4th International Conference on Integrating GIS and Environmental Modeling (GIS/EM4):
Problems, Prospects and Research Needs. Banff, Alberta, Canada, September 2 - 8, 2000.

GIS-based modeling of human-environment interactions for natural resource management: applications in Asia

GIS/EM4 No. 116

Peter H. Verburg
Youqi Chen
Welmoed Soepboer
Tom (A.) Veldkamp

Abstract

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. Land use changes are clearly driven by human activities. However, the actual location where land use changes take place is determined by biophysical conditions as well. Spatially explicit assessments of environmental change are needed because environmental change does not affect all places similarly, differential impacts and abilities to respond creates winners and losers in this change. The identification of the dynamics giving rise to vulnerability of people and places in the face of global change is therefore essential.

A GIS-based modelling approach is developed which includes the analysis of relations between land use and its (proximate) driving factors as well as the dynamic simulation of near-future land use changes by a numerical model. Relations between land use and its (proximate) driving factors, including both biophysical and human factors, are quantified by multi-variate statistical techniques. These relations are used in a dynamic model which explores changes in the land use pattern under near future conditions of demand for agricultural production and other land utilization. The approach is illustrated with applications of the model for case-studies in Asia (China, Java and Philippines).

Keywords

land use and land cover change, human-environment interactions, GIS, dynamic modeling, cross-disciplinary, scale, Asia

Introduction

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 is 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).

Land-use changes, mostly driven by human activities, result in global environmental change (Riebsame *et al.* 1994; Vitousek *et al.* 1997; Houghton, 1994; Tinker, 1997). The individual activities leading to land-use changes meet locally defined needs and goals, but aggregated they have an impact on the regional and global environment (Turner II, 1994; Ojima *et al.* 1994). Changes in land use affect biodiversity, water and radiation budgets, trace gas emissions and other processes that, cumulatively, affect global climate and biosphere.

Land-use change is directly linked to the theme of transition to a sustainable world. With origins in the Brundtland report and increasingly embedded in global change science agendas, the overarching concern is achieving this provisioning in a warmer, more crowded, and more resource demanding world characterized by unexpected and extreme events. This transition requires an improved understanding of the trajectories of land-use change that invoke positive or negative human-environment relationships (Turner II *et al.* 1987; Holling *et al.* 1996).

A better understanding of the processes of land-use change is essential to assess and foresee the effects of land use change for ecosystems and society. Greenhouse emission inventories and reduction objectives need to include the foreseen changes in emission source strengths as a consequence of land-use change, rates and patterns of land-use change need to be understood to design appropriate biodiversity management. Priority areas of land use change need to be identified to focus land use planning at the appropriate regions.

Problem statement

Land use and cover change are the result of many interacting processes. Studying the dynamics of these processes requires an understanding of the two fundamental issues in land use change research, namely, integration of human and environmental driving factors of land-use change and the study of system behavior over a range of spatial scales. Each of the identified human-environment interaction processes operates over a range of scales in space and time. Many interactions and feedbacks between these processes at different levels of organization occur. If for all processes involved with land use and land cover change these hierarchies must be distinguished as well as their mutual interactions the situation gets enormously complicated.

Researchers in the field of land-use studies share the formidable task of coming to grips with the complex causal web linking social and biophysical processes (Turner II, 1997). Even more challenging are models of land use change that provide tools for understanding the causes and consequences of rapid land-cover changes. Models are useful for disentangling the complex suite of socio-economic and biophysical factors that influence the rate and spatial pattern of land-use change and in estimating the impacts of changes in land use. Furthermore, models have the capability to make predictions of the possible developments of the land-use system into the future. This paper presents an approach for studying and modeling the dynamics of land-use change in a spatially explicit way, directly linked to Geographic Information Systems, the method is illustrated with a number of examples from case-study areas in Asia.

Background

Different research approaches, strongly divided by scientific discipline and tradition, have emerged for the different scales of the analysis of land-use change. Researchers in the field of the social sciences have a long tradition in studying individual behavior in human-environment interactions at the micro-scale, mostly by narrative approaches (Bilsborrow *et al.* 1992); (Bingsheng, 1996). 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 find understanding in the organisation and institutions of society and landscapes that establish opportunities and constraints on decision making. There are fundamental differences between these two approaches and the underlying assumptions concerning the functioning of the land-use system. Macro and micro scale studies are supposed to complement each other to produce comprehensive theories. They do not because problems are artifacts whose structure depends upon various philosophical and methodological positions (Watson, 1978). These create opposing sets of assumptions and inferences about human behavior. The following paragraphs highlight the characteristics of the different perspectives.

Micro-level analysis

For social scientists behavior is the central topic of study. Social science disciplines and subdisciplines have their preferred levels of analysis and often do not communicate across those levels. For instance, psychologists and sociocultural anthropologists tend to work with individuals and small groups; while sociologists tend to specialize in one level of analysis or another, from individuals to small groups to communities. Another characteristic is that social science is generally more concerned with why things happen than where they happen. Even areas of social science in which one might expect a spatial orientation are curiously a-spatial. Relatively few social scientists outside the field of geography value the importance of spatial explicitness, nor do the typical social science data sets contain the geographic co-ordinates that would facilitate linking social science data and remotely sensed or other geographic data (Rindfuss *et al.* 1998).

The lack of a spatial perspective in micro-studies ignores the context of the studied behavior. People live their lives in contexts, and the nature of those contexts structures the way they live (Fotheringham, 2000). When the individual is the unit of analysis, the individual's household is also a context, as well as the community, the biophysical environment and the political powers to which the individual might be subjected. Contexts can provide advantages or produce constraints. Hypotheses from theories of context may involve additive effects or interactive effects - but in either event, the hypotheses concern the effects of context on individuals or households (Rindfuss *et al.* 1998).

New theories linking individual behavior to collective behavior are being developed to deal with scaling issues in the social sciences (Ostrom, 1990) while at the same time a couple of new research projects attempt to link social science research with geographical data (Geoghegan *et al.* 1998; Walsh *et al.* 1999; Walker *et al.* 2000; Mertens *et al.* 2000). This type of linkage between socio-economic and geographical data can be a means to provide information on the context that shapes social phenomena.

Macro-level analysis

Ecologists and geographers have a long tradition of focussing on the biophysical subsystem of the environment. Analysis of spatial heterogeneity and patterns of ecosystems and land use have been the main focus. Most often these studies have a coarser scale of study than normal for social scientists. So instead of studying how individual processes have resulted in land-use change the approach tries to unravel the processes that have caused land use to change based on observed patterns of land use (e.g., de Koning *et al.* 1998; Mertens *et al.* 1997; Liu *et al.* 1993).

A macro approach appears to be a very useful research strategy to start with. Macro-level research can be used as lens or filter to focus on problems that require micro scale explanations. By working high up the cone of resolution where there is little detail, it is possible to determine what aspects of the problem are relatively unimportant. Aggregate analysis of structure and process are almost mandatory when exploring terra incognito, since a macro viewpoint is better equipped to identify the bounds of a complex system and subdivide it into more tractable components.

Methods

The CLUE methodology (Veldkamp *et al.* 1996; Verburg *et al.* 1999a) is based on theories about the functioning of the land-use system derived from landscape ecology (Holling, 1992); (Levin, 1992; Turner *et al.* 1992). Natural ecosystems have large correspondences in structure, function and change with land-use systems and the social systems underlying changes in land use. Social systems and agro-ecosystems are, just like natural ecosystems, complex adaptive systems which can be described by theories and methodologies developed in ecology (Holling *et al.* 1996).

The CLUE methodology is made up of two parts. The first part aims at establishing relations between land use and its driving factors taking scale dependencies into account explicitly. The second part aims at dynamic modeling.

Multi-scale analysis of driving factors of land-use change

The multi-scale analysis of the driving factors of land-use change is based on the analysis of spatial patterns of actual land-use. Except for areas with minimal human influence, the patterns reflect the result of a long history of land-use change and contain, therefore, valuable information about the relation between land use and its driving factors. Because it is assumed that the relations between land-use and driving factors are extremely complex due to scale dependencies, interconnections and feedbacks no attempts are made to unravel the individual processes. Instead, empirical relations between land use and its supposed determining factors explain the observed pattern of land use, e.g., through regression analysis. Another characteristic of the approach is that no a priori levels of analysis, e.g., landscape or regional level, are superimposed. Instead, the analysis is repeated at a selection of artificial resolutions, imposed by the gridded data structure. An example of the results of such an analysis is presented below. These results are of interest by themselves and can be subjected to extensive interpretation. They can, however, also directly be used for the dynamic modeling of near-future land use changes.

Dynamic modeling

The CLUE modeling framework (Veldkamp *et al.* 1996; Verburg *et al.* 1999a) uses the derived multi-scale relations between land-use change and its driving factors as a direct input for modeling. The modeling approach has the following characteristics:

- All simulations are made in a spatially explicit way so that the geographical pattern of land use change is resulting. The spatial resolution of the simulations is dependent on the extent of the study area and the resolution of data available for that study area.
- Allocation of land use changes is based on the dynamic simulation of competition between different land use types. Competitive advantage is based on the ‘local’ and ‘regional’ suitability of the location and the national level demand for land use type related products (e.g., food demand or demand for residential area).
- The ‘local’ and ‘regional’ suitability for the different land use types is determined by quantified relations between land use and a large number of explanatory factors derived in the multi-scale analysis described above.
- Different scenarios of developments in land-use can be simulated. At the national level scenarios include different developments of agricultural demands that can be determined on the basis of developments of consumption patterns, demographic characteristics, land use policies and export volumes. At the sub-national level different restrictions towards the allocation of land use change can be implemented, e.g., the protection of nature reserves or land allocation restrictions in areas susceptible to land degradation.

Findings

The CLUE model was first developed for, and applied to, Costa Rica (Veldkamp *et al.* 1996). Recent and current applications are those for Ecuador (de Koning *et al.* 1999a), Central America (Kok *et al.* 2000), China (Verburg *et al.* 1999b) and Indonesia (Verburg *et al.* 1999c).

Analysis of driving factors for China

The above described method was used to study the (proximate) driving factors that determine the spatial distribution of land-use in China. These driving factors were studied by systematically varying the spatial extent and resolution of analysis (Figure 71-1). The extent is varied between the country as a whole, and a subdivision in 8 delineated regions. The resolution of analysis was increased in 6 steps from grid-cells of 32x32 km (~1000 km^2; n=9204) to grid-cells of 192x192 km (~36800 km^2; n=258). For these different scales of observation the land-use distribution (represented by the relative area covered by the individual land-use types in the grid cells) was related to a large set of potential driving factors by correlation and regression analysis. As an example of the results, reported by (Verburg *et al.* 2000a) the five explanatory factors having the highest correlation with the distribution of cultivated land are presented in Table 71-1. The analysis demonstrated that for the country as a whole the pattern of cultivated land corresponds best with the agricultural population distribution. When the extent of analysis is decreased, by repeating the statistical analysis for separate regions within China, agricultural population is not always the most important explanatory variable anymore. 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 dominant factors.

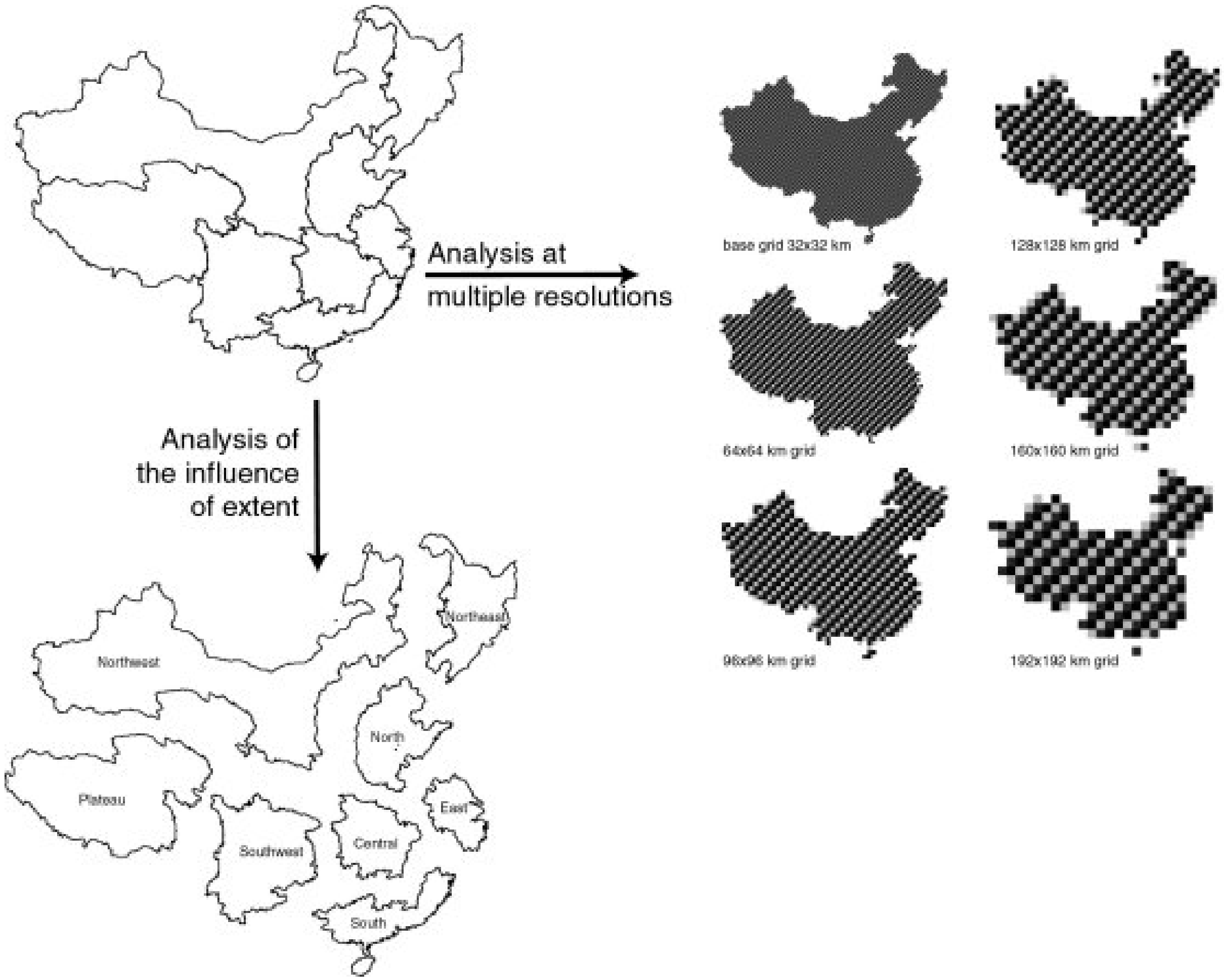

Figure 71-1 Subdivision of China into different units of extent and resolution to allow analysis at multiple scales

The effect of resolution was studied by comparing the results of a correlation and regression analysis at six different artificial aggregation levels. Figure 71-2 displays the correlation coefficient between a selection of variables and 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 area 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 and mean elevation stay approximately constant over the range of grain sizes, the coefficients for soil suitability and urban population density 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 correlation.

Whole country (n=9204)	Northeast (n=764)	North (n=674)	Northwest (n=3361)	East (n=336)
Agric. population	Max. temperature	Mountains	Agric. population	Total precipitation
Agric. labor	Mountains	Agric. population	Agric. labor	Mountains
Total population	Deep soils	Slope	Rural labor	Elevation range
Rural labor	Level land	Agric. labor	Total population	Well drained soils
Soil suitability R-S1>	Agric. population	Plain land	Loess	Bad drained soils

Central (n=554)	South (n=547)	Southwest (n=1098)	Plateau (n=1870)
Mountains	Mountains	Agric. labor	Rural labor
Agric. population	Slope	Agric. population	Agric. labor
Total population	Max. temperature	Rural labor	Agric. population
Plain land	Avg. temperature	Total population	Total population
Well drained soils	Mean elevation	Mean elevation	Urban population

Table 71-1 Most important explanatory factors for the distribution of cultivated land based on Pearson correlation coefficients (all significant at $P<0.0001$, n=9204)

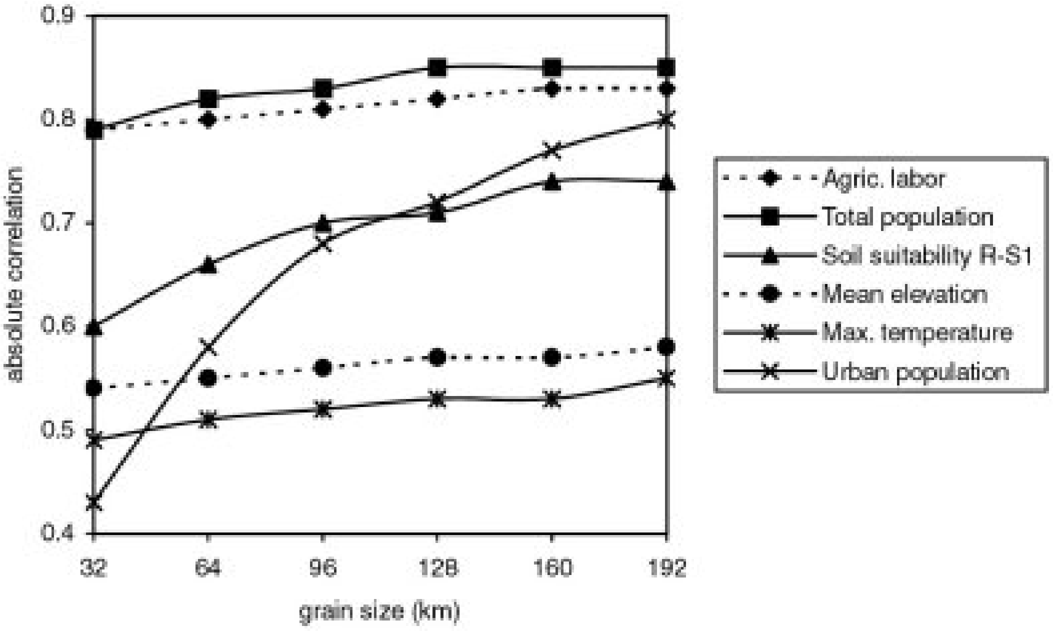

Figure 71-2 Absolute correlation between the relative cover with cultivatd land and a number of explanatory factors at different resolutions for China; all correlations significant at P<0.0001; source: Verburg and Chen, 2000.

Modeling results for Java, Indonesia

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. 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 urbanized society. With the CLUE model a scenario is evaluated which is assumed to be representative for future land use changes in Java. The scenario is based on developments expected by the World Bank (1992). As this World Bank study was made before the recent Asia Crisis it projects a continuation of economic growth. The major land use change represented in this 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 in Java. The results of the scenario simulations are presented in Figure 71-3. 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 neighborhood of the urban centers 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 summarized 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.

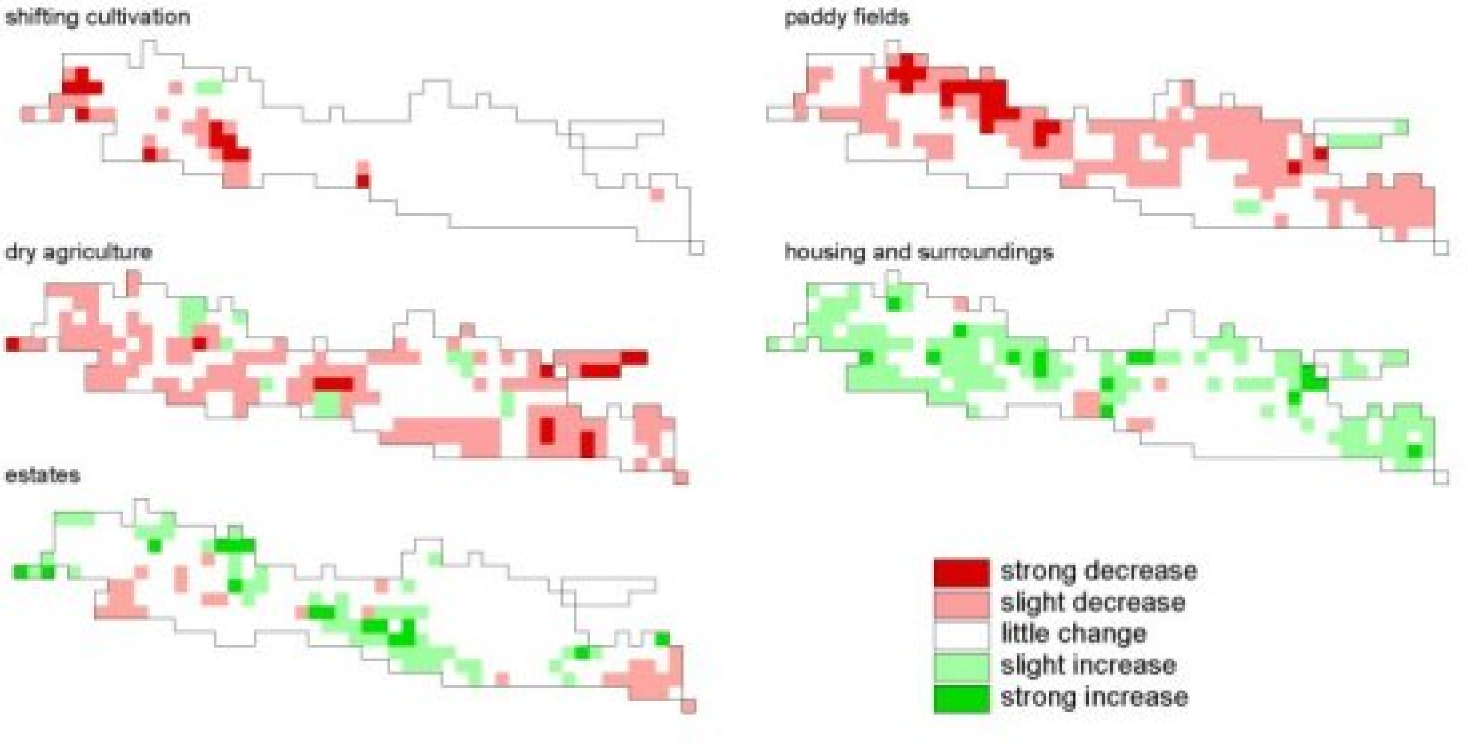

Figure 71-3 Simulated changes in land use between 1994 and 2010.

Modeling results for Sibuyan Island, Philippines

The CLUE model is applied to the island Sibuyan in the province of Romblon, Philippines. The island measures 28 km east to west at its widest point and 24 km north to south, with a land area of approximately 456 km^2 surrounded by deep water. In the centre of the island lies a large protected area (Mount Guiting-Guiting Natural Park). It is characterised by its steep mountain slopes, covered with forest canopy. The land surrounding the high mountain slopes gently to the sea and is used for natural and plantation forest and agricultural, mining and urban activities. The island is believed to be completely covered by forest until the 1940’s. From then on the forest has been cleared from the footslopes. Highest on the footslopes are the grassland derived from deforestation, used for pastures. They are regularly burnt to stimulate new grass growth. Rice paddies are common at low-lying land. Most cleared areas are however used for coconut plantation. The island is surrounded by some mangrove forests, sandy beaches and coral reefs (DENR, 1997). See also figure 71-4 A.

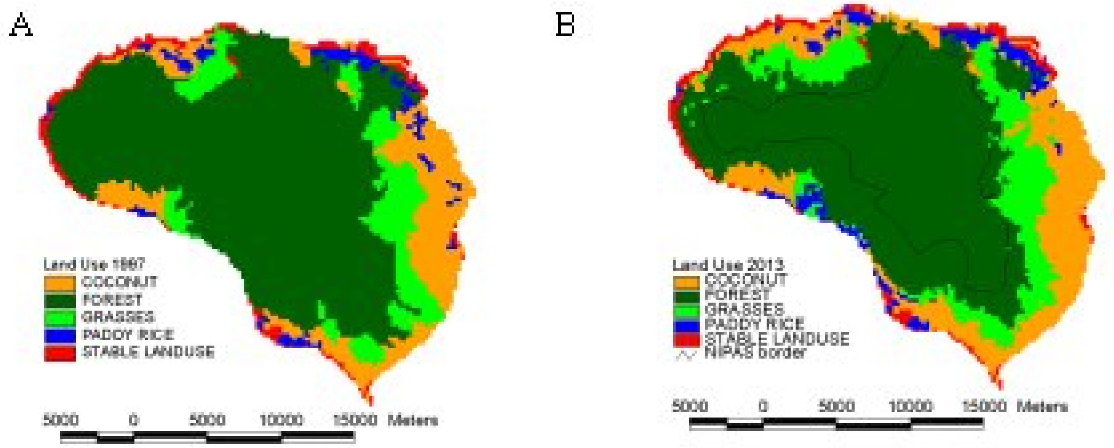

Figure 71-4 Land use patterns in Sibuyan 1997 (A) and 2013(B).

The CLUE high resolution model version evaluates a base line scenario for Sibuyan for 15 years (1997-2013). The higher resolutions demand a different data representation and modelling approach. Where the low-resolution data made use of non-homogeneous grid cells, this model version is based on homogeneous grid cells. The scale is 250x250 m.

A statistical analysis based on logistic regression is used to find the most important determinants of the land use patterns. Five to ten driving factors are necessary to explain the four dynamic land use types, coconut, forest, grass and rice. The population density, which acts over large distances, is taken into account by using an upscaling of grid information by a focal function.

The demands that are used are the linear extensions of the development between 1940-1997. The assumption is that the island is first opened up from 1940 on and that a linear development has occurred until 1997.

The model predicts the further development along the footslopes of the mountains especially in the west and the north (figure 17-4 B). Especially the coconut plantations expand towards the northern part of the island. The northwestern part consists of very steep slopes, too steep for coconut, but some patches of grassland are developing. Some of the rice paddies will move to the southwest, and also more new paddies will develop here.

The black line in figure 71-4 B indicates the NIPAS-area. This is the border of the Mount Guiting-Guiting National Park. Without taking the border into account, the park will slowly be invaded for agricultural purposes, especially on the east side. However, it also shows that new agricultural developments mainly occur at the west side of the island.

Validation

Uncertainties in predicted land use change can arise from both non-realistic scenario conditions and allocation errors. The allocation algorithm of the CLUE model has been validated successfully in a number of cases (de Koning *et al.* 1999a; Verburg *et al.* 1999c; Kok *et al.* 2000). The validations were made through the simulation of historic, documented land use changes. However, any land-use change scenario and model has a high, inherent, uncertainty due to the complexity of the system addressed. Therefore results of land use change models should never be treated as predictions for future land use but rather as exploration of the potential dynamics of the land use system.

Discussion

Land use change information is essential to assess the effects of human influence on natural resources. Estimates of carbon emission are subject to high degrees of uncertainty, due in large part to difficulties in assessments of land conversion across local to regional scales (Dietz *et al.* 1997; Moran, 2000). It is also a consequence of the fact that terrestrial vegetation and soils are extremely heterogeneous over the land surface, and estimates of the magnitude of carbon emissions during clearing and of carbon gains during regrowth of vegetation vary substantially. Hence, for improved assessments there is a need of spatially explicit assessments of land use change. Similar considerations hold for assessments of changes in nutrient balances, important for sustainability in agricultural production and environmental quality (Smaling *et al.* 1993; de Koning *et al.* 1999b). Other applications that directly use spatially explicit information on land-use change are erosion/sedimentation models and water resource assessments (Wear *et al.* 1998) and biodiversity (Lebel *et al.* 1998; van der Meer *et al.* 1998). Maintaining biological diversity depends on the spatial arrangement of land-uses on the landscape, because of the importance of fragmentation and habitat size on the risks of extinction. The spatial arrangement of land-uses also has implications for ecosystem function, and hence the goods and services. For example, the way in which residual forest is distributed relative to the stream margin can have an impact on soil erosion and hydrology of a catchment. Finally, how natural disturbances like fires, pests and diseases propagate through a heterogeneous landscape clearly depends on its structure. The evaluation of different scenarios based on different policies and development trajectory can help to assess these spatial patterns and their effects on biodiversity, food production and other ecosystem functions (Figure 71-5). This way spatial modeling can improve land use planning and inform policy making (Farrow *et al.* 2000).

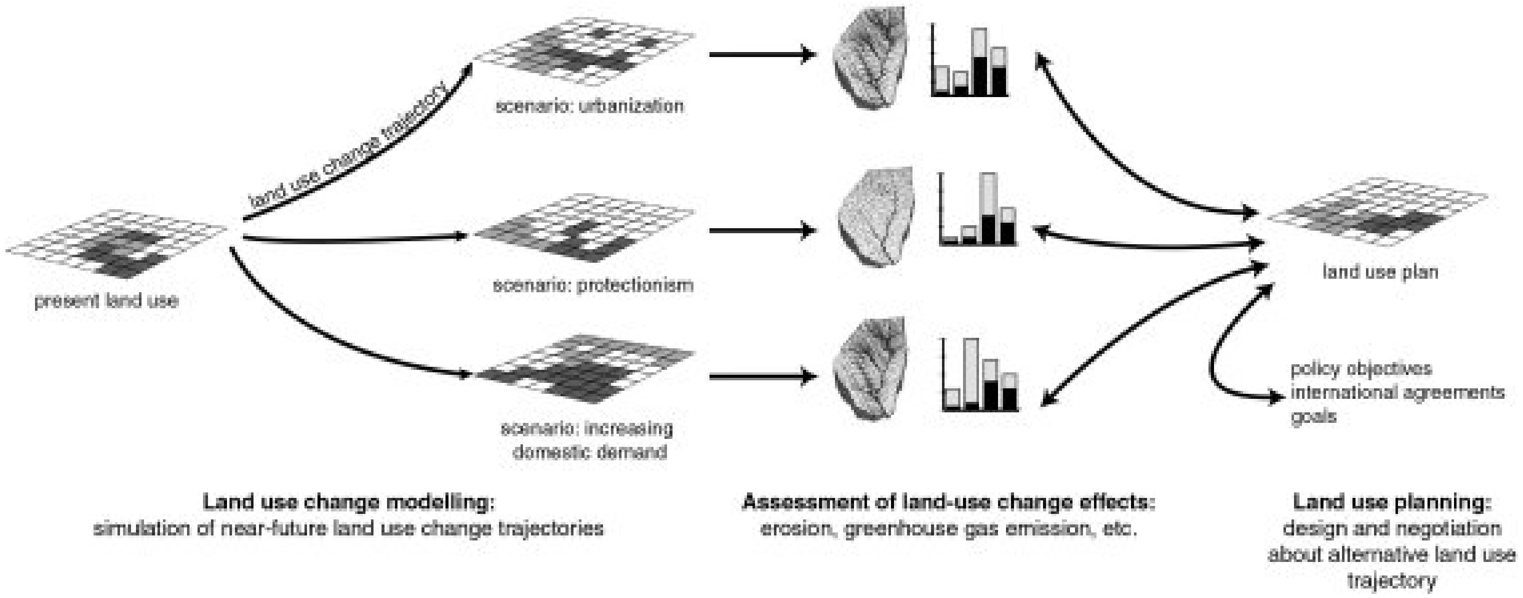

Figure 71-5 The role of land-use change modelling within studies aiming at improved land use planning

Apart from these biophysical assessments land use change studies can also help to identify vulnerable people and places in the face of global change. Differential impacts and abilities to respond create winners and losers in this change. Whether involving land fragmentation, degradation of agricultural productivity, declines in economic well being, or involuntary human migration, land-use/land-cover change plays an important role. The results of spatially explicit land-use change models allow a straightforward 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. Based upon results of the CLUE modelling framework (Verburg *et al.* 2000b) identified regions in China that are lacking behind in economic development while, at the same time, these regions are faced with deteriorating land resources. The identification and understanding of the dynamics underlying these regional differences will help to focus in-depth research and policy intervention at the most threatened regions.

After all intellectual efforts of properly describing land use dynamics and their associated effects the main task scientists are faced with is the communication of their results to the stakeholders. Ideally, stakeholder have been involved during the research itself in ‘social learning’ processes (Röling *et al.* 1999), which ensures that the appropriate questions are answered. Appropriate presentation of the result is extremely important. Most stakeholders are not eligible to read scientific papers or bulk reports. For the presentation of spatially explicit assessments of land use change the researcher can make use of the visual capabilities of geographical information systems. The presentation of maps to decision-makers is appropriate to communicate results and provoke discussions between policy makers and scientist on the seriousness of the foreseen changes (Goodchild, 2000). Spatially explicit representation of land-use changes has also proven to be an appropriate means to discuss resource bases, spatial interconnectivities between areas and the consequences of local actions with farmers (Gonzalez, 2000).

Conclusion

Integration of disciplines over different spatio-temporal scales is necessary in order to address the issues relevant for actors and stakeholders at different organizational levels in land use and natural resource management. The methodology demonstrated in this paper offers an analysis of land use change dynamics at the landscape level and can supplement land use change studies at the individual actor or community level. The applications of the information generated by the model are large and can help to better manage natural resources in a sustainable manner.

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Authors

Peter H. Verburg, Post-doc, Department of Environmental Sciences
Wageningen University, PO Box 37, 6700 AA Wageningen, The Netherlands
Email: pverburg@gissrv.iend.wau.nl, Tel: +31-317-485208, Fax: +31-317-482419

Youqi Chen, Senior scientist, Institute of Natural Resources and Regional Planning, Chinese Academy of Agricultural Sciences, Beijing, China

Welmoed Soepboer, Graduate student, Department of Environmental Sciences, Wageningen University, The Netherlands

Tom (A.) Veldkamp, Senior scientist, Department of Environmental Sciences, Wageningen University, The Netherlands