production Function		
Intercept	β_0	6.282 (159)*
FERT	β_1	0.309 (38.7)*
IRRI	β_2	0.092 (15.0)*
LABOUR	β_3	-0.071 (-8.95)*
MANURE	β_4	0.144 (15.4)*
MACH	β_5	0.027 (6.98)*
Inefficiency Function		
Intercept	δ_0	0.442 (5.97)*
TMP_AVG	δ_1	0.0291 (7.51)*
PRC_TOT	δ_2	-0.000839 (-12.8)*
SOIL	δ_3	0.00245 (6.67)*
MEANELEV	δ_4	0.000134 (6.04)*
DISTCITY	δ_5	0.00197 (4.33)*
ILLIT	δ_6	0.422 (3.33)*
%AGLF	δ_7	-0.00519 (-2.95)*
INCOME	δ_8	-0.000379 (-24.2)*
EROSION	δ_9	0.000615 (2.22)**
Diagnostic Statistics		
Gamma ($\gamma = \sigma_u^2 / \sigma_s^2$)	γ	0.88
Sigma-square ($\sigma_s^2 = \sigma_u^2 + \sigma_v^2$)	σ_s^2	0.16
Log likelihood		-178.2
Likelihood-ratio statistic		1827***

Figures in parentheses are the t-ratios of the estimates

*significant at the 0.01 level; **significant at the 0.05 level

***significant at 0.01 level according to Table 1 of Kodde and Palm (1986)

All coefficients in the inefficiency function are significant. The relation with precipitation is as expected: the more precipitation, the smaller the inefficiency. Although higher temperatures might enhance crop growth they are associated with higher inefficiencies. Also the coefficient for soil fertility does not obey our expectations, grid-cells with large areas of fertile soils have generally low efficiencies. So, natural soil fertility does not seem to enhance production efficiency. This can probably be attributed to the relatively small contribution of natural soil fertility to total nutrient supply in intensive farming systems. Elevation has the expected positive contribution in the inefficiency function. Illiteracy and distance to city, proxies for the access to information and means of production, both hamper efficiency. The share of agricultural labour force of the total population has a positive influence on production efficiency. This suggests that the possibilities for non-farm labour decrease the technical efficiency of grain production. Income is an important variable in the inefficiency function, having a positive effect on the efficiency of input use, probably through the opportunities to buy higher quality, more balanced inputs (e.g. potash fertiliser) and invest in the land (e.g. terracing). In correspondence with other studies (Lambert and Parker, 1998; Yao and Liu, 1998) we found that erosion is also an important source of inefficiency in agricultural production.

The average efficiency of grain production in China as calculated with the derived frontier production function is 0.74 (on a scale 0-1). The spatial distribution of the efficiency is

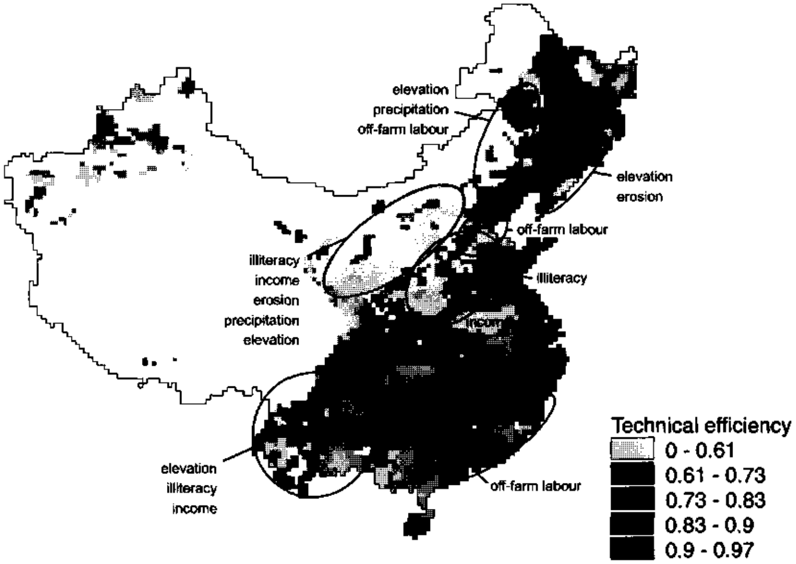

Figure 7.9 *Technical efficiency in grain production 1991 and indication of areas and variables with high contribution to the inefficiency*

displayed in Figure 7.9. Low efficiencies are especially found in the north-western part of the agricultural area and in the south-western province Yunnan. High efficiencies are found in the north-eastern part of China and in the central region. The heavily urbanised strip along the southern coast also has relatively low efficiencies in grain production. In the same figure the most important variables in the inefficiency function are denoted for the different regions with low efficiencies, indicating that inefficiencies have different causes in different parts of the country.

7.3.5 Technological progress

The coefficient for the time trend in the production function fitted for the data from 1986, 1991 and 1996 indicates a 1.2% yearly change in production level. All other coefficients in the production function are similar to those presented in Table 7.5. Huang and Rozelle (1995) derived for a similar production function a technical change of 2.9% yearly, based upon provincial data between 1975 and 1990. Agricultural research is an important determinant of the rate of technological change. Unfortunately, China's agricultural research system itself is negatively affected by budget cutbacks and other measures in recent years, which might further decrease the rate of technological change, and hence grain production (Lin, 1998). More detailed analyses of technological change in Chinese agriculture are presented by Stone (1988), Huang et al. (1995) and Huang and Rozelle (1996).

7.4 Discussion

The methodologies used in this paper all explore changes, or possibilities for change, in land use based on an analysis of the regional variability of land use in China. Only the analysis of the changes in agricultural area is based on dynamic modelling, all other assessments only explore the options for increases in grain production. However, also the modelling results should not be interpreted as forecasts of future events. Rather, they indicate possible patterns of land-use change, given the underlying assumptions of the scenario.

The methodologies used in this paper are specific for the scale of analysis. Because the basic unit of analysis, the individual grid-cells, measure approx. 1000 km^2, most research methods based on causal, deterministic understanding of processes of land-use change are inappropriate. Single units of observation contain large numbers of different actors of land-use change with numerous interactions in a diverse biophysical environment. Simple aggregation of the processes known at the level of individual actors will generate large errors due to scale dependencies and simple aggregation errors as result of non-linear system responses (Rastetter et al., 1992; Gibson et al., 1998). The methodologies used in this paper are appropriate for the scale of analysis as the relations between land-use patterns and its explanatory factors are quantified in an empirical way with data collected at the same aggregation level as the analysis and the presented results. The drawback of the empirical quantification of the relations is the lack of causality, which forces us to interpret the results with caution.

Changes in agricultural area and grain-sown area occur throughout the entire agricultural area of China. Hot-spots of change are found in the Ordos and Loess plateau regions where degradation is the main land-use change process, and around the growing cities in eastern China. It can be argued to what extent this process can be stopped. All decreases in agricultural area need to be compensated for by more intensive cultivation on the remaining agricultural area to keep up food production. The model results indicate for some areas large decreases in the share of grain crops. Cash crops and vegetables take over a large share in the cropping systems, especially in the urban surroundings in southern and eastern China. In these areas the production of vegetables and cash crops make more intensive use of abundant labour per unit of scarce arable land. However, at the same time this leads to increased grain imports. The patterns of agricultural input use and the efficiency of grain production correspond to a large degree. Generally, low inputs are associated with low efficiencies. Our analysis made clear that part of the lower efficiencies and the less intensive farming can be explained by the less favourable environmental conditions in the western part of China. Agricultural research, aimed at new varieties of higher adaptability, and better resistance and endurance could help to overcome these constraints (Lin, 1998). The main problem underlying farming intensity and efficiency are the large differences between well endowed areas around major cities and the rural areas associated with income and illiteracy. Bridging the gap between urban and rural development is, therefore, essential to increase productivity in the less endowed regions. Policies to bridge the gap could include intensifying the construction of infrastructure including storage, communication, and transport facilities and improving marketing conditions. Our results have also shown that increasing investment in rural education might, in the long-term, enhance agricultural production. The low income of peasants is correlated with their low education. So it is an important measure to narrow the differences in human capital and hence income gaps. This will create conditions for peasants to enhance their quality of life.

These results suggest that China has, at least in certain areas, the potential to increase production and compensate losses in agricultural area, by increasing production per unit area. However, China's land use already has a negative impact on its natural resources through land degradation, pollution and decreasing land qualities. A further intensification might threaten the long-term sustainability of agricultural production (Smil, 1993). The transition towards intensive, but sustainable land-use systems is therefore more important for food security than a further intensification alone. Thus, more emphasis should be paid to production systems that not only strive for a high production but to maintaining environmental quality as well.

This study has proven that a spatially explicit analysis of land-use change can reveal information that is not accounted for in aggregated assessments that is provided by economic analyses (e.g., Garnaut and Ma, 1992; Paarlberg, 1997; Weersink and Rozelle, 1997). Aggregated analysis, e.g., at the national level, cannot adequately shed insight in the production situation because agricultural systems are, in nearly every country, very diverse and variable. Spatially explicit methods focus on diversity of situations rather than on average situations. These deviations from the average situation, and the reasons underlying the deviations, provide insights into possibilities and constraints for increasing agricultural production.

Although the spatial resolution of this study is much more detailed than those of most nation-wide assessments, the scale of analysis is still very coarse. At more detailed scales other forms of variability and other options and constraints for increasing agricultural production will be found. Similar types of analysis should therefore be used to analyse the variability of land use at more detailed scales, e.g. for individual provinces and counties located in 'hot-spots' of land-use change identified in this study. At these more detailed scales, studies on variability can also link up with socio-economic studies of the processes and actual motives of people for certain agricultural strategies. In this sense, the presented study is only a first step towards a full, multi-scale, analysis of land-use change and agricultural production; a more complete insight into the land-use situation of China can only be attained by linking up this research with other studies, using a set of complementary research methodologies over a wide range of scales.

Chapter

8

Concluding Remarks

8.1 Land-use change and agricultural development in China

In the preceding chapters a set of methodologies is presented that allow the analysis of regional variability of land-use change and the dynamic simulation of land-use change patterns. Results permit the identification of areas that are likely to face high rates of land-use change in the near future, so-called 'hot-spots' of land-use change. China was used as the main case-study area for applying these methods.

No new estimates of the capacity of China to feed its own population are added to the existing multitude of studies that are most often based on aggregate analysis alone. Instead, new insights are provided through the quantification of the spatial variability and (proximate) driving factors of land use and agricultural production. Chapters 4, 5 and 7 have shown that land use and its changes are very diverse throughout China. Aggregate analysis is clearly inappropriate to make a reliable assessment of the ongoing processes and the identification of critical regions and vulnerable places. The model structure, based on our understanding of land-use systems and ecosystem theory (Chapter 3), enables an evaluation of the behaviour of the land-use system for different scenarios. Resulting maps provide insights into the interconnectivity between regions and the sensitivities of land-use patterns for different scenario conditions. In this sense, the model provides a tool for the analysis of different land-use policies, as illustrated with the scenarios presented in Chapter 5.

Presentation of simulation results to Chinese scientists and policy makers has proven to be a suitable means to provoke discussions about the seriousness of the foreseen land-use changes. Present knowledge of land-use change is often qualitative. Results of the CLUE model synthesise much of this knowledge and add a quantitative dimension, so that regions can be compared with respect to change.

The analysis of intensity and efficiency of land management in grain production, presented in Chapter 7, confirms the general notion that unequal development of China's economy is hampering agricultural production in the western part of China's agricultural area (Lin and Wen, 1993; Yang, 1998). The empirical analysis and maps point out to what extent agricultural development lags behind in these regions. Our results support the conclusions of papers by Bingshen (1996) and Guobao et al. (1996) that not only natural resource endowments are responsible for rural poverty and less productive agriculture. Demographic and man-made endowments are important causes of the differences between regions. This study indicates that a more equal development between different regions in China will favour grain production and at the same time decrease rural poverty. Awareness of this problem led already in the mid-1980s to a regionally targeted investment program aimed at eliminating rural poverty, recognising the potential danger of social and political instability due to rising inequality accompanying economic reforms. An evaluation of this investment program for a number of counties in Shaanxi province (one of the 'backward' areas indicated in our study) by Rozelle et al. (1998) provided strong evidence that investments in agriculture, focussed on households, have positive effects on agricultural growth. Investment programs targeted at infrastructure projects did not seem to enhance agricultural growth. The authors warn, however, that this might be caused by the specific implementation of these funds in the case-study areas. The agricultural action plan for China's Agenda 21 (Ministry of Agriculture, 1999) foresees in a new series of measures aimed at the promotion of regional development and elimination of rural poverty, recognising the potential of 'backward' regions for agricultural development.

Awareness of the importance of spatial variability in agricultural development, rather than being convenient with the analysis of national averages, will help policy makers and scientists to focus future programs on the appropriate areas. In-depth studies of the causes of retarded agricultural development, which are still needed as a follow-up to the studies reported here, will help to design proper measures for specific locations.

8.2 Methodological remarks

A common characteristic of the methodologies for land-use analysis presented in this thesis is the use of statistical techniques, mainly regression analysis, to explore spatial variability in land use and to establish relations between the land-use system and its explanatory factors ('drivers'). Statistical techniques are often criticised because they do not ensure satisfactory identification of the fundamental drivers of the land-use system (Leamer, 1983). Multicollinearity and the use of proximate variables, due to limited data availability, often cause indirect relations between the dependent and the independent variables. Although a set of statistical and econometric techniques has been used to reduce these effects, they can by no means be eliminated. However, replacing the empirical relations by deterministic, causal, relations is not possible in a straightforward way. Land-use patterns are the result of a large number of interrelated processes and feedbacks, which are difficult to measure and quantify directly. Most of our understanding of these processes is only valid for local situations. The processes and their relative importance at higher aggregation levels, as used in our analysis, are not necessarily the same through scale dependency of the relations and emergent properties (see Chapter 2). Therefore, even if we would be able to quantify in a process-based way all relations between land use and its explanatory variables, we would still not be able to use these relations straightforwardly at higher aggregation levels. These limitations for process-based land-use change modelling should not stop us from unraveling the processes underlying our empirical relations in more detail. Relating local-scale knowledge of processes leading to land-use change to aggregate behaviour of diverse groups of actors, as represented by the statistical analysis in our paper, will help to further understand land-use systems and its scalar dynamics. A possible means to relate individual behavior to aggregate behavior of groups of agents are multi-agent models (Hillebrand and Stender, 1994), which model individual behaviour as well as the interactions between individuals. Such an approach might validate the empirical relations used in the preceding chapters, and will contribute to theory development in the field of ecological and social systems, such as hierarchy theory (Allen and Starr, 1982), (macro-) economic theory and collective action theory (Ostrom, 1990).

No comprehensive and integrative theory of land-use change processes is yet available (Lambin et al., 1999). For different parts of the land-use system, theories exist originating from specific scientific disciplines, such as ecology or economy. These disciplinary theories are very valuable for the analysis of the land-use system, as is illustrated by the use of theoretical understandings from landscape ecology (e.g., Chapter 2 and 3) and econometrics (Chapter 7). Implicitly, theories of agricultural development (Boserup, 1965; Malthus, 1967; Pender, 1998) are underlying the assumptions made in the models. None of these theories is however capable to fully describe the observed dynamics and variability of land use. A further confrontation and integration of the existing theories and empirical evidence of land-use change should lead to the emergence of new, truly interdisciplinary, theories that will form the scientific basis of future land-use change assessments.

8.3 The role of the methodologies in land-use change research sequences

In Chapter 1 a land-use change research sequence was presented where we subdivided a common sequence of methods for land-use studies into four phases: the problem identification phase, the system description phase, the design phase and the implementation phase. The methodologies presented in this thesis fit within this research sequence. Results from studies in the problem identification phase, e.g. trends and projections of land demand, are a direct input for the simulations presented in Chapter 4, 5 and 6. These simulations provide insights in the functioning of the land-use system, therefore they belong to the system description phase. Resulting land-use change trajectories are useful inputs for the design phase. Studies in the design phase commonly result in static realisations of optimised land-use configurations (often obtained by linear programming models) that can only be realised in a distant future (Figure 8.1). In this thesis developments in land-use patterns (during the next 10-20 years) that are expected to take place more or less autonomous are given. Comparing these developments with the optimised land-use configurations helps to indicate locations and conditions that constrain the implementation of the designed land-use alternatives. Evaluation of model runs for different scenarios, including different land-use policies, indicates which conditions cause land-use change trajectories that lead towards the desired land-use configuration. Furthermore, this confrontation with near-future developments might lead to a

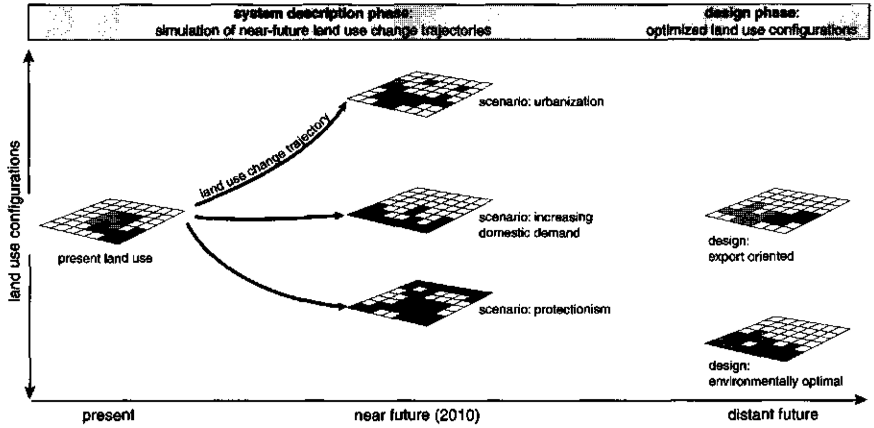

Figure 8.1 *Schematic representation of land-use studies in the system description and design phase of the land-use change research sequence*

more realistic definition of the objectives of the linear programming and prototyping models. Identified 'hot-spots' of land-use change can help to focus research belonging to the design phase to the appropriate areas and land-use systems.

Apart from linking up methodologies in different phases of the research sequence it is also needed to link up different scales of analysis. The analysis and understanding of complex systems over a wide range of scales is still problematic and an issue of discussion and research (Müller, 1992; Caldwell and Fernandez, 1998; Gibson et al, 1998; Lambin et al., 1999). The multi-scale analysis of land use in China presented in Chapter 2 confirms the importance of explicitly dealing with scale dependencies within land-use system studies. The multi-scale modelling methodology presented in Chapter 3 is a first start to really implement these scale dependencies within a dynamic simulation model. However, the most detailed units of analysis in China have a size of 32×32 km while the Java application has a minimum resolution of 20×20 km. These resolutions are detailed when compared to studies for China at the national or provincial level, but very coarse as compared to local studies at the farming system or village level. This means that local driving factors, bottom-up effects and interactions are not well presented in the model. On the other hand, most local level studies disregard the impact of processes and feedbacks occurring at higher levels of scale. Therefore, higher-scale systems, as analysed in this thesis, should be represented in local scale studies. That should at least guarantee that important changes in the context of the situation are taken into account and that the system does no simply export its problems to its neighbours (Musters et al., 1998). Further understanding of the scalar dynamics of land-use change is however urgently needed to better link up with studies at the farming systems or village level. The challenges for future land-use change research should therefore not be sought in a further refinement of existing land-use change research methodologies and models, but rather in connecting and integrating these models over a wider range of scales and disciplines. This type of research will also favour the communication and implementation of scientific understanding by stakeholders, policy makers and land-use planners. When specific characteristics of the land-use system cannot be steered at one scale level, it does not necessarily mean that they can not be steered at other scale levels. Therefore, multi-scale land-use knowledge is a necessary input into negotiations over interventions in the land-use system at the appropriate scale-levels.

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Summary

Verburg, P.H., 2000. Exploring the spatial and temporal dynamics of land use - with special reference to China. Ph.D. thesis Wageningen University, Wageningen, The Netherlands

Land-use and land-cover change have large impacts on our natural environment. Changes in our natural environment directly influence our living conditions through the possibilities that we have to obtain a safe food in a healthy environment, but also in aesthetic ways through our perception of landscapes and diversity. To avoid unfavorable consequences of land-use changes, systematic approaches for land-use intervention are developed for policy makers. Systematic intervention in the dynamics of land-use systems is impossible without a proper understanding of the driving factors in these systems and their behavior.

The general objective of this thesis is to present a set of methodologies to explore the spatial and temporal dynamics of land-use systems at the regional level. These methods provide insight into the spatial variability of land use, indicate which (proximate) factors determine the spatial distribution of land use and identify potential, near-future 'hot-spots' of land-use change. The identification of 'hot-spots' of land-use change, i.e., areas that are expected to face high rates of land-use change, is essential to focus follow-up in-depth research and policy measures to address the appropriate issues and geographical locations.

Case-studies for the application of the developed methodologies are the countries of China and Ecuador and the Island of Java in Indonesia. Most attention in this thesis is given to the developments in China, whereas the country of Ecuador is used for model development and sensitivity analysis while the case of Java allows for a validation of the model performance. China and the island of Java face large pressures on agricultural land resources due to urban and industrial expansion and limited capacities for agricultural expansion. At the same time, economic growth and urbanization result in an increasing demand for agricultural products. In Ecuador agricultural expansion is still the major land-use change process.

The first step in studying land-use change is the quantification of the relations between land use and its driving factors. These relations are derived from a spatial analysis of actual land-use patterns, which reflect the results of historic land-use changes. Correlation and regression analysis are used to identify the most important explanatory variables of the land-use pattern from a large set of biophysical and socio-economic variables that are generally considered to be of potential importance for the distribution of land use. An integrated set of biophysical and socio-economic variables was found to best describe the spatial distribution of the different land-use types. Specific attention is given to the influence of the scale of analysis on

the relations between the distribution of land-use and the biophysical and socio-economic explanatory variables. Both the resolution of the data and the extent of the study area have a major impact on the derived relations. Relations obtained at a certain scale of analysis may therefore not be directly applied at other scales or in other areas.

The relations between the land-use distribution and the derived sets of biophysical and socio-economic explanatory variables are used to parameterize a land-use change model. This land-use change model, the CLUE modeling framework (the Conversion of Land Use and its Effects), allocates changes in demand for different land-use types at the national level to individual grid cells. Changes in the relative coverage of land-use types in the different grid-cells are calculated in an iterative procedure using the earlier established spatial relations after a change in one of the explanatory variables of the land-use pattern or a change in competitive advantage for a land-use type. Changes in explanatory variables include changes in population density, labor force or urbanization, while changes in competitive advantage originate from changes in demand at the national level. For every year changes are calculated until the allocated changes match the demand at the national level for the different land-use types. For every grid-cell, allocation is constrained by the total land area available in the grid cell, so that competition between the land-use types is explicitly taken into account. A multi-scale approach is followed to account for the scale dependencies of the relations between the land-use pattern and its explanatory variables. This approach provides also a balance between bottom-up effects, resulting from local conditions and top-down effects as a result of changes at national and regional scales. An analysis of the behavior and sensitivity of the model is made for the country of Ecuador. Different scenarios are tested to illustrate the realistic simulation of interconnectivity between regions and bottom-up / top-down interactions in land-use change.

The application of the CLUE model for China has a minimum spatial resolution of 32x32 km. The most important land-use conversions in China, caused by urbanization, desertification and afforestation, are simulated for a scenario over the period 1990-2010. This scenario is based upon expected developments in demand for land-use types described in literature. The spatially explicit results allow an analysis of the consequences of a decrease in cultivated area and related production capacity. A preliminary analysis shows that the average production capacity of the lost arable lands is somewhat less than the average production capacity of all agricultural lands together. Regional differences are, however, large.
Additionally, a scenario of shifts in the relative importance of different agricultural crops is simulated. The results indicate regions where larger shares of high value crops within the cropping system are to be expected.

Large changes are expected in China's livestock sector as a consequence of increasing demands for animal products. Based upon the CLUE modeling framework a livestock module was developed that allows the exploration of changes in the spatial distribution of livestock production systems. The livestock module is directly linked to the simulations of land-use change so that changes in land cover directly influence livestock distributions. Two scenarios are evaluated: a baseline scenario and a scenario that assumes improved management of grasslands to stimulate livestock production in the pastoral regions. For both scenarios most increases in livestock numbers are expected in China's agricultural region. Poor transportation systems and vast distances, causing low prices and high costs of inputs, are the main constraints for more intensive use of the pastoral region.

A validation of model performance was made for the island of Java based upon historic data. Simulations from 1979 to 1994 indicated that the model could adequately simulate the pattern of land-use change. The performance on a cell-to-cell basis was reasonable whereas the overall pattern of change was well simulated. Additionally a scenario of land-use change between 1994 and 2010 was simulated assuming a continuation of urbanization on Java. The results identified Java's fertile lowlands as areas where most intensive land-use changes are expected to take place.

Apart from changes in the land area of different land-use types also the land-use intensity is subject to changes. Especially when opportunities for agricultural expansion are limited, land intensification is an option to increase agricultural production. A separate analysis was made of the different components of the land-use system that influence the agricultural production capacity of China. Included are changes in agricultural area, multiple cropping index, input use, technical efficiency and technological change. Research methodologies to analyze the spatial and temporal patterns of these land-use system components are all based on semi-empirical analyses of spatial variability in relation to biophysical and socio-economical explanatory variables. The results indicate that different processes and patterns of land-use change are found in various parts of the country. Inefficiencies in the use of agricultural inputs and relatively low input-use intensities, especially in some of the rural, less endowed, western regions, indicate that in these regions of China increases in grain yield are well possible. Awareness of the importance of spatial variability in agricultural development, rather than analyzing developments at the national level only, will help policy makers and scientists to focus future agricultural development programs on the appropriate areas. In-depth studies of the causes of retarded agricultural development, which are still needed as a follow-up to the studies reported here, will help to design proper measures for specific regions.

The introduced and applied methodologies provide an essential link between existing research tools needed for adequate land-use negotiations. Projectory studies at the national level that identify land-use change problems or extrapolate trends are used as direct inputs to formulate scenarios for the CLUE simulations. Land-use change trajectories for different scenario conditions are useful inputs for research aiming at the design of alternative land-use configurations or intensities. Policy measures can be derived from scenario conditions resulting in trajectories leading into the direction of desired land-use configurations, to be designed by land-use planners or with the help of optimization models. Furthermore, a confrontation of desired land-use configurations with the simulated land-use trajectories of the CLUE model can lead to a more realistic definition of the objectives and constraints of land-use planning activities.

Samenvatting

Verburg, P.H., 2000. Verkenning van de ruimtelijke en temporele dynamiek van landgebruik - met bijzondere aandacht voor China. Proefschrift Wageningen Universiteit, Wageningen

Veranderingen in landgebruik hebben grote invloed op onze natuurlijke leefomgeving. Veranderingen in onze leefomgeving hebben gevolgen voor voedselzekerheid en de conditie van het milieu, maar ook voor onze perceptie van het landschap en diversiteit. Om ongewenste gevolgen van veranderingen in landgebruik te voorkomen zijn systematische benaderingen ontwikkeld om in te kunnen grijpen in de dynamiek van het landgebruik. Zulke ingrepen in het landgebruiksysteem zijn onmogelijk zonder een goed begrip van de sturende factoren en de dynamiek van het landgebruik.

Het doel van dit proefschrift is het presenteren van een serie methodes om de ruimtelijke en temporele dynamiek van landgebruik te onderzoeken op regionaal niveau. Deze methodes geven inzicht in de ruimtelijke variabiliteit van landgebruik, geven aan welke factoren de ruimtelijke verspreiding van landgebruik beïnvloeden en identificeren mogelijke 'hot-spots' van landgebruikveranderingen. Het identificeren van 'hot-spots' van landgebruikveranderingen, m.a.w. gebieden waar veranderingen in landgebruik snel plaats vinden, is essentieel om vervolg onderzoek en beleidsmaatregelen te richten op de juiste locaties en processen.

De ontwikkelde methodes zijn toegepast in de landen China en Ecuador en op het eiland Java in Indonesië. De meeste aandacht is in dit proefschrift gegeven aan de toepassing in China. De studie voor Ecuador is gebruikt om het model te ontwikkelen en de gevoeligheid van het model te testen terwijl de studie voor Java een validatie van het model heeft mogelijk gemaakt. China en Java zijn gebieden waar het landbouwareaal sterk onder druk staat als gevolg van stedelijke en industriële expansie. Tegelijkertijd is er een verhoogde vraag naar landbouwproducten, veroorzaakt door economische groei en verdere verstedelijking. In Ecuador is de kolonisatie van gronden ten behoeve van de landbouw het belangrijkste process dat leidt tot veranderingen in landgebruik.

De studie naar landgebruikveranderingen begint met het kwantificeren van de relaties tussen landgebruik en de sturende factoren daarvan. Dit is gedaan door middel van een ruimtelijke analyse van het huidige landgebruikpatroon. Het huidige landgebruikpatroon weerspiegelt het resultaat van historische landgebruikveranderingen. Correlatie en regressie analyse zijn gebruikt om de belangrijkste variabelen te selecteren uit een grote serie van biophysische en sociaal-economische variabelen die algemeen bekend zijn als sturende factoren van landgebruik. Een geïntegreerde set met zowel biophysische als sociaal-economische factoren bleek het meest geschikt om de ruimtelijke verspreiding van de verschillende landgebruiktypes te verklaren. Specifieke aandacht is gegeven aan de invloed van de schaal van analyse op de relaties tussen landgebruik en de biophysische en sociaal-economische verklarende variabelen. Zowel de resolutie van de gegevens als de grootte van het studiegebied hebben invloed op de gevonden relaties. Relaties verkregen door analyse op een bepaalde schaal mogen daarom niet direct ook op andere schalen of in andere gebieden gebruikt worden.

De relaties tussen de landgebruikdistributie en de sets van biophysische en sociaal-economische verklarende variabelen zijn gebruikt om een landgebruikmodel te parametriseren. Dit landgebruikmodel, het CLUE model ('Conversion of Land Use and its Effects'), wijst veranderingen in de vraag naar verschillende landgebruiktypes toe aan individuele cellen in een raster. Veranderingen in de relatieve bedekking van de verschillende landgebruiktypes binnen deze raster-cellen worden berekend in een iteratieve procedure. Veranderingen in landgebruik vinden plaats als gevolg van een verandering in een van de verklarende variabelen of een verandering in de concurrentiepositie van de landgebruiktypes. Veranderingen in verklarende variabelen zijn het gevolg van populatiegroei, wijzigingen in de samenstelling van de beroepsbevolking en urbanisatie. Veranderingen in de concurrentiepositie van de landgebruiktypes zijn het resultaat van veranderingen in de vraag op nationaal niveau. Veranderingen worden berekend op een jaarlijkse basis totdat de toegewezen hoeveelheid verandering gelijk is aan de vraag op nationaal niveau. Deze toegewezen verandering is gelimiteerd door de hoeveelheid land die in een cel van het raster aanwezig is; hierdoor moet concurrentie tussen de landgebruiktypes expliciet meegenomen worden. Verschillende schaalniveaus worden synchroon gesimuleerd om rekening te houden met de schaalafhankelijkheid van de relaties tussen landgebruik en zijn verklarende variabelen. Door deze benadering wordt een balans gevonden tussen micro- en macro- processen van landgebruikveranderingen. Een analyse van het gedrag en de gevoeligheid van het model is gemaakt voor Ecuador. Verschillende scenario's zijn getest om te illustreren dat de simulaties een realistisch beeld van de dynamiek van landgebruikveranderingen geven.

De toepassing van het CLUE model voor China heeft een minimale ruimtelijke resolutie van 32x32 kilometer. De belangrijkste landgebruikveranderingen in China, veroorzaakt door urbanisatie, verwoestijning en herbebossing, zijn gesimuleerd voor een scenario geldig voor de periode 1990 tot 2010. Dit scenario is gebaseerd op veranderingen in de vraag naar de verschillende landgebruiktypes zoals beschreven in literatuur. De ruimtelijk-expliciete resultaten maken het mogelijk om de gevolgen van de afname van het landbouwareaal voor de agrarische productiecapaciteit van China te maken. Een eenvoudige analyse daarvan laat zien dat de productiecapaciteit (per hectare) van de landbouwgrond die uit productie genomen wordt enigszins lager is dan de gemiddelde productiecapaciteit van het gehele landbouwareaal. Regionale variaties zijn echter groot.

Met het CLUE model is tevens een simulatie gemaakt van een scenario waarin veranderingen in het relatieve belang van verschillende gewassen wordt verondersteld. De resultaten geven de geografische locaties aan waar binnen het landgebruiksysteem een groter aandeel gewassen met hoge marktwaarde (b.v. groenten) te verwachten zijn.

Grote veranderingen zijn verwacht in China's dierlijke productiesystemen als gevolg van een toenemende vraag naar dierlijke producten. Voor het CLUE model is een module ontwikkeld die het mogelijk maakt om veranderingen in de ruimtelijke verspreiding van verschillende dierlijke productiesystemen te simuleren. Deze module is gekoppeld aan de simulaties van landgebruik om een interactie mogelijk te maken. Twee scenario's zijn geëvalueerd: een basis scenario en een scenario waarin is aangenomen dat er een verbetering optreedt in het management van de graslanden om dierlijke productie in de pastorale regio te stimuleren. Voor beide scenarios zijn de grootste toenames van het aantal dieren te verwachten in China's landbouw regio. Slechte infrastructuur en grote afstanden met als gevolg lage prijzen en hoge kosten voor inputs zijn de voornaamste beperkingen voor een meer intensief gebruik van de pastorale regio.

Een validatie van het model is gemaakt voor Java, gebaseerd op historische gegevens. Simulaties van 1979 tot 1994 laten zien dat het model veranderingen in het landgebruikpatroon adequaat kan simuleren. Evaluatie voor individuele rastercellen gaf een redelijk resultaat terwijl het algemene patroon goed was gesimuleerd. Voor Java is tevens een scenario voor landgebruikveranderingen tussen 1994 en 2010 gesimuleerd aannemende dat urbanisatie verder doorzet. De resultaten laten zien dat de meest intensieve landgebruikveranderingen kunnen worden verwacht in de laaglanden van Java.

Behalve veranderingen in het areaal van verschillende landgebruiktypes is ook de intensiteit van landgebruik onderhevig aan verandering. Vooral wanneer de mogelijkheden voor verdere vergroting van het landbouwareaal beperkt zijn is intensivering van landgebruik een optie om de totale landbouwproductie te verhogen. Voor China is een aparte analyse gemaakt van de verschillende componenten van het landgebruiksysteem die invloed hebben op de productiecapaciteit voor granen. Naast veranderingen in areaal zijn ook veranderingen in het aantal malen per jaar dat van een stuk land geoogst kan worden, veranderingen in het gebruik van inputs, technische efficiëntie en veranderingen in technologie bestudeerd. Methodes gebruikt om de ruimtelijke en temporele dynamiek van deze componenten te bestuderen zijn allen gebaseerd op semi-empirische analyse van de ruimtelijke variabiliteit in relatie tot een set van biophysische en sociaal-economische verklarende factoren. De resultaten laten zien dat verschillende processen en patronen van landgebruikveranderingen worden gevonden in verschillende delen van het land. Inefficiënties in het gebruik van landbouwinputs en relatief lage hoeveelheden inputs, voornamelijk in een aantal van de rurale, minder ontwikkelde, westelijke regio's, geven aan dat het in deze delen van China goed mogelijk is om graan opbrengsten te verhogen. Besef van het belang van ruimtelijke variabiliteit voor agrarische ontwikkeling in plaats van het gebruik van gegevens op nationaal niveau, is van nut voor beleidsmakers en wetenschappers om toekomstige agrarische ontwikkelingsprogramma's op de juiste locaties te richten. Diepgaand onderzoek naar de oorzaken van achterliggende ontwikkeling is nodig als vervolg op de hier gerapporteerde studie en zal het ontwerpen van gepaste maatregelen mogelijk maken.

De geïntroduceerde en toegepaste methodes kunnen een essentiële schakel vormen tussen reeds bestaande onderzoektechnieken, hetgeen nodig is voor adequate planning van landgebruik en onderhandelingen daarover. Studies op nationaal niveau die mogelijke problemen met landgebruik identificeren of simpelweg trends extrapoleren kunnen direct gebruikt worden bij het formuleren van scenario's voor het CLUE model. Na het uitvoeren van de simulaties kunnen de resultaten van het CLUE model gebruikt worden als basis voor het ontwerp van alternatieve landgebruikconfiguraties. Van scenario's die tot gewenste landgebruikveranderingen leiden kunnen beleidsmaatregelen afgeleid worden. De confrontatie van de gesimuleerde landgebruikdynamiek met landgebruikpatronen die ontworpen zijn door landgebruikplanners, evt. m.b.v. optimaliseringmodellen, kan leiden tot een meer realistische definiëring van de doelstellingen en beperkingen van de planning van landgebruik.

Curriculum vitae

Pieter Hendrik Verburg was born in Loenen aan de Vecht on May 18th, 1972. He completed secondary school (VWO) in 1990 at 'Comenius College' in Hilversum. In 1990, he started his study 'Soil, Water and Atmosphere' at Wageningen Agricultural University, which he finished 'cum laude' in 1996, with specializations in land evaluation, soil chemical processes, ecohydrology and geohydrology. During this period he spent six months in Vietnam and three months in South Africa. From March 1996 until February 2000 he worked on his Ph.D. research within a project financed by the Dutch National Research Programme on Global Air Pollution and Climate Change. From March 1996 until February 1999 he was stationed at the Department of Agronomy while he continued his work from March 1999 onward at the Laboratory of Soil Science and Geology of Wageningen University. Until December 2000 he will continue his work for the project 'Upscaling and Downscaling of Regional Methane Sources - Rice agriculture as a case-study'.