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Editorial

Predicting land-use change

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Abstract

Land use change modelling, especially if done in a spatially-explicit, integrated and multi-scale manner, is an important technique for the projection of alternative pathways into the future, for conducting experiments that test our understanding of key processes in land use changes. Land-use change models should represent part of the complexity of land use systems. They offer the possibility to test the sensitivity of land use patterns to changes in selected variables. They also allow testing of the stability of linked social and ecological systems, through scenario building. To assess current progress in this field, a workshop on spatially explicit land-use/land-cover models was organised within the scope of the Land-Use and Land Cover Change project (LUCC). The main developments presented in this special issue concern progress in: 1) Modelling of drivers of land-use change; 2) modelling of scale dependency of drivers of land use change; 3) modelling progress in predicting location *versus* quantity of land-use change; 4) the incorporation of biophysical feedbacks in land-use change models. © 2001 Elsevier Science B.V. All rights reserved.

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1. Introduction

Over the last decades, a range of models of land-use change have been developed to meet land management needs, and to better assess and project the future role of land-use and land-cover change in the functioning of the earth system. Modelling, especially if done in a spatially explicit, integrated and multi-scale manner, is an important technique for the projection of alternative pathways into the future, for conducting experiments that test our understanding of key processes, and for describing the latter in quantitative terms (Lambin et al., 2000; Lambin et al., 2001). Land-use change models represent part of the complexity of land-use systems. They offer the possibility to test the sensitivity of land-use patterns to changes in selected variables. They also allow testing of the stability of linked social and ecological systems, through scenario building. While, by definition, any model falls short of incorporating all aspects of reality, it provides valuable information on the system's behaviour under a range of conditions. Different modelling approaches have been adopted in the study of land-use/land-cover change (see reviews by Sklar and Costanza, 1991; Lambin, 1994; Riebsame et al., 1994; Angelsen and Kaimowitz, 1999; Lambin et al., 2000).

To assess current progress in this field, a workshop on spatially explicit land-use/land-cover models

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was organised within the scope of the land-use and land-cover change project (LUCC), a core project of the international geosphere–biosphere programme (IGBP) and the international human dimensions of global environmental change programme (IHDP). The ultimate objective of the LUCC project is to improve understanding of regionally based, interactive changes between land-uses and covers, especially as manifested in modelling approaches. A related goal is the development of improved means for projecting land-uses and covers (Turner et al., 1995). Selected papers of the presentations given at the workshop were invited to contribute to this special issue.

A prerequisite to the development of realistic models of land-use change is the identification of the most important drivers of change. A related issue is how best to represent these drivers in a model. Simulation of decisions by and competition between multiple actors and land managers is required. Models should be able to generate reliable projections into the future or, in backward mode, to the past. This requires linking dynamically the processes (and models) of land-use change to biophysical processes (and models), to represent biophysical feedbacks to land-use changes and land-use adaptations to biophysical changes. This has to be based on dynamic system models, which represent functional complexity. Finally, a solid framework for a systematic validation of projections generated from land-use change models is an essential component of this research field.

In addition to these scientific requirements for land-use change models, there are some system-related requirements associated with the properties of complex land-use/land-cover systems. One of such properties is the scale dependency of explanatory variables of land-use change. It is thus essential to understand how the scale of analysis affects modelling results. A second requirement is the necessity to distinguish between projections of the quantity and location of change. While some models are focussed on predicting the rates (or quantities) of change, others put more emphasis on spatial patterns. This has also implications for data requirements and validation strategies.

In this introductory paper, we identify the major new findings from the workshop. We first discuss current progress in incorporating the relevant drivers of land-use change within models, followed by a discussion of the scale dependency of these drivers. We then discuss the issue of modelling and validating quantity versus location of changes. We conclude by assessing the potential for incorporating biophyscial feedbacks into land-use change models.

2. Drivers of land-use change and their modelling

The complexity of land-use systems calls for multidisciplinary analyses (Clayton and Radcliffe, 1996). Initial efforts aimed at modelling land-use change have focussed primarily on biophysical attributes (e.g. altitude, slope or soil type), given the good availability of such data. Incorporation of data on a wide range of socio-economic drivers of change is however required (Turner et al., 1995; Musters et al., 1998; Wilbanks and Kates, 1999). Most case studies highlight for instance the important role of policies in driving land-use changes (Lambin et al., in press), e.g. international environmental treaties such as the Kyoto Protocol may drive significant changes in land-use in the future. Incorporation of social, political and economic factors is however hampered by a lack of spatially explicit data and by methodological difficulties in linking social and natural data. For example, the relevant spatial units for biophysical processes may be very different from the spatial units of decision making by actors. Proxy variables, which are easier to measure spatially (e.g. distances to a road or a town), are often used for deeper underlying driving forces (e.g. influence of markets). This shift from driving forces to proximate causes, for data convenience, might obscure causality. Subtle land-cover or land-use modifications, e.g. related to changes in cropping patterns, input use or tree density of forests, also need to be taken into account in addition to the more easily measurable land-cover conversions. Moreover, land-use change models need to account for the endogeneity of variables such as land management technologies, infrastructures or land-use policies.

A fundamental difference in modelling tradition between different disciplines concerns the use of process-based (or structural) models versus statistical (or reduced form) models. While models of the first group have a sound theoretical basis, the second type of models are easier to implement. The two families of models are however highly complementary, as structural models are used for hypothesis formulation and to identify which variables should be incorporated in a reduced form model. The later allows testing hypotheses given limitations in data availability. Statistical models often rely on the implicit assumption that land-use change processes are stationary. By contrast, process-based models are able to deal with temporal heterogeneity, i.e. fundamental changes in driving forces or processes through time related to a change in system properties. Such shifts in system behaviour can take place once some threshold is passed or can be triggered by single events, whether these are biophysical (e.g. drought, hurricanes) or socio-economic (e.g. technological innovation, war, economic crisis).

Some models represent the decision-making processes by actors. The expertise from economy is crucial in this area. Land-use change models recently developed by economists integrate spatial heterogeneity and broaden the objective function of actors from profit to utility maximisation, including multiple uses of land (Irwin and Geoghegan, 2001). Behavioural models of land-use decisions by agents can be made spatially explicit, thanks to cellular automata techniques. This accounts for the well-known fact for geographers that landscape patterns and spatial interactions do influence land-use decisions. In another related vein of research, spatially explicit land-cover data derived by remote sensing are directly linked to household survey data at a fine spatial resolution, using geographic information systems (Walsh et al., 2001; Serneels and Lambin, 2001; Schneider and Pontius, 2001; Nelson, 2001; Geoghegan et al., 2001). Time series of remote sensing data with a high frequency of data acquisition allow prediction of the timing of changes, opening new avenues to better link macro-economic transformations to land-use changes (Kaufmann and Seto, 2001) and to understand time lags in land-use responses to socio-economic or natural perturbations. With these new developments, analyses at the level of actors can be linked to regional-scale processes. Multi-scale regression analyses (Fischer and Sun, 2001) or other multi-level techniques (Polsky and Easterling, 2001; Kok and Veldkamp, 2001) provide the statistical methods to advance this research. This hierarchical dependence between drivers of land-use change does create spatial dependency — and thus spatial autocorrelation — between observations, which requires a cautious application of statistical methods for data analysis.

3. Scale dependency of drivers of land-use change

Given the scale dependency of the analysis of drivers of land-use changes, models should be based on an analysis of the system at various spatial and temporal scales (Turner et al., 1995). Yet, most existing regional-scale models address neither structural nor functional complexity. Recognising the excessive complexity of the system, land-use modellers often confine themselves to either a single process (e.g. deforestation, see Lambin, 1994; Angelsen and Kaimowitz, 1999), or a single discipline (e.g. economic models, see Bockstael, 1996). Models that opt to incorporate and link a larger number of factors for a spatially heterogeneous area (e.g. integrated assessment models, see Zuidema et al., 1994) severely simplify the land-use system. Incorporating structural complexity becomes necessary at the coarser scales. Actually, at local scales, the direct actors of land-use change can be identified and process-based relationships can be determined. With decreasing resolution and increasing extent, it becomes increasingly difficult to identify key processes. Thus, at these aggregated levels, the model's structure and assumptions have to be adapted, as one cannot simply use knowledge derived from local studies and apply it at another level (Rastetter et al., 1992). A large number of global change models incorporating land-use change have been developed, e.g. DICE (Nordhaus, 1992), PAGE (Hope et al., 1993) and IMAGE (Alcamo et al., 1998). This forces the scientific community to understand the consequences of spatial extent and/or resolution on predicted patterns of land-use changes.

Two new approaches allowing to deal with scale dependency are presented in this issue. One uses fixed spatial units (grids) and changes both resolution and extent in a spatial regression analysis (Walsh et al., 2001; Kok and Veldkamp, 2001). The other one is changing the spatial units in a scale sensitive way for specific purposes (Nelson, 2001). From a few case studies, it appears that variations in explanatory variables of land-use change with scale follow a consistent pattern: at farm scale, mostly social and accessibility variables do influence land-use, at landscape scale, topography and agroclimatic potential are the key determinants, while at regional to national scale, climatic variables as well as macro-economic and demographic factors seem to drive land-use. A more systematic case study comparison is likely to generate important insights in this respect.

4. Predicting location versus quantity of land-use change

Models of land-use change can address two separate questions: where are land-use changes likely to take place (location of change) and at what rates are changes likely to progress (quantity of change). The first question is often much easier to deal with through models, as it mostly requires identification of the natural and cultural landscape attributes which are the spatial determinants of change, i.e. local proximate causes directly linked to land-use changes. Such research has tended to confuse spatial determinants for underlying causes and has led to an overemphasis of factors such as roads, soil types or topography as a cause of deforestation for example. The rate or quantity of change are driven by demands for land-based commodities (Stephenne and Lambin, 2001) and are often modelled using an economic framework (Fischer and Sun, 2001). The deeper underlying driving forces which control the rates of changes are often remote in space and time, and operate at a higher hierarchical level. They often involve macro-economic transformations and policy changes. Modelling these driving forces often require the combination of system, actor-based and narrative approaches (Lambin et al., 1999).

A few land-use change models deal with both the location and quantity issues in an integrated way (Geoghegan et al., 2001; Verburg and Veldkamp, 2001; Schneider and Pontius, 2001). However, they offer case specific solutions and a generally valid methodology has still to be developed. Multiple-criteria evaluation are often used in this context (Pontius et al., 2001). Model validation needs also to clearly separate an evaluation of the performance of the model in terms of quantities and location (Pontius and Schneider, 2001), in addition to perform such validations at multiple scales (Kok et al., 2001).

5. Biophysical feedbacks in land-use change models

Land-use change models are often used to assess the impact of land-cover on biophysical processes, e.g. climate variability, land degradation, ecosystem stability and diversity. The biophysical responses to changes in land-cover themselves feedback on drivers of land-use, calling for a dynamic, endogenous coupling between models of land-use change and biophysical models. This research area is just emerging, but is likely to quickly grow in importance in the coming years. For example, the influence of land-cover on climate, particularly in relation with carbon sequestration, has recently become an important policy issue.

Coupling land-use change models with biophysical models has to be conceived in the context of a hierarchy theory (O'Neill, 1988), allowing for multi-level interactions and feedbacks. Current applications with nutrient balance (Priess et al., 2001), soil erosion (Schoorl and Veldkamp, 2001) or global climate models (Stephenne and Lambin, 2001) often represent unidirectional impacts only (i.e. impact of land-use changes on biophysical processes). Hardly any feedback are incorporated and, therefore, no self-organising behaviour is possible. Note however that the major difficulty in representing many potential feedbacks is the numerical instability that it generates for such models. Small measurement errors in input data can propagate and lead to spurious results, given the non-linear behaviour of the modelled system.

Such coupled models can be used as decision-support systems to inform policy formulation. Scenarios of land-use change help to explore possible futures under a set of simple conditions. In this way, land-use change models can generate indicators of ecological sustainability, or of vulnerability of places and people. Recent experiences involve policy makers and stakeholders to define and negotiate relevant scenarios (Farrow and Winograd, 2001).

6. Conclusions

Land-use change modelling is a highly dynamic field of research with many new developments. The main current developments presented in this special issue concern progress in

1. The modelling of drivers of land-use change.
2. Modelling of scale dependency of drivers of land-use change.
3. Modelling progress in predicting location versus quantity of land-use change.
4. The incorporation of biophysical feedbacks in land-use change models.

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