GeoJournal **61:** 309–324, 2004.



# Land use change modelling: current practice and research priorities

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*Key words:* land use change, integrated assessment, modelling, spatial dynamics

**Abstract**

Land use change models are tools to support the analysis of the causes and consequences of land use dynamics. Scenario analysis with land use models can support land use planning and policy. Numerous land use models are available, developed from different disciplinary backgrounds. This paper reviews current models to identify priority issues for future land use change modelling research. This discussion is based on six concepts important to land use modelling: (1) Level of analysis; (2) Cross-scale dynamics; (3) Driving forces; (4) Spatial interaction and neighbourhood effects; (5) Temporal dynamics; and (6) Level of integration. For each of these concepts an overview is given of the variety of methods used to implement these concepts in operational models. It is concluded that a lot of progress has been made in building land use change models. However, in order to incorporate more aspects important to land use modelling it is needed to develop a new generation of land use models that better address the multi-scale characteristics of the land use system, implement new techniques to quantify neighbourhood effects, explicitly deal with temporal dynamics and achieve a higher level of integration between disciplinary approaches and between models studying urban and rural land use changes. If these requirements are fulfilled models will better support the analysis of land use dynamics and land use policy formulation.

## Introduction

Models of land use change are tools to support the analysis of the causes and consequences of land use changes in order to better understand the functioning of the land use system and to support land use planning and policy. Models are useful for disentangling the complex suite of socio-economic and biophysical forces that influence the rate and spatial pattern of land use change and for estimating the impacts of changes in land use. Furthermore, models can support the exploration of future land use changes under different scenario conditions. Summarising, land use models are useful and reproducible tools, supplementing our existing mental capabilities to analyse land use change and to make more informed decisions (Costanza and Ruth, 1998).

The objective of this paper is to review the currently available approaches to model land use change in order to identify the priorities for future land use change research. We limit the discussion to descriptive models that aim at simulating the functioning of the land use system and the spatially explicit simulation of near future land use patterns. Another group of land use models are prescriptive models aiming at the calculation of optimised land use configurations that best match a set of goals and objectives. In this paper we will not further discuss prescriptive models but refer the reader to reviews by Van Ittersum et al. (1998) and Briassoulis (2000).

The group of descriptive land use change models represents a wide variety of modelling traditions and theoretical backgrounds. Reviews that characterise and classify land use models are provided by Lambin (1997) and Kaimowitz and Angelsen (1998) for deforestation, Miller et al. (1999) for integrated urban models, Lambin et al. (2000a) for agricultural intensification models, and by Bockstael and Irwin (2000) for land use models based on economic theory. Agarwal et al. (2001) reviews a selection of 19 models based on their spatial, temporal and human-choice complexity. Briassoulis (2000) gives a more extended review of all types of land use models. In this paper we will not repeat such a characterisation and classification of models but focus our discussion on a number of features of land use systems that need to be taken into account by land use modellers. Based on the discussion of these features we will show, for a wide range of models, how these features are presently implemented in land use models, discuss the (dis)advantages of these methods, and identify the research requirements for improving land use models.

## Land use change modelling concepts and implementation

This section is based on a discussion of six features that are considered to be of importance to modelling land use change: (1) Level of analysis; (2) Cross-scale dynamics; (3) Driving factors; (4) Spatial interaction and neighbourhood effects; (5) Temporal dynamics; and (6) Level of integration. These features have been mentioned frequently in a series of recent papers, reports and workshops by members of the Land Use and Land Cover Change (LUCC) research community (Turner II et al., 1995; Moran, 2000; Lambin et al., 2000b; Geist et al., 2001; McConnell and Moran, 2001; van der Veen and Rotmans, 2001; Veldkamp and Lambin, 2001). For each of the features a description of the underlying theory and rationale is given followed by an overview of the practical implementation in models. No complete descriptions of the individual models are given, instead, only the implementation of the specific features is described. This discussion therefore solely reviews the methods and applications available for addressing these specific features without providing a full description of the model or model category. The reader is referred to publications that describe the individual models for more details on the functioning of the model as a whole, its technical specification and the specific applications. A few, well known models that are frequently referred to in this paper, are listed in Table 1. These models are representative for different modelling approaches and the reader might wish to consults some of the references to model documentation.

*Level of analysis*

*Theory and rationale*

Scientific discipline and tradition have caused two distinctly different approaches to emerge in the field of land use studies. Researchers in the social sciences have a long tradition of studying individual behaviour at the micro-level, some of them using qualitative approaches (Bilsborrow and Okoth Ogondo, 1992; Bingsheng, 1996) and others using the quantitative models of micro-economics and social psychology. Rooted in the natural sciences rather than the social, geographers and ecologists have focussed on land cover and land use at the macro-scale, spatially explicated through remote sensing and GIS, and using macro-properties of social organisation in order to identify social factors connected to the macro-scale patterns. Due to the poor connections between spatially explicit land use studies and the social sciences, the land use modellers have a hard time to tap into the rich stock of social science theory and methodology. This is compounded by the ongoing difficulties within the social sciences to interconnect the micro and macro levels of social organisation (Watson, 1978; Coleman, 1990).

*Implementation in models*

*Micro-level perspective*. Models based on the micro-level perspective are all based on the simulation of the behaviour of individuals and the upscaling of this behaviour, in order to relate it to changes in the land use pattern. Two of the most important approaches will be discussed here: multi-agent simulation and micro-economic models.

Multi-agent models simulate decision-making by individual agents of land use change explicitly addressing interactions among individuals. The explicit attention for interactions between agents makes it possible for this type of models to simulate emergent properties of systems. Emergent properties are properties at the macro-scale that are not predictable from observing the micro-units in isolation. Such properties 'emerge' if there are important interactions between the micro-units that feedback on the micro-behaviour. If the decision rules of the agents are set such that they sufficiently look like human decision-making they can simulate behaviour at the meso-level of social organisation, i.e. the behaviour of in-homogeneous groups of actors.

Multi-agent models are part of distributed artificial intelligence methods. An agent is "a real or abstract entity that is able to act on itself and on its environment; which can, in a multi-agent universe, communicate with other agents; and whose behaviour is the result of its observations, its knowledge and its interactions with other agents" (Sanders et al., 1997). Multi-agent models can shed light into the degree in which system-level properties simply emerge from local evolutionary forces, and the degree to which those local processes are influenced and shaped by their effect on the persistence and continued functioning of ecosystems or the biosphere (Levin, 1998). Until a couple of years ago mathematical and computational capacity limited the operation of this type of models. Nowadays, different research teams have developed systems to simulations, most often for totally different purposes than land use change modelling (DIAS, 1995; Cubert et al., 1997; Lutz, 1997). The best known system that can be adapted for ecological and land use simulation is the SWARM environment that was developed at the Santa Fe Institute (Hiebler et al., 1994). Such models should be based on detailed information of socio-economic behaviour under different circumstances (Conte et al., 1997; Tesfatsion, 2001). This information can be obtained from extensive field studies of sociologists; the relative importance of the different processes influencing land use change can be tested by sensitivity analysis and a link to higher levels of aggregation can be made. The simulated behaviour at aggregate levels can help the development of new theories linking individual behaviour to collective behaviour. Such meso-level studies typically show how individual people interact to form groups and organise collective action, and how such collective decisions vary with group size, collective social capital, and so on.

Most current multi-agent models are only able to simulate very simplified, hypothetical landscapes, as the number of interacting agents and variety of factors that need to be taken into account, is still too large to make comprehensive models (Kanaroglou and Scott, 2001). An example of a multi-agent model for an hypothetical landscape is the SIMPOP model which simulated the evolution of settlement and urban transition (Bura et al., 1996; Sanders et al., 1997). Efforts are currently

*Table 1.* Characteristics of a number of representative land use change models.

| Model name | Classification according to Lambin et al. (2000a) | References | Application area + spatial and temporal extent | Land use change | Description |
|---|---|---|---|---|---|
| Urban Growth Model UGM / SLEUTH | Cellular Automata model | Clarke and Gaydos (1998); Candau et al. (2000) | San Francisco and Washington/Baltimore region, Mid Atlantic Region. Possibility for urban regions in general. Temporal: 1900–2100 | Urbanisation | Self-modifying cellular automata model. Four processes included: spontaneous growth (neighbourhood; suitability); diffusive growth (slope determined); edge growth (neighbourhood); road influenced growth. Calibration is used to determine relative influence. SLEUTH includes 'deltatrons' to enforce spatial and temporal autocorrelation |
| Constrained CA models: RamCo, LOV, MODULUS, SIMLUCIA | Cellular Automata model and/or Integrated/Hybrid model | White and Engelen (2000) | St. Lucia (Caribean Island); Netherlands; City of St. John's, Newfoundland, Canada; Ujung Pandang in south-west Sulawesi (Indonesia) Temporal: ± 30 years | Multiple land use types | Constrained cellular automata: demands for land use are calculated in sectoral models at an aggregated spatial level (LOV: gravity model) and allocated using cellular automata. The cellular automata are quantified using expert knowledge |
| CLUE and CLUE-S | Empirical-statististical model and/or Simulation model | Veldkamp and Fresco (1996), Verburg et al. (1999a), Verburg et al. (2002) | Continental level: Central-America, China; National level: Ecuador, Central-American countries; Sub-national level: Philippines, Indonesia, Costa-Rica. Temporal: ± 20 years | Multiple land use types | Dynamic simulation model using empirically derived relations between land use change and driving forces from cross-sectional analysis at multiple scales. |
| IIASA-LUC | Integrated/Hybrid model and/or Optimisation model | Fischer and Sun (2001) | China: agro-ecological analysis for detailed pixels; integrated analysis for 8 regions. Temporal: projections to 2025. | Multiple land use types | General Equilibrium Model based on multi-sector input-output tables and detailed agro-ecological characterisation. |
| Cormas: a Multi-Agent Simulation Software for Renewable Resource Management | Agent-based model | Bousquet et al. (1998), Barreteau and Bousquet (2000), Rouchier et al. (2001) | Different case-studies at village level Temporal: variable | Specific land use types relevant for application | Multi-agent simulations based on behaviour of individuals towards other individuals and natural resources. |
| PLM: Patuxent landscape model | Empirical-statistical model and/or Simulation model | Irwin and Geoghegan (2001); Bockstael (1996); Voinov et al. (1999) | Patuxent watershed (several US counties); based on integrated ecological models for the Everglades. Temporal: decades | Urbanisation, habitat change | Integrated economic/ecological model. Land use change allocation is based on economic modelling (hedonic modeling combining distance and location operators). The neighbourhood of the location is taken into account by quantifying its effect on land value. |

underway to build operational multi-agent models for realistic land use change simulations (Bousquet et al., 1998; Vanclay, 1998; Manson, 2000; Barreteau and Bousquet, 2000; Berger, 2001; Polhill et al., 2001; Rouchier et al., 2001). The validity of these models will depend on the strength of the model of human decision-making and interaction. The challenge in this area is to obtain sufficient data at the individual/household level to develop a well-parameterised and validated model of decision-making. Observed land-use or land-cover change outcomes are not sufficient to validate such a model.

A wide variety of land use models exist that are based on micro-economic theory, reviewed by Kaimowitz and Angelsen (1998) and Irwin and Geoghegan (2001). Most economic land use change models begin from the viewpoint of individual landowners who make land use decisions with the objective to maximise expected returns or utility derived from the land, and use economic theory to guide model development, including choice of functional form and explanatory variables (Ruben et al., 1998). The assumptions of behaviour are valid for the micro level. This limits these models to applications that are able to discern all individuals. Difficulties arise from scaling these models, as they have primary been designed to work at the micro-level. Jansen and Stoorvogel (1998) and Hijmans and Van Ittersum (1996) have shown the problems of scale that arise when this type of models are used at higher aggregation levels.

*Macro-level perspective.* Studies that use the macro-level perspective are often based on macro-economic theory or apply the systems approach. A typical example of an economic model that uses the macro-perspective is the LUC model of IIASA developed for China (Fischer and Sun, 2001). The model is designed to establish an integrated assessment of the spatial and intertemporal interactions among various socio-economic and biophysical forces that drive land use and land cover change. The model is based on recent advances in applied general equilibrium modelling. Applied general equilibrium modelling uses input–output accounting tables as the initial representation of the economy and applies a dynamic welfare optimisation model. In mathematical terms, the welfare optimum levels of resource uses and transformations are a function of the initial state of the economy and resources, of the parameterisation of consumer preferences and production relations, and of (exogenously) specified dynamics and constraints such as population growth and climate changes. The model has a low spatial resolution (8 regions in China) and is very data-demanding due to the multiple sectors of the economy that are taken into account.

Other land use change models are based on an analysis of the spatial structure of land use; therefore, they are not bound to the behaviour of individuals or sectors of the economy. Among these models are the CLUE model (Veldkamp and Fresco, 1996; Verburg et al., 1999a); GEOMOD2 (Pontius et al., 2001); LOV (White and Engelen, 2000) and LTM (Pijanowski et al., 2000). The functioning of some of these models will be clarified in the next sections.

## *Cross-scale dynamics*

### *Theory and rationale*

The discussion on the micro- and macro-level research perspective already referred to the issue of scale. Scale is the spatial, temporal, quantitative, or analytic dimension used by scientists to measure and study objects and processes (Gibson et al., 2000). All scales have extent and resolution. Extent refers to the magnitude of a dimension used in measuring (e.g. area covered on a map) whereas resolution refers to the precision used in this measurement (e.g. grain size). For each process important to land use and land cover change, a range of scales may be defined over which it has a significant influence on the land use pattern (Meentemeyer, 1989; Dovers, 1995). These processes can be related to exogenous variables, the so-called 'driving forces' of land use change. Often, the range of spatial scales over which the driving forces and associated land use change processes act correspond with levels of organisation. Level refers to level of organisation in a hierarchically organised system and is characterised by its rank ordering in the hierarchical system. Examples of organisational levels include organism or individual, ecosystem, landscape and national or global political institutions. Many interactions and feedbacks between these processes occur at different levels of organisation. Hierarchy theory suggests that processes at a certain scale are constrained by the environmental conditions at levels immediately above and below the referent level, thus producing a constraint 'envelope' in which the process or phenomenon must remain (O'Neill et al., 1989).

Most land use models are based on one scale or level exclusively. Often, this choice is based on arbitrary, subjective reasons or scientific tradition (i.e. micro- or macro-level perspective) and not reported explicitly (Watson, 1978; Gibson et al., 2000). Models that rely on geographic data often use a regular grid to represent all data and processes. The resolution of analysis is determined by the measurement technique or data quality instead of the processes specified. Other approaches chose a specific level of analysis, e.g. the household level, which can be the level of the processes studied in the particular case-study. For specific data sets optimal levels of analysis might exist where predictability is highest (Veldkamp and Fresco, 1997; Goodwin and Fahrig, 1998), unfortunately these levels are not consistent through analysis. Therefore, it might be better not to use a priori levels of observation, but rather extract the observation levels from a careful analysis of the data (Gardner, 1998; O'Neill and King, 1998).

The task of modelling sociocultural forces is difficult because humans act both as individual decision makers (as assumed in most econometric models) and as members of a social system. Sometimes these roles have conflicting goals. Similar scale dependencies are found in biophysical processes: the aggregated result of individual processes cannot always be straightforwardly determined. Rastetter et al. (1992) and King et al. (1989) point out that the simple spatial averaging of fine-scale non-linear functional forms of ecosystem relationships, or of the data required to compute the spatially aggregate versions of such functional forms, can lead to substantial aggregation errors. This is widely known as the 'fallacy of averages'. Besides these fundamental issues of spatial scale another scaling issue is related to scales of observation, and is, therefore, more related to practice. Due to our limited capacities for the observation of land use, extent and resolution are mostly linked. Studies at large spatial extent invariably have a relatively coarse resolution, due to our methods for observation, data analysis capacity and costs. This implies that features that can be observed in case studies with a small extent are generally not observable in studies for larger regions. On the other hand, due to their small extent, local studies often lack information about the context of the case study area that can be derived from the coarser scale data. Scales of observation usually do not correspond with the scale/level at which the process studied operates, causing improper determination of the processes (Blöschl and Sivapalan, 1995; Schulze, 2000).

The discussion of scale issues can be summarised by the three aspects of scaling important for the analysis of land use change:

- Land use is the result of multiple processes that act over different scales. At each scale different processes have a dominant influence on land use.
- Aggregation of detailed scale processes does not straightforwardly lead to a proper representation of the higher-level process. Non-linearity, emergence and collective behavior cause this scale-dependency.
- Our observations are bound by the extent and resolution of measurement causing each observation to provide only a partial description of the whole multi-scale land use system.

*Implementation in models*

Although the importance of explicitly dealing with scaling issues in land use models is generally recognised, most existing models only take a single scale of analysis into account. Especially economic models tend to aggregate individual action but neglect the emergent properties of collective values and actions (Riebsame and Parton, 1994). Approaches that do implement multiple scales can be distinguished by the implementation of a multi-scale procedure in either the structure of the model or in the quantification of the driving variables. The latter approach acknowledges that different driving forces are important at different scales and it takes explicit account of the scale dependency of the quantitative relation between land use and its driving forces. Two different approaches of quantifying the multi-scale relations between land use and driving forces are known. The first is based on data that are artificially gridded at multiple resolutions; at each individual resolution the relations between land use and driving forces are statistically determined (Veldkamp and Fresco, 1997; de Koning et al., 1998; Walsh et al., 1999, 2001; Verburg and Chen, 2000). The second approach uses multi-level statistics (Goldstein, 1995). The first applications of multi-level statistics were used in the analysis of social science data of educational performances in schools. Aitkin et al. (1981) analysed the individual performance of children, exposed to different styles of teaching, in the context of the class they belonged to and demonstrated that when the analysis accounted properly for the grouping of children into classes, the significant differences between children disappeared and the children that were exposed to different teaching style could not be shown to differ from the others. More recently it was found that this technique for the analysis of hierarchically structured data could also be useful for the analysis of land use, taking different driving forces at different levels of analysis into account. Hoshino (2001) analysed the land use structure in Japan by taking different factors at each level into account using data for municipalities (level-1 units) nested within prefectures (level-2 units). A similar approach was followed by Polsky and Easterling (2001) for the analysis of the land use structure in the Great Plains of the USA. Also in this study administrative units at different hierarchical levels were used.

A number of land use change models are structured hierarchically, thus taking multiple levels into account. In its simplest form the total amount of change is determined for the study area as a whole and allocated to individual grid-cells by adapting the cut-off value of a probability surface (Pijanowski et al., 2000). The demand-driven nature of land use change could be used as a rationale for this approach. Population and economic developments change the demand for different land use types at aggregate levels whereas the actual allocation of change is determined by regional and local conditions. This structure is also implemented in the CLUE modelling framework (Veldkamp and Fresco, 1996). However, this framework uses three scales: the national scale for demand calculations and two spatially explicit scales to take driving forces at different scales into account (Figure 1). Apart from the top–down allocation a bottom-up algorithm is implemented to feed back local changes to the regional level.

Pure cellular automata models determine the number of cells that change in each step of the simulation endogenously based on cellular dynamics. This bottom-up approach might not be very suitable for land use systems where the area of land use change is at least partly determined by the demand for the activity that is carried out on the cells. Within the models developed by White and Engelen (2000), White et al. (1997) and Engelen et al. (1995) use is made of constrained cellular

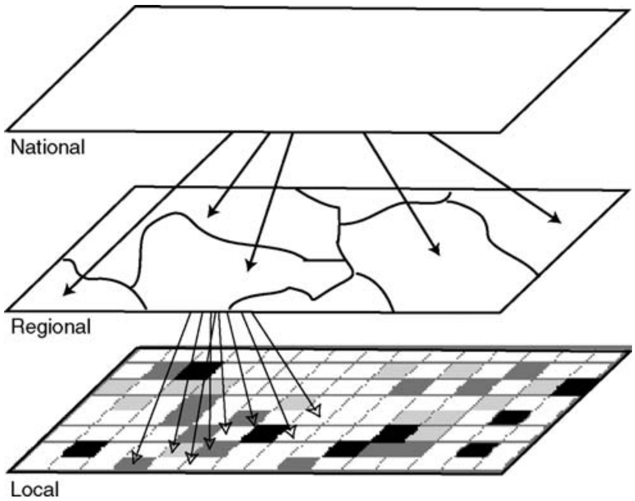


*Figure 1.* Top–down allocation procedure.

automata. In such a constrained cellular automata model a higher level constraint is used to regulate the quantity of change at the cell-level. In the application for the Netherlands (White and Engelen, 2000) national level projections for population and sectoral economic activity are translated to 40 urban-centred economic regions (COROPs) where they are converted via productivity functions into regional demands for cell space for the land uses corresponding to each activity. These demands constitute the constraints for the grid-based allocation with cellular automata, which then determines the actual land use patterns. A feedback to the regional level is incorporated through the influence of land use densities and suitabilities at cell level on the regional demand in the next iteration.

## *Driving forces*

### *Theory and rationale*

A unifying hypothesis that links the ecological and social realms, and an important reason for pursuing integrated modelling, is that humans respond to cues both from the physical environment and from their sociocultural context and behave to increase both their economic and sociocultural well-being. Land use change is therefore often modelled as a function of a selection of socio-economic and biophysical variables that act as the so-called 'driving forces' of land use change (Turner II et al., 1993). Driving forces are generally subdivided in three groups (Turner II et al., 1995): socio-economic drivers, biophysical drivers and proximate causes (land management variables). Although biophysical factors mostly do not 'drive' land use change directly, they can cause land cover changes (e.g. through climate change) and they influence land use allocation decisions (e.g. soil quality). At different scales of analysis different driving forces have a dominant influence on the land use system: at the local level this can be the local policy or the presence of small ecological valuable areas whereas at the regional level the distance to the market, port or airport might be the main determinant of the land use pattern.

Driving forces are most often considered exogenous to the land use system to facilitate modelling. However, in some cases this assumption hampers the proper description of the land use system, e.g. if the location of roads and land use decisions are jointly determined. Population pressure is often considered to be an important driver of deforestation (Pahari and Marai, 1999), however, Pfaff (1999) points out that population may be endogenous to forest conversion, due to unobserved government policies that encourage development of targeted areas, or that population may be collinear with government policies. If the former is the case, then including population as an exogenous 'driver' of land use change would produce a biased estimate and lead to misleading policy conclusions. If the latter were the case, then the estimates would be unbiased, but inefficient, leading to a potential false interpretation of the significance of variables in explaining deforestation. Other examples of endogeneity of driving forces in land use studies are given by Chomitz and Gray (1996), Mertens and Lambin (2000) and Irwin and Geoghegan (2001).

The temporal scale of analysis is important in deciding which driving forces should be endogenous to the model. In economic models of land use change demand and supply functions are the driving forces of land use change. Whereas prices at the short term can be considered exogenous to land use change they are endogenous on longer time spans.

### *Implementation in models*

All models address in some way or other the issue of driving forces of land use change. For model implementation two aspects of the use of driving forces are of importance: their selection and the quantification of the relations between driving forces and land use change.

*Selection of driving forces.* The selection of the driving forces is very much dependent on the simplification made and the theoretical and behavioural assumptions used in modelling the land use system. In most economic approaches optimisation of utility is the assumed behaviour, leading to bid-rent models. Most economic models of land use change are, therefore, related to the land rent theories of Von Thünen and Ricardo. Any parcel of land, given its attributes and location, is assumed to be allocated to the use that earns the highest rent (e.g. Jones and O'Neill (1992) and Chomitz and Gray (1996)). In its most simple form, the monocentric model, the location of a central city or business district to which households commute, is the main factor determining the rent of a parcel. All other features of the landscape are ignored. Individual households optimise their location by trading off accessibility to the urban centre and land rents, which are bid up higher for locations closer to the centre. The resulting equilibrium pattern of land use is described by concentric rings of residential development around the urban centre and decreasing residential density as distance from the urban centre increases. In this case 'distance to urban centre' is the most important driving variable. The limitation of the monocentric model is partly due to its treatment of space, which is assumed to be a 'featureless plain' and is reduced to a simple measure of distance from the urban centre. Others explains spatial variability in land rent by differences in land quality that arise from a heterogeneous landscape, but abstract from any notion of relative location leading to spatial structure. Many models that try to explain land values (for example, hedonic models) combine the two approaches by including variables that measure the distance to urban center(s) as well as specific locational features of the land parcel (Bockstael, 1996).

Models of urban and peri-urban land allocation are, generally, much more developed than their rural counterpart (Riebsame and parton, 1994). More recent urban models are no longer solely based upon economic modelling using either equilibrium theory or spatial disaggregated intersectoral input–output approaches. Rather than utility functions they use discrete choice modelling through logit models (Landis, 1995; Alberti and Waddell, 2000). This also allows a greater flexibility in behavioural assumptions of the actors. Conventional economic theory makes use of rational actors, the *Homo economicus*, to study human behaviour. This powerful concept of the rational actor is not always valid and various modifications to this conception of human choice are suggested (Rabin, 1998; Janssen and Jager, 2000). Examples of such modifications of the concept of the rational actor include the difficulty that people can have evaluating their own preferences, self-control problems and other phenomena that arise because people have a short-run propensity to pursue immediate gratification and the departure from pure self-interest to pursue "other-regarding" goals such as fairness, reciprocal altruism and revenge.

Models that integrate the analysis of different land use conversions within the same model commonly use a larger set of driving forces. Apart from the drivers that determine urban land allocation, such as land value and transportation conditions, they need information on the suitability of the land for agricultural production (e.g. soil quality and climatic variables), market access a.s.o. Also the extent of the study area influences the selection of variables. In larger areas it is common that a larger diversity of land use situations is found, which requires a larger variety of driving forces to be taken into account, whereas in a small area it might be only a few variables that have an important influence on land use.

*Quantification of relations between land use and driving forces*. Three different approaches to quantify the relations between land use change and its driving forces can be distinguished. The first approach tries to base all these relations directly on the processes involved, using theories and physical laws. Examples are economic models based on economic input-output analysis (Waddell, 2000; Fischer and Sun, 2001) or utility optimisation (Ruben et al., 1998). For integrated land use change analysis this approach is often not very successful due to the difficulty of quantifying socio-economical factors without the use of empirical data. Therefore, the second approach uses empirical methods to quantify the relations between land use and driving forces instead. Many econometric models rely therefore on statistical techniques, mainly regression, to quantify the defined models based on historic data of land use change (Bockstael, 1996; Chomitz and Gray, 1996; Geoghegan et al., 1997; Pfaff, 1999). Also other models, not based on economic theory, use statistical techniques to quantify the relationships between land use and driving forces (Veldkamp and Fresco, 1996; Turner et al., 1996; Mertens and Lambin, 1997; Wear and Bolstad, 1998; Mertens and Lambin, 2000; Pijanowski et al., 2000; Pontius and Schneider, 2001; Pontius et al., 2001; Serneels and Lambin, 2001 and many more). Most of these approaches describe historic land use conversions as a function of the changes in driving forces and location characteristics. This approach often results in a relatively low degree of explanation due to the relative short time-period of analysis, variability over this time period and a relatively small sample size (Hoshino, 1996; Veldkamp and Fresco, 1997). Cross-sectional analysis of the actual land use pattern, which reflects the outcome of a long history of land use changes, results in more stable explanations of the land use pattern (de Koning et al., 1998; Hoshino, 2001). A drawback of the statistical quantification is the induced uncertainty with respect to the causality of the supposed relations.

A third method for quantifying the relations between driving forces and land use change is the use of expert knowledge. Especially in models that use cellular automata expert knowledge is often used. Cellular automata models define the interaction between land use at a certain location, the conditions at that location and the land use types in the neighbourhood (Engelen et al., 1995; Clarke and Gaydos, 1998; Wu, 1998; Hilferink and Rietveld, 1999). The setting of the functions underlying these cellular automata is hardly ever documented and largely based upon the developer's knowledge and some calibration.

The difficulties in quantified modelling of complex systems has lead to the development of qualitative modelling which avoids quantification when quantitative information is not available. This method is exemplified by the Syndromes approach (Petschel-Held et al., 1999). This is not a real land use change model, but the approach is able to indicate to what extent a certain 'syndrome', which is closely related to land use change, is active in an area. Directly relevant for land use change are e.g. an urban sprawl syndrome and a green revolution syndrome. The approach is dynamic, the intensity of occurrence of the different syndromes in time can be forecasted. Although spatially explicit, the present extent is global with associated coarse resolution. Much needs to be done before these techniques become useful for regional land use change modelling.

*Spatial interaction and neighbourhood effects*

*Theory and rationale*

Land use patterns nearly always exhibit spatial autocorrelation. The explanation for this autocorrelation can be found, for a large part, in the clustered distribution of landscape features and gradients in environmental conditions that are important determinants of the land use pattern. Another reason for spatially autocorrelated land use patterns are the spatial interactions between land uses types itself: urban expansion is often situated right next to the already existing urban area, as is the case for business parks etc. Scale economies can provide an explanation for such patterns. In agricultural landscapes adoption of particular farming technologies or cultivation patterns might also exhibit observable spatial effects. Other land use types might preferably be located at some distance from each other, e.g. an airport and a residential area, leading to negative spatial autocorrelation. The importance of such structural spatial dependencies is increasingly recognised by geographers and economists. Spatial statistical techniques are developed to quantify spatial dependencies in econometrics (Anselin, 1988; Bell and Bockstael, 2000).

Spatial autocorrelation in land use patterns is scale dependent. At an aggregate level residential areas are clustered, having a positive spatial autocorrelation. However, Irwin and Geoghegan (2001) found that at the scale of individual parcels in the Patuxent watershed there was evidence of a negative spatial interaction among developed parcels, implying that a developed land parcel 'repels' neighbouring development due to negative spatial externalities that are generated from development, e.g., congestion effects. The presence of such an effect implies that, ceteris paribus, a parcel's probability of development decreases as the amount of existing neighbouring development increases. The existence of different causal processes at different scales means that spatial interactions should again be studied at multiple scales while relations found at a particular scale can only be used at that scale.

Spatial interactions can also act over a larger distances: a change in land use in the upstream part of a river might affect land use in the downstream part through sedimentation of eroded materials leading to a functional connectivity between the two areas. Another example of spatial connectivity is the migration of companies from one part of the country to another part when all available land area is occupied at the first location. This type of connectivity is a result of a network interaction. We can distinguish three types of networks (Dupuy, 1991):

- Physical networks. These networks (roads, ecological corridors, communication lines, etc.) form the spatial conditions for flows of people, animals, goods, energy, water etc. Flows are intricately associated with functions, which may be interpreted as static forms of land use e.g. places for work, recreation, habitation by people, flora or fauna.
- Settlement networks. These networks result from the specific demands economic, social and ecological land use functions exert on their spatial positioning with respect to the above-mentioned physical networks.
- Interaction networks. Companies, households, plant- and animal species all maintain relations with functions on other locations. These functional relations are influenced by the physical networks and associated land use patterns.

Analysis of these networks is essential to understand the spatial structure of land use. Globalisation of the economy will cause these networks to have a large spatial extent, leading to connectivity in land use between continents.

*Model implementation*

Cellular automata are a common method to take spatial interactions into account. They have been used in studies of urban development (White et al., 1997; Clarke and Gaydos, 1998; Wu, 1999; Li and Yeh, 2000) but have now also been implemented in land use models that are able to simulate multiple land use types (White and Engelen, 2000). Cellular automata calculate the state of a pixel based on its initial state, the conditions in the surrounding pixels (Figure 2), and a set of transition rules. Although very simple, they can generate a very rich behaviour (Wolfram, 1986).

The Urban Growth Model (Clarke and Gaydos, 1998), a classical cellular automata model for urban expansion was combined with so-called 'deltatrons' that enforce even more spatial interaction than achieved with cellular automata alone in order to achieve the desired degree of spatial and temporal autocorrelation (Candau, 2000).

Neighbourhood interactions are now also increasingly implemented in econometric models of land use change. Although this implementation can be done through advanced measures of autocorrelation (Bell and Bockstael, 1988; Walker et al., 2000; Brown et al., 2002), more often simple measures of neighbourhood composition, e.g. the area of the same land use type in the neighbourhood, are included as explanatory factors in regression models explaining land use change (Geoghegan et al., 1997; Nelson and Hellerstein, 1997; Munroe et al., 2001).

A different method for implementing spatial interaction, especially interaction over larger distances, is the use of network analysis. In many models driving forces have been included that indicate travel times or distances to markets, ports and other facilities that are important to land use. Especially models that are based on economic theory take the travel costs to a market into account (Jones, 1983). Most often simple distance measures are used. However, it is also possible to use sophisticated techniques to calculate travel times/costs and use the results to explain the land use structure. This type of calculations are often included in combined urban-transportation models (Miller et al., 1999).

Spatial interactions can also be generated more indirectly through the hierarchical structure of the

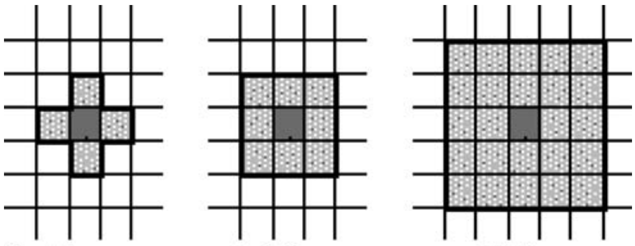


*Figure 2.* Alternative neighbourhoods used in cellular automata models.

model. Multi-scale models like CLUE (Veldkamp and Fresco, 1996) and Environment Explorer (White and Engelen, 2000) can generate spatial interactions through the feedback over a higher scale. If a certain, regional, demand cannot be met at the local level (due to a location condition or policy, e.g. nature reserve), it will feedback to the regional level and allocation to another location will proceed. This type of modelling can indicate the trade-off of a measure at a certain location for the surrounding area.

*Temporal dynamics: trajectories of change*

*Theory and rationale*

The previous sections all dealt with spatial features of land use change. Much of the issues addressed are also relevant for the temporal dimension of land use change. Changes are often non-linear and thresholds play an important role. Non-linear behaviour asks for dynamic modelling with relatively short time steps. Only then land use change analysis can take into account the path-dependency of system evolution, the possibility of multiple stable states, and multiple trajectories. Land use change cannot be simply explained as the equilibrium result of the present set of driving forces. In other words, land use change may be dependent on initial conditions, and small, essentially random events may lead to very different outcomes, making prediction problematic. Exemplary is the effect of transportation infrastructure on the pattern of development. Road expansion and improvement not only lead to more development but may also lead to a different pattern through a reorganisation of the market structure, which then feeds back to further infrastructure development. Thus, certain trajectories of land use change may be the result of "lock in" that comes from systems that exhibit autocatalytic behaviour.

Connected to the temporal dimension of models is the issue of validation. Validation of land use change models is most often based on the comparison of model results for a historic period with the actual changes in land use as they have occurred. Such a validation makes it necessary to have land use data for another year than the data used in model parameterisation. The time period between the 2 years for which data are available should be sufficient to actually compare the observed and simulated dynamics. Ideally this time period should be as long as the period for which future scenario simulations are made. Such data are often difficult to obtain and even more often data from different time periods are difficult to compare due to differences in the classification scheme of land use maps or the resolution of remote sensing data. Methods for validation of model performance should make a clear distinction in the model performance concerning the quantity of change and the quality of the spatial allocation of the land use changes. Appropriate methods for validation of land use change models are described by Pontius (2000), Costanza (1989) and by Pontius and Schneider (2001).

*Implementation in models*

In a number of models temporal dynamics are taken into account using initial land use as a criterion for the allowed changes. Cellular automata do this explicitly in the decision rules that determine the conversion probability. In the CLUE-S model (Verburg et al., 2001) a specific land use conversion elasticity is given to each land use type. This elasticity will cause some land use types to be more reluctant to change (e.g. plantations of permanent crops) whereas others easily shift location (e.g. shifting cultivation). In the SLEUTH urban growth model (Candau, 2000) even more explicit functions to enforce temporal autocorrelation are implemented that also take the 'age' of a new urban development centre into account. The economic land allocation model of the Patuxent Landscape Model (Irwin and Geoghegan, 2001) also explicitly considers the temporal dimension. The land use conversion decision is posed as an optimal timing decision in which the landowner seeks to maximise expected profits by choosing the optimal time, in which the present discounted value of expected returns from converting the parcel to residential use are maximized. These latter two model implementations of temporal dynamics already take account of a longer time span than most models, which only account for the initial state. However, most models are currently unable to account for land use change as influenced by land use histories that extent over longer time scales. For a proper description of certain land use types, e.g. long fallow systems, or feedback processes such as nutrient depletion upon prolonged use of agricultural land, incorporation of land use histories could make an important improvement (Priess and Koning, 2001).

The combination of temporal and spatial dynamics often causes a complex, non-linear behaviour. However, a large group of models does not account at all for temporal dynamics. These models are simply based on an extrapolation of the trend in land use change through the use of a regression on this change (Mertens and Lambin, 2000; Pijanowski et al., 2000; Schneider and Pontius, 2001; Serneels and Lambin, 2001; Geoghegan et al., 2001). This type of models are therefore not suitable for scenario analysis, as they are only valid within the range of the land use changes on which they are based. The validity of the relations is also violated upon a change in competitive conditions between the land use types, e.g. caused by a change in demand. This critique does not apply to all models based on statistical quantification. When these models are based on the analysis of the structure (pattern) of land use instead of the change in land use and are combined with dynamic modelling of competition between land use types, they have a much wider range of applications.

Land use change decisions are made within different time scales, some decisions are based on short term dynamics (such as daily weather fluctuations), others are only based on long-term dynamics. Most land use models use annual time steps in the calculations. This means that short-term dynamics are often ignored or, when they can have an additive effect, are aggregated to yearly changes. However, this aggregation can hamper the linkage with the actual decision making taking at shorter time scales. The need for multi-scale temporal models was acknowledged in transportation modelling, where short-term decisions depend on the daily activity schedules and unexpected events (Arentze and Timmermans, 2000; Arentze et al., 2001). The link between this type of transportation models and land use is straightforward. If changes in the daily activity schedule are required on a regular basis individuals will need to adjust their activity agenda or the factors affecting the agenda, for example by relocation. Such a decision is a typical long-term decision, evolving from regular changes in short-term decisions.

A quick scan through the land use modelling literature mentioned in this paper reveals that only a relatively small number of all land use change models have been validated on the basis of temporal data, e.g. Kok et al. (2001), Schneider and Pontius (2001), Verburg et al. (1999b). Many models have not been validated at all.

*Level of integration*

*Theory and rationale*

Land use systems are groups of interacting, interdependent parts linked together by exchanges of energy, matter, and information. Land use systems are therefore characterised by strong (usually non-linear) interactions between the parts, complex feedback loops that make it difficult to distinguish cause from effect, and significant time and space lags, discontinuities, thresholds, and limits (Costanza and Wainger, 1993). This complexity makes the integration of the different sub-systems one of the most important issues in land use modelling. Generally speaking, two approaches for integration can be distinguished that differ in the degree of integration. The first approach involves a rather loose coupling of sub-systems that are separately analysed and modelled. To allow the dissection of system components, it must be assumed that interactions and feedbacks between system elements are negligible or the feedbacks must be clearly defined and information between the sub-systems must be achieved through the exchange of input and output variables between the sub-system models (Figure 3). The second approach takes a more holistic view. Instead of focussing all attention on the description of the sub-systems explicit attention is given to the interactions between the subsystems. In this approach more variables are endogenous to the system and are a function of the interactions between the system components. The approach chosen is very much dependent on the time-scale (endogeneity assumptions) and the purpose for which the model is built. Generally speaking, integration has only an added value as compared with disciplinary research when feedbacks and interactions between the sub-systems are explicitly addressed. An appropriate balance should be found, as the number of interactions that can be distinguished within the land use system is very large and taking all of those into account could lead to models that are too complex to be operational.

*Model implementation*

The group of models that are commonly referred to as integrated assessment models are models that attempt to portray the social, economic, environmental and institutional dimensions of a problem (Rotmans and van Asselt, 2001). In practice, most integrated assessment models are directed to the modelling of climate change and its policy dimensions (review by Schneider (1997). Some integrated assessment models, e.g. the IMAGE2

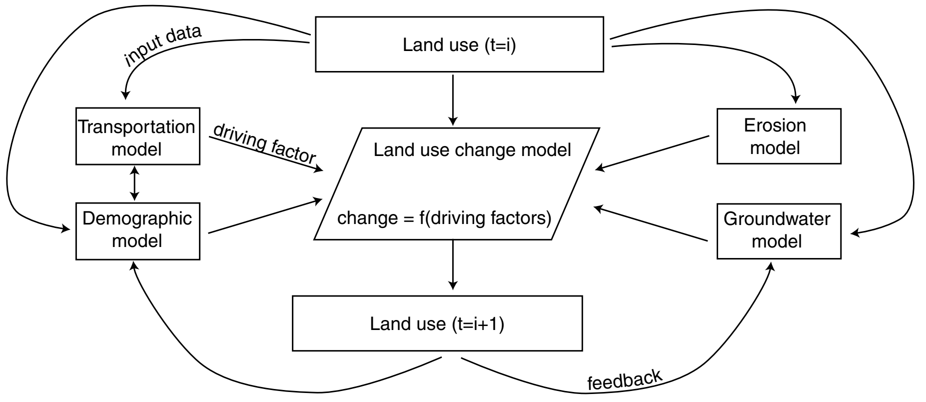


*Figure 3.* Interaction between the land use change model and models describing sub-systems.

model (Alcamo et al., 1998) contain land use modules, but these are often much less elaborated than models that are specifically developed for land use studies. For integrated assessment models the same conclusions hold as for land use models: many large models consist of linked subsystems that are not fully integrated. This means that these models are complicated but not complex, as a result of which their dynamic behaviour is almost linear and does not adequately reflect real world dynamics (Rotmans and van Asselt, 2001).

An example of a fully integrated model is the IIASA-LUC model (Fischer and Sun, 2001). Although this model incorporates many sub-systems, interactions and feedbacks it has become complex to operate and, aboveall, difficult to parameterise due to the high data requirements that are difficult to collect for most countries (see Briassoulis (2001) for a discussion of data needs). Another disadvantage of highly complex, integrated models is that the degree and type of integration often appears to be subjective based on the modellers disciplinary background. As a fully integrated approach, qualitative modelling (Petschel-Held et al., 1999) allows a focus on the system as a whole, however, also this approach is completely based on the knowledge of the developer about the existence and importance of the feedbacks important to the studied system, so it is likely to be biased and incomplete.

An integrated approach that models the behaviour of the different subsystems individually but includes numerous connections between these submodels is the Patuxent Landscape Model (Geoghegan et al., 1997; Voinov et al., 1999) that is designed to simulate fundamental ecological processes on the watershed scale, in interaction with a component that predicts the land use patterns. Land use change is dealt with in the economic module (Bockstael, 1996; Irwin and Geoghegan, 2001) whereas all hydrological and ecological processes in the watershed are simulated in the ecological module. The ecological module integrates all processes involved based on the General Ecosystem Model (Fitz et al., 1996). The coupling between the economic module and the ecological module is less elaborated. Output of the economic module, land use change patterns, is used as input in the ecological module whereas the possibility exists that output of the ecological module, e.g. water table depths, habitat health etc., are used as inputs of the economic module, allowing for feedbacks within the system. Also in other integrated land use-ecosystem models, the ecological sub-models tend to be far more integrated than the associated land use models (McClean et al., 1995).

An important finding in the literature of urban systems is the description of the behaviour of actors such that the transportation and land use subsystems are interdependent. The way activities are organised over space has a lot to do with the level of transportation demand. Conversely, supply in transportation infrastructure and services affects how activities are organised in space. The circular nature of the impacts between transportation and land use argues for the integration of land use and transportation analysis. In spite of the need for such an integration, most planners still use separate models for transportation and land use (Kanaroglou and Scott, 2001). The Integrated Transportation and Land Use Package (ITLUP) is credited for first implementing a link between an urban land use model and a transportation model (Putman, 1983). More models followed and are summarised by Kanaroglou and Scott (2001). These are fruitful integrations but still focussed on the urban system and its two main components: employment and transportation. Although integration between these systems can reach a fair degree of complexity (e.g. Fan et al. (2000)), integration with location characteristics is often limited to some site constraints (available land area in a zone) and interactions with the rural hinterland are not addressed. This is surprising as urbanisation is among the most important drivers of change in rural areas. Growing urban agglomerations cause multiple impacts on land use and social structures in the peri-urban areas and their hinterlands. These relate to the provision of non-farm job opportunities, shifts to higher-valued farm commodities (such as vegetables, fruits, or livestock) to meet the demands of urban consumers, and the provision of environmental services and landscape amenities. They also relate to rapid and often chaotic changes in land use along the urban peripheries, and place heavy demands on the ecological system in terms of resource extraction, disposal of waste, and discharge of pollutants. Such alterations of the environment do not come without consequences for land use and land productivity. Regional land use/land cover change models must devise suitable mechanisms for recognising the distinction between urban and rural sectors and for representing the opportunities and tensions that derive from their interaction. The increasing urbanisation of the world population has triggered major qualitative and quantitative changes in the pressures on land use and land cover that must be modelled through a more complete representation of the relevant processes (Grimm et al., 2000).

## Discussion and conclusions

The discussion of the theoretical and practical aspects of land use change modelling has shown that a wide variety of approaches and techniques exists, rooted in a multitude of disciplinary backgrounds, to model land use change. A first assessment already makes clear that different modelling groups have focussed on different concepts to elaborate upon and that a further integration of the different approaches and techniques will enable progress. At the same time the discussion also indicates a number of issues where we still lack enough understanding to judge which approach will most efficiently improve land use modelling. This leads to a list of priorities that need to be given specific attention in a new generation of land use models:

*Better address the multi-scale characteristics of land use systems*

The rising awareness of scale dependencies and upscaling problems has provided land use modellers with the challenge to find approaches to deal with multiple scales. It is, however, still unclear to what extent scale dependencies in driving forces are really important. Preliminary studies provide different conclusions on the magnitude of the effect of scale on the relations with driving forces (Veldkamp and Fresco, 1997; Kok and Veldkamp, 2001; Walsh et al., 2001). If scale-effects are small, it is possible to simply extrapolate the behaviour of individuals to larger groups of people, which would render micro-economic models (given their behavioural assumptions) valid for applications at the regional level. Multi-agent models might help us to explore scale dependencies in more detail by linking the behaviour of individuals to the behaviour of groups. These modelling techniques have only recently found their application in land use modelling, but have a lot of potential to unravel some of the structural complexity of the system.

Another problem in land use modelling is the quantification of the interactions of processes operating at different scales. How important are bottom-up processes as compared to top–down processes? To what extent do regional dynamics impact on local conditions? Few methodologies are available to study this type of scalar dynamics. Multi-level statistics provide a first method to fill this gap, but it is certain that more methodological developments are needed.

*Development of new techniques to assess and quantify neighbourhood effects*

Cellular automata models are very common in land use studies, especially when focussed on urban development. The theoretical basis of the quantification of the neighbourhood functions for the cellular automata is however poor. Quantification of this type of relations is now mostly based upon expert knowledge. It is recommended that a more sophisticated and reproducible way is developed to define these neighbourhood effects. A few recent publications address this issue and provide techniques to empirically quantify cellular automata models (Sui and Zeng, 2001; Li and Yeh, 2002; Verburg et al., 2004). At the same time a balance must be achieved between neighbourhood effects as a consequence of direct interactions between neighbouring land uses and neighbourhood effects caused by spatial autocorrelation in the driving forces. If too much weight is attributed to the interaction between land use types themselves the modeller takes the risk to end up with a model that lacks causality.

*Explicit attention for temporal dynamics*

The geographical disciplines have given considerable attention to the spatial dynamics of land use. The temporal aspects, especially the interaction between spatial and temporal dimensions, have been given much less attention. Also the influence of non-linear pathways of change, feedbacks and time-lags deserve considerable attention in future studies. Availability of data with the necessary temporal and spatial resolution will be the most important constraint for such research. Connected to this issue is the validation of models: how good are the models that we produce for projections into the future. Validation is possible on historic data and should be standard to any model. The lack of validation of most current land use models makes it impossible to properly assess the performance of these models. Validation would enable to inform policy makers, and other users of model results, on the uncertainties in the model outcomes and help the modeller to assess the suitability of the model for a particular situation and provide ideas to improve the model.

*Further thematic and methodological integration*

Although all land use models integrate different disciplines by definition, they are often still too much based on the concepts and methods of a certain discipline. Three aspects of integration have been given very limited attention:

- Methodological integration: techniques and methods developed in very different disciplines might help to better develop simulation algorithms. Multi-level statistics, originating from educational research have already proven to be useful in the analysis of the hierarchical structure of land use. Hydraulic models might help to understand traffic congestion and ecological models can give hints of dealing with the hierarchical organisation of land use (Dale and Pearson, 1999).

  This type of integration requires land use researchers to move beyond their disciplinary traditions and loosen the theoretical paradigms set by these disciplines. A couple of research projects in land use analysis has already shown that such approaches can result in innovative results, e.g. recent attempts to link social science research with geographical data (Geoghegan et al., 1998; Walsh et al., 1999; Mertens et al., 2000; Walker et al., 2000; Walsh and Crews-Meyer, 2002). Linking socio-economic and geographical data is a means to provide information on the context that shapes social phenomena.
- Assessment of the effects of land use change and their feedback on land use, e.g. soil degradation, water resources and infrastructure development.
- Urban/rural interactions: presently few models explicitly address the interaction between urban and rural areas. Large impacts are to be expected of these interactions both in developed countries through the emergence of multi-functional land uses in the rural hinterlands of cities, and in developing countries where unequal development between cities and rural areas and food security are important issues.

The large volume of recent papers referred to in this study, the multitude of new models and the growing group of researchers gathered in the Land Use and Land Cover Change (LUCC; Lambin et al., 2001) research community indicates that large investments are being made to improve land use change models. This paper has shown that for such research a large variety of concepts, approaches and techniques is already available: combining the strength of these concepts, approaches and techniques instead of elaborating on the approach belonging to the modeller's own discipline alone will help to built a new generation of land use models. Such interdisciplinary models will be based on bundling of strengths of the multi-disciplinary land use research community and help to better understand these complex systems and to better communicate with the stakeholders of land use change.

### Acknowledgements

We would like to acknowledge two anonymous reviewers for helpful comments and suggestions on an earlier version of this manuscript.

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